Research Report
KTC-09-08/FR136-04-5F

KENTUCKY TRANSPORTATION CENTER

VEHICLE TIRE-PAVEMENT INTERFACIAL SURFACE PRESSURE MEASUREMENTS AND ASSESSMENTS

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Research Report

KTC-09-08/FR 136-04-5F

Vehicle Tire-Pavement Interfacial Surface Pressure Measurements and Assessments

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ABSTRACT

This report examines a method of using Piezoelectric Pressure-Sensitive Ink (Tekscan) Pressure Measurement System to evaluate vehicle tire pressures that are exerted on the surface of pavements. Upgrades to the Tekscan system facilitated refinements from previous research and allows for procedures to be modified in order to account for these improvements. Among the most significant advances is the ability to select various sensitivities within the software program. In addition to the methodology of evaluating calibration practices, sensitivity and sensor selection, it was important to determine how accurately the pressures and wheel loads can be computed from pavement tests. Also examined are the effects of variations of the measured tire inflation pressures on the measured contact areas. The Tekscan system is recognized as being applicable for measuring pressures in a variety of settings and conditions. This pavement research testing program adds to the knowledge base. The findings will ultimately lead to an enhanced understanding of how a pavement structure functions at the surface. This will aid in improving pavement design procedures.

Keywords: Tire-Pavement Pressure, Piezoelectric Pressure-Sensitive Ink, Tekscan, Pressure Measurement, Highway Pavements

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16. Abstract

This report examines a method of using Piezoelectric Pressure-Sensitive Ink (Tekscan) Pressure Measurement System to evaluate vehicle tire pressures that are exerted on the surface of pavements. Upgrades to the Tekscan system facilitated refinements from previous research and allows for procedures to be modified in order to account for these improvements. Among the most significant advances is the ability to select various sensitivities within the software program. In addition to the methodology of evaluating calibration practices, sensitivity and sensor selection, it was important to determine how accurately the pressures and wheel loads can be computed from pavement tests. Also examined are the effects of variations of the measured tire inflation pressures on the measured contact areas. The Tekscan system is recognized as being applicable for measuring pressures in a variety of settings and conditions. This pavement research testing program adds to the knowledge base. The findings will ultimately lead to an enhanced understanding of how a pavement structure functions at the surface. This will aid in improving pavement design procedures.

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EXECUTIVE SUMMARY

A Piezoelectric Pressure-Sensitive Ink (Tekscan) Pressure Measurement System was used to assess and predict passenger vehicle tire pressure intensities exerted on highway pavement surfaces. Recent upgrades to the measurement system include the abilities to select various sensitivities and adjust capacities within the software program. The accuracy of the system was evaluated for both the calibration procedure and direct pavement tests.

The sensitivity and associated capacity can be directly adjusted in the Tekscan I-Scan software. Repeatable results can be achieved with Tekscan sensors with little variations and repetitive loads do not negatively affect the sensor's memory. The repeatability depends on calibration factors remaining stable or being accounted for. Sensor drift is minimal in its affects, but calibrations should be performed in conjunction with the testing. Pavement pressures can be accurately computed directly from calibrations and indirectly from calibrations. Net pavement pressures are always higher than gross pavement pressures for treaded tires. As the tire inflation pressure increases, the measured contact area decreases. The relationship between measured contact area and measured tire inflation pressure can effectively be modeled as a 2nd order polynomial.

The Tekscan system is recognized as being applicable for measuring pressures in a variety of settings and conditions. The pavement research testing program described herein adds to the knowledge base. The findings can ultimately lead to an enhanced understanding of how a pavement structure functions at the surface and will aid in improving pavement mixture and structural design procedures.

CHAPTER 1. INTRODUCTION AND SCOPE OF RESESARCH

1.1 BACKGROUND

In today's economy, funds are less prevalent for investing in major infrastructure improvements, especially transportation related facilities. However, a key component to the continued success of this country remains the need for an efficient transportation system. Unfortunately, developing this new infrastructure sometimes isn't always possible because the increasing funds that must be dedicated to the maintenance of these systems.

Although recent reports have highlighted that Americans have been driving less in reaction to high fuel prices, it seems inevitable that there will be an increase of vehicle miles travelled in the future. Previous research has detailed the damaging effects of wheel loads upon the pavement. Therefore in order to fully fund new infrastructure projects it is important to investigate possible solutions in creating transportation facilities that are sustainable, so that the future maintenance and operation budgets of the agencies responsible for their continued upkeep can be significantly reduced.

1.2 OBJECTIVES

In order to fully understand the magnitude of pressures exerted on a roadway when subjected to vehicle wheel loads, surface pressure measurements must be recorded and the results analyzed. The specific goal of the research reported herein is to evaluate the performance of the Tekscan I-Scan system in predicting wheel loads and measuring pavement pressures. Tekscan utilizes sensors that exhibit piezoelectric properties and are able to generate electric potential in response to mechanical stress. In order to accomplish the goal, it was necessary to use the following multi-step approach:

- Review and summarize previous graduate student research focusing on Tekscan,
- Develop procedure to select proper sensitivity setting,
- Assess the ability of the system to predict wheel loads and pavement pressures, and
- Evaluate the effects of tire inflation pressure on measured pavement pressures and contact areas.

CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION

2.1.1 Overview

This section reviews and evaluates research completed by previous graduate students at the University of Kentucky whose research utilized Tekscan sensors as the primary data collection device. The use of Tekscan at the University of Kentucky began in 2003, and has since evolved. The two most recent pertinent reports are those submitted by Shawn Ray in 2007 (Ray, 2007) and Justin Anderson in 2006 (Anderson, 2006).

2.2 TEKSCAN MEASUREMENT SYSTEM

2.2.1 Early Research

The initial research evaluated the pressures in railroad applications. Jason Stith developed a procedure to effectively collect and analyze pressure at rail/tie plate/tie interfaces (Stith, 2004)(Rose & Stith, 2004). Stephanie Christian researched pressure measurements in highway applications. She used a section of a radial tire to imitate a wheel load onto asphalt pavement, and from that calculated the pressure placed onto the pavement (Christian, 2005).

While the research and results were meaningful, the data collection hardware used with this testing was cumbersome and bulky. The original Tekscan system was PCI based, and thus required the use of a magma box and battery to supply power to the sensors. This system was hard to transport and didn't easily facilitate field experimentation. Also, the system required the purchase of sensors based upon potential loading magnitudes without the ability to select the desired sensitivity.

2.2.2 USB System Upgrade

Developments in enhancing the Tekscan system to become USB based followed this early research and results in a more user friendly product eliminating the need for the magma box and battery to supply power to the sensor. The new system consists of a USB based handle that connects directly to the sensor and plugs directly into a USB port on a computer, which powers the sensor. This permits researchers to become more mobile, expand upon earlier research, and enables them to address some of the documented shortfalls.

2.2.3 Tire/Asphalt Pressure Distributions

Tekscan related research continued to expand with Justin Anderson developing a procedure for measuring the pressure distributions throughout the layers of an asphalt pavement. He created a model that included asphalt pavement sections that remained unbounded so that the sensors could be inserted between layers. Various tires were loaded on the aforementioned specimen, and these known loads provide the pressures using sensors located at varying depths (Anderson, 2006).

As a result of Anderson's research, the following conclusions were drawn:

> *"Using a pressure sensitive material, like the Tekscan sensor, for measuring pressures on the surface and within an asphalt pavement is an intriguing concept. The goal of this research was to develop a means for taking a simple measurement of pressure at various interfaces on and within an asphalt pavement structure in an effort to directly assess the damaging effects of different wheel loadings. The results of the data can be compared to*

> *the classic empiricalistic and mechanistic approaches to asphalt pavement design and analysis, as well as the more modern finite-element computer modeling programs.*
>
> *Various types of wheel loadings have been considered throughout this study. It has been determined that the type of tire, tire inflation pressure, applied load, and the asphalt pavement all have an effect on the pressures on the surface of and within an asphalt pavement structure. This was accomplished by incorporating a higher technology into the much older science of asphalt pavement design. The technical aspects of the Tekscan Pressure measurement system is constantly being improved and researchers are finding new and beneficial uses for it. However, the applications for the Tekscan system within asphalt pavement studies have yet to be exhausted" (Anderson, 2006).*

Subsequent research, performed by Shawn Ray, attempted to account for the documented shortcomings in previous research, and that led to the use of smaller tires in order to reduce the boundary effects of the model. The procedure remained the same, while the calculation of the pressure at the varying levels slightly changed in order to account for the variation in load experienced throughout the specimen (Ray, 2007).

In addition Ray was able to draw the following conclusions from the research:

> "*Bond between layers still has unknown effects on pressure measurements for similar layer thicknesses.*
>
> *Boundary conditions have been maximized in relation to the size of tire during this study; however it is unknown how well it represents an actual roadway.*
>
> *Calibration factors derived from asphalt/asphalt interface should be used during laboratory experimentation to be more representative of what the Tekscan sensor experiences within the pavement specimen.*
>
> *Tekscan sensors are applicable for measurements of pressure and contact areas at the tire/asphalt interface of various textured pavements.*
>
> *In review, Tekscan sensors are applicable for measuring pressures on and within asphalt pavements. The results are repeatable and produce data that is intuitive in both the laboratory and at the test track" (Ray, 2007).*

CHAPTER 3. TEKSCAN PRESSURE MEASUREMENT SYSTEM

3.1 INTRODUCTION

3.1.1 Overview

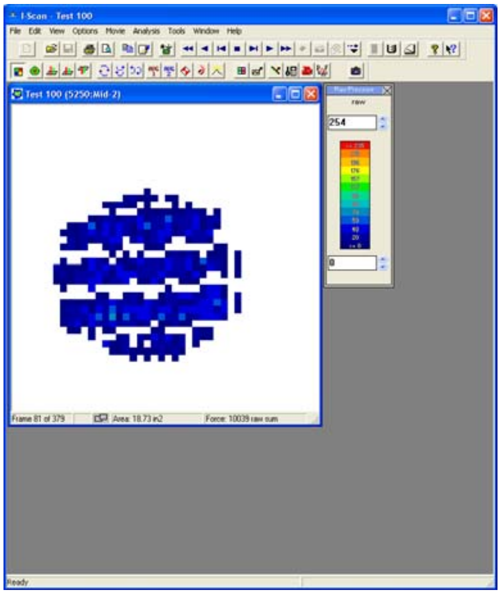
Tekscan Pressure Measurement systems can be used for a variety of applications including automotive and industrial to medical and dental. Each system is specially designed to function in the desired environment.

Many major tire manufacturers utilize the Tekscan system to constantly improve their product. Tekscan offers a system called Tirescan that is specially manufactured for these purposes. The I-Scan Pressure Measurement System was used for the testing described in this report. It consists of a proprietary measurement handle and the Windows based I-Scan software. A variety of sensors (also known as sensor maps) can be used with this particular system, therefore allowing for maximum flexibility of testing scenarios. As compared to the more specialized Tirescan system, the overall flexibility afforded in the chosen I-Scan system allows for a wide range of testing with this single system.

3.2 I-SCAN SYSTEM FUNCTIONALITY

3.2.1 Overview

Essentially, the system functions by connecting the chosen sensor to the proprietary handle that connects to a computer USB port. The output is displayed via the I-Scan software and can be saved to the computer hard drive. The output, a sample is shown in Figure 3.1, provides an image of the measured specimen supplying the force in a color plot that contains a measured contact area as well as a measured raw sum. The raw sum measure is proprietary to the software, but easily allows the user to convert to an engineering unit such as pounds-force (lbf) or Newtons depending on the particular application.



Frame 81 of 379 | Area: 18.73 in2 | Force: 10039 raw sum

Figure 3.1. I-Scan Software Screenshot

3.2.2 USB Handle Upgrade

A major aspect of this research seeks to investigate the improvements made in early 2008 to the USB Handle. Previous research with the I-Scan system didn't allow for the adjustment of the sensitivity of the chosen sensors. Instead sensors had to be purchased based upon predicted pressure ranges for each particular application. The upgrade allows for the user to select a sensor based more on size and shape, and then to adjust the sensitivity of the said sensor through added capability in I-Scan software. A typical view of the handle, sensor, and computer is contained in Figure 3.2.

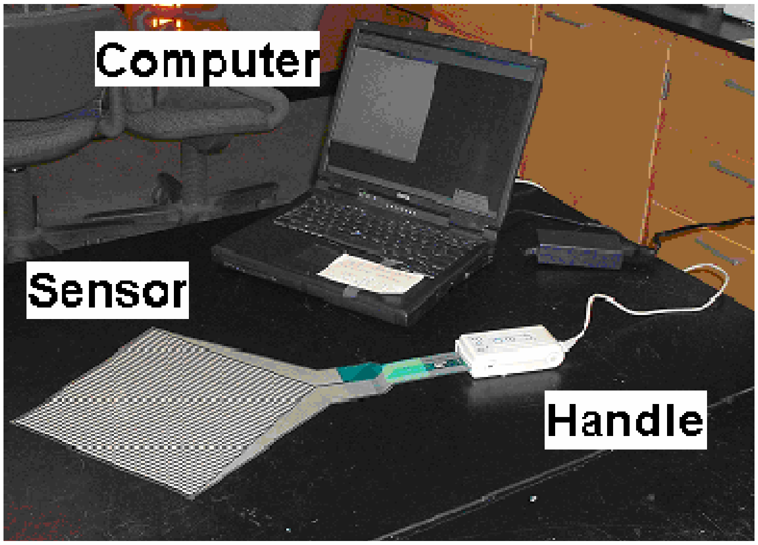


Figure 3.2 Tekscan USB Handle, Sensor and Computer (Anderson, 2006)

3.3 SENSOR SELECTION

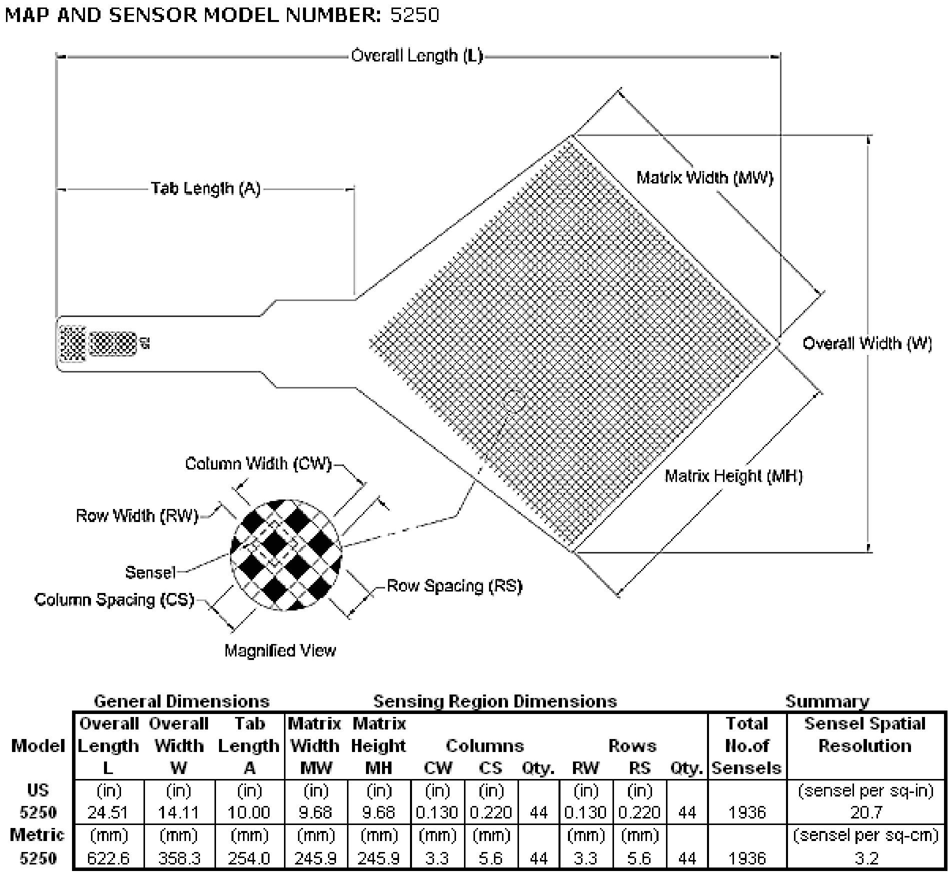
3.3.1 Overview

While the decision on the type of Tekscan system to be used is important, the particular sensor selected is also important, since the sensor is the means of capturing the desired data.

Tekscan identifies six selection criteria that must be noted in order to aid in the sensor selection (Tekscan, 2006). Descriptions of these follow:

3.3.2 Size and Shape

The size and shape must be configured to accommodate the desired measurement area. The sensors are available in a large variety of sizes and shapes and can also be custom ordered for unique situations. Figure 3.3 shows details for a typical 5250 series sensor.



	General Dimensions			Sensing Region Dimensions								Summary	
Model	Overall Length L	Overall Width W	Tab Length A	Matrix Width MW	Matrix Height MH	Columns CW	Columns CS	Columns Qty.	Rows RW	Rows RS	Rows Qty.	Total No.of Sensels	Sensel Spatial Resolution
US	(in)	(in)	(in)	(in)	(in)	(in)	(in)		(in)	(in)			(sensel per sq-in)
5250	24.51	14.11	10.00	9.68	9.68	0.130	0.220	44	0.130	0.220	44	1936	20.7
Metric	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)		(mm)	(mm)			(sensel per sq-cm)
5250	622.6	358.3	254.0	245.9	245.9	3.3	5.6	44	3.3	5.6	44	1936	3.2

Figure 3.3 Tekscan Sensor # 5250 Specifications (Tekscan, 2006)

3.3.3 Pressure Range

Even though the sensitivity of the sensors can be adjusted, as previously noted, a general pressure range must be selected based upon the expected loadings. It is important to remember that concentrated point loads will deliver a more piercing imprint to the sensor, so this must be accounted for in selecting the range. It is generally better to have a sensor that will allow for larger loads than anticipated, so that the loads can be measured properly even if there are areas of higher pressure. When the sensor saturates, it means that the sensor reaches the highest available pressure. The saturation pressure (maximum measured pressure) of 255 raw sum is given in this scenario, even though the actual pressure could be any amount greater than this, thus producing inaccurate results.

3.3.4 Spatial Resolution

The spatial resolution refers to the smallest dimensional area that the system can measure. The grid is made of two layers of piezoelectric pressure sensitive ink that are placed upon one another so that a criss-cross pattern ensues. The areas where these crosses are located are referred to as sensing areas (sensels). The more closely spaced the sensels, then the more accurate the testing. If the sensel area is larger and a small point load is applied, then the value returned will indicate the entire sensel area is being affected. Therefore, if it is known that sharp point loads will be experienced, it may be important to upgrade the spatial resolution of a sensor. It was not deemed necessary to upgrade the spatial resolution requirements for the research reported herein.

3.3.5 Sensor Durability

The durability of the sensor also is of particular importance. Most sensors used are only 0.004 in. (0.10 mm) thick in order to allow for the most realistic contact patterns. Unfortunately, the Ultrathin material is less durable, so care must be taken to avoid damage to the sensels. This research used a thin layer of Mylar and Teflon on each side in order to protect the sensor and reduce the effects for shear stresses that may occur during loading.

3.3.6 Sensor Performance

Tekscan recommends that frequent calibration of sensors will increase the accuracy of the obtained data. During calibration it is recommended that the material used to calibrate the sensor should closely resemble the properties of the material that will be tested. In order to account for this, all of the calibrations were performed on the same day as testing with the same material and loading conditions expected to be encountered during testing.

3.3.7 Sensor Life

How long that a sensor will provide accurate data varies. Typically when the sensor is loaded many times, the pressure range increases causing the sensor to become what is called ‘cold’. Tekscan recommends periodic testing using a load with a known test condition. When results of testing begin to vary greatly beyond the acceptable error, then it is advised that the sensor be replaced.

3.4 DATA ACQUISITION

3.4.1 Overview

There are several ways to capture and view the test data and results. Tekscan allows users to either take snapshots or movies of the imprint of the loadings. As soon as the snapshot function is executed, the image shown is exactly the imprint at that instant. A movie is simply a series of snapshots at a specified frame rate, and becomes useful when the loading is not consistent. In this research, the nature of testing only allowed for movies to be used, therefore only these methods in capturing data will be discussed. The Tekscan USB Evolution Handle Specifications are contained in Appendix A.

3.4.2 USB Handle

The USB handle, Figure 3.4, is also referred to as the Evolution Handle. The handle serves as the connection between the sensor (input) and the computer (output), and has the ability to convert analog measurements to digital electronics. The handle utilizes an 8-bit digital conversion to a deliver an output image of the particular imprint along with a raw sum and contact area of that image.

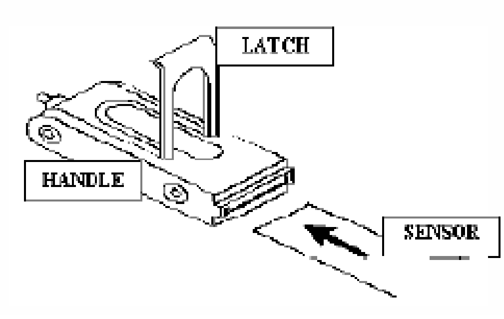


Figure 3.4 Illustration of Sensor Connection to the USB Handle (Tekscan, 2006)

3.4.3 I-Scan Software

The output of the sensor is converted to a digital image via the handle and is transmitted to the computer in the I-Scan software program. The I-Scan software serves as the primary means of evaluating and viewing the data. The program also allows the user many options to control how the data is to be collected. The sensitivity of the sensor is of particular importance, and based upon the loading, the sensitivity can be adjusted to obtain more accurate results.

Movie mode has controls that allow for adjustment for how data is collected along with how it is to be viewed. Adjustments can be made to the frame rate and length of movie. The viewing of the data in movie mode is set up to resemble modern DVD format and is comprised of buttons that allow for the data to be played forward and backward, along with pause, stop, and frame by frame searching. Figure 3.5 illustrates the setup of the upper toolbar that contains these features among many others.

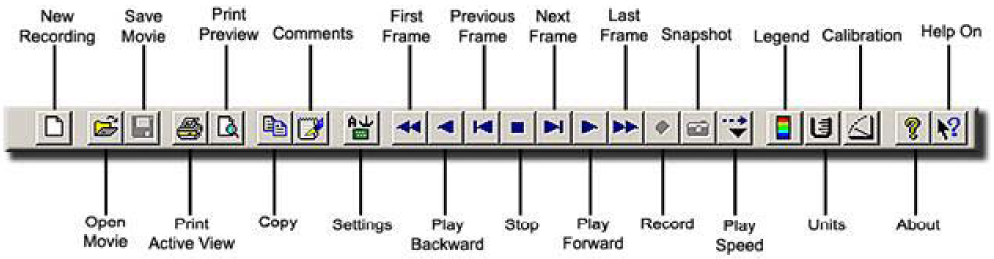
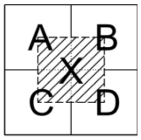


Figure 3.5 I-Scan Upper Toolbar (Tekscan, 2006)

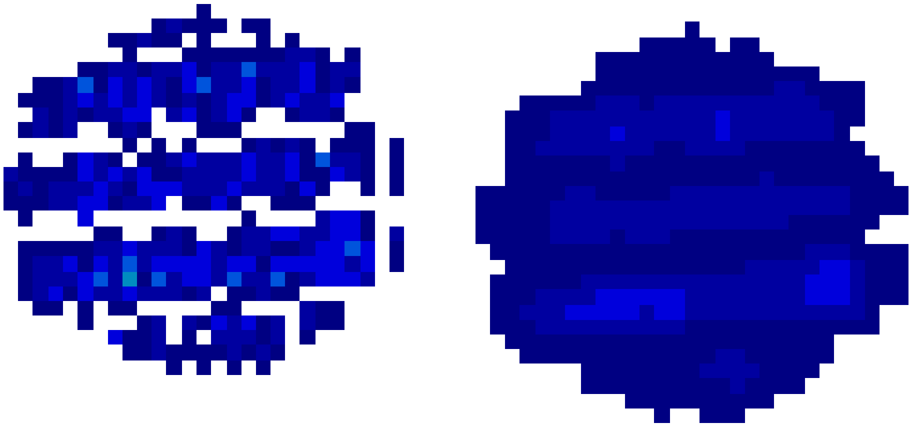
I-Scan delivers the output in a 2-D **default view**, which will be referred to as the net view in this report. At the point where the four sensels meet, one quarter of each of sensels is averaged together to create the displayed cell. The formula used to compute this view is shown in Figure 3.6. Each cell has an assigned color based upon the pressure experienced in that section of sensels. This view will be the most representative of what is actually in direct contact with the sensor.



$$X = \frac{A+B+C+D}{16}$$

Figure 3.6 Tekscan Formula Used to Produce Net View.

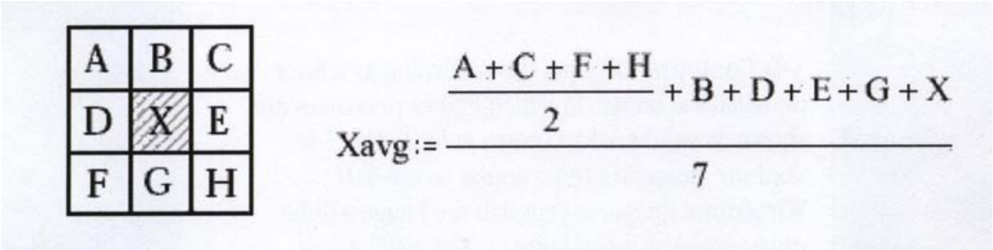
Also of importance is the 2-D **averaging view**, which will be referred to as the gross view in this report. The gross view will provide an average of the entire data set, and is more representative of a flat uniform surface in contact with the sensor. These two views are shown in Figure 3.7. Specifically, Tekscan uses a formula to calculate the average view based upon the results of the net view. This formula, shown in Figure 3.8, will compute a weighted average of the surrounding cells (Tekscan, 2006).



Default (Net)

Averaging (Gross)

Figure 3.7 I-Scan Views



$$\mathrm{Xavg} := \frac{\frac{A+C+F+H}{2} + B + D + E + G + X}{7}$$

Figure 3.8 Tekscan Formula Used to Average View (Tekscan, 2006)

3.5 SENSOR CALIBRATION

3.5.1 Overview

In order to obtain accurate, repeatable results, Tekscan recommends that the sensors be calibrated regularly with a known test condition. Environmental conditions can also affect results, so it is desirable to complete calibrations on the same day as testing with specimens that have similar properties to those that will be tested.

3.5.2 Calibration Factor

The calibration factor is especially important because it allows the user to convert the proprietary unit of raw sum into a known engineering unit of force such as pounds-force. In order to compute the calibration factor for a particular test it is first necessary to use a known test condition with a known load that exhibits similar properties as the specimen to be tested. With this known load, a test can be performed, and the output will deliver both a measure of contact area in square inches along with a measure of raw sum. Therefore, the user can then take the output of raw sum and divide it by the known force to get a calibration factor. This is illustrated in Figure 3.9. This calibration factor becomes especially important when analyzing data, and without an accurate calibration factor, it becomes nearly impossible to predict accurate results.

$$CalibrationFactor = \frac{RawSum}{KnownForce} = \frac{10000RS}{840lbs} = 11.90\frac{RS}{lbs}$$

Figure 3.9 Calibration Factor Calculation

3.5.3 Sensor Drift

The phenomenon known as sensor drift occurs over a period time of repeated use of a particular sensor. The sensor itself is known to be affected by different environments. This can be attributed to the materials used to formulate the sensor, but also to sensor drift. Drift occurs when, over a period of time, the sensor reports different measurements of raw sum and area for the same known load. Therefore it reinforces the need for calibration of the sensors for testing, so that when drift is suspected, the proper steps to address the effects can be taken.

CHAPTER 4. INITIAL INVESTIGATIONS

4.1 INTRODUCTION

This section details the procedure used in the experimental testing to obtain the desired data. Previously, testing was done primarily in the laboratory setting, but this research relied solely on field measurements. The procedure is similar to that used in previous research, but some changes were made to accommodate the field testing methods utilized in this research.

In addition, explanations will be given on the reasons why the particular sensitivity and sensor selected are significant. Although an in-depth analysis is not needed at the beginning of testing, it is important to understand the data, because decisions made during the testing, following these initial tests, are crucial to providing accurate results. Detailed data tabulation is contained in reference (Guenther, 2008).

4.2 PROCEDURES

4.2.1 Field Testing Location

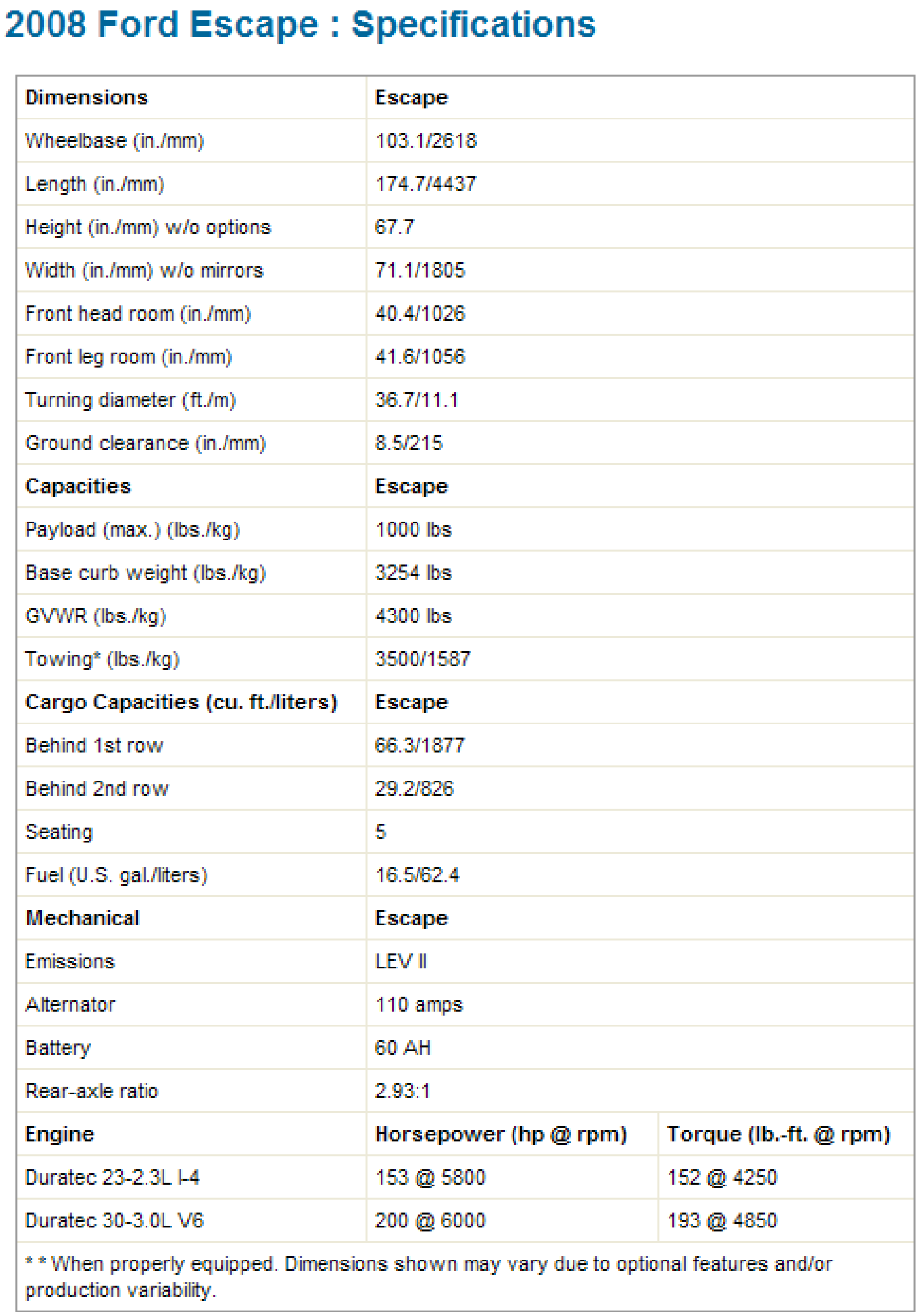
The first task is to find a suitable test location. Contact with a local asphalt paving contractor yielded an opportunity to use their facilities for the testing. The test site is located at 1637 Jaggie Fox Way in Lexington Kentucky. Figure 4.1 is a map that illustrates its location. This proved to be an ideal location because the facility had an on-site calibrated industrial vehicle scale. The scale is used by the contractor to measure the weights of tractor trailers before and after they were loaded with liquid asphalt so that an accurate measure of their bill of lading can be computed. For this testing, the scale allowed for the proper weight of the test vehicle and its individual tire weights to be recorded with both precision and accuracy.

Figure 4.1 Testing Location Map

4.2.2 Field Test Vehicle

The test vehicle utilized for this research was a 2008 Ford Escape, a compact sport utility vehicle. Although the specifications of the vehicle weight were obtained from the manufacturer (Ford, 2008), it was necessary to measure the weight of the vehicle because variables such as payload and fuel levels will affect the actual weight on a given day. Also, the manufacturer doesn't specify the individual wheel loads, so it was imperative that weights of each axle and individual wheels be recorded. Table 4.1 contains the specifications for the 2008 Ford Escape.

Table 4.1 2008 Ford Escape: Specifications



2008 Ford Escape : Specifications

Dimensions	**Escape**	
Wheelbase (in./mm)	103.1/2618	
Length (in./mm)	174.7/4437	
Height (in./mm) w/o options	67.7	
Width (in./mm) w/o mirrors	71.1/1805	
Front head room (in./mm)	40.4/1026	
Front leg room (in./mm)	41.6/1056	
Turning diameter (ft./m)	36.7/11.1	
Ground clearance (in./mm)	8.5/215	
Capacities	**Escape**	
Payload (max.) (lbs./kg)	1000 lbs	
Base curb weight (lbs./kg)	3254 lbs	
GVWR (lbs./kg)	4300 lbs	
Towing* (lbs./kg)	3500/1587	
Cargo Capacities (cu. ft./liters)	**Escape**	
Behind 1st row	66.3/1877	
Behind 2nd row	29.2/826	
Seating	5	
Fuel (U.S. gal./liters)	16.5/62.4	
Mechanical	**Escape**	
Emissions	LEV II	
Alternator	110 amps	
Battery	60 AH	
Rear-axle ratio	2.93:1	
Engine	**Horsepower (hp @ rpm)**	**Torque (lb.-ft. @ rpm)**
Duratec 23-2.3L I-4	153 @ 5800	152 @ 4250
Duratec 30-3.0L V6	200 @ 6000	193 @ 4850

* * When properly equipped. Dimensions shown may vary due to optional features and/or production variability.

4.2.3 Field Testing Preparation

Before arriving at the test facility, it was extremely important to be well prepared and know the type of testing planned for each particular day. Configuration of the testing equipment was completed prior to arrival on site. All equipment that would not be in the test vehicle during the testing was unloaded from it so that accurate measurements of the vehicle's weight could be obtained.

4.2.4 Field Testing Setup

At the beginning of testing, the vehicle weight was obtained by utilizing the scale at the facility. The individual who would be operating the vehicle throughout the testing remained in the vehicle while the weights were recorded. Located inside the office at the facility was the digital output of the mechanical scale. The placement allowed for measurements to be recorded while visually verifying the wheels of the vehicle that were in direct contact with the scale. The configuration of the scale allowed for the front axle to be weighed, then the entire vehicle, then the rear axle. In addition, individual wheels were also weighed and recorded. Figure 4.2 is a picture of the test vehicle on the scale. The facility's scale measured to the closest twenty pounds, so the ability to record the wheel weights in many different configurations provided the ability to verify and back check the results.

Figure 4.2 Test Vehicle on Facility's Scale

After the vehicle weights were recorded, it was important to measure and record the tire inflation pressures of the test vehicle's tires. These were measured and confirmed using two different measuring devices, because the accuracy of the results would be extremely important for the data analysis and conclusions to follow.

4.2.5 Field Testing Tekscan Procedure

Most of the procedure was well documented (Anderson, 2006) and was used in this research, but some necessary changes were made in the initial setup necessitated by the use of the expanded features included in the upgrade, most notably the sensor sensitivity setting.

Descriptions of the equipment setup and testing procedure follow:

- The first activity is to power up the Computer. If testing is expected to last longer than the laptop computer's battery life, then it is necessary to access a standard 110 volt power outlet or inverter to connect the power cable from the laptop into so that the battery life will not be an issue.

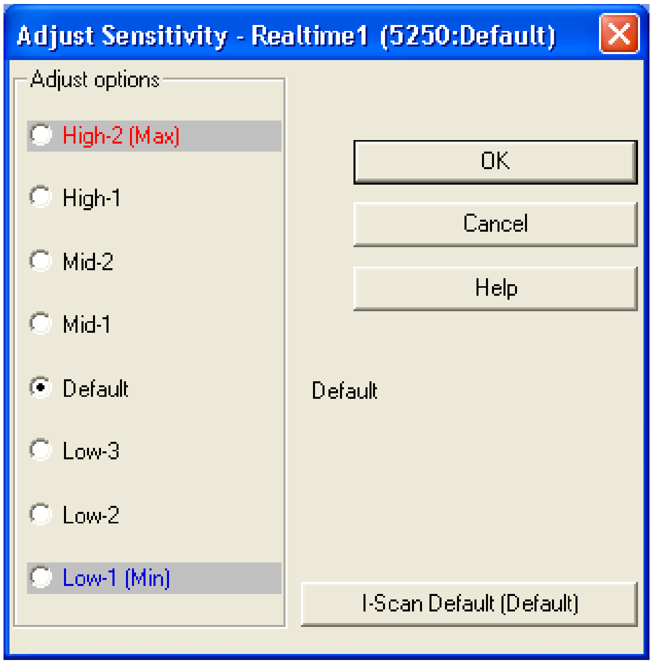
- After the Windows operating system has loaded, locate and plug in the USB handle into the computer's unoccupied USB port.

- After a few moments the USB device will be recognized. Open the I-Scan software from the computer.

- On the menu toolbar, select File, and click New Session. Choose the USB Handle and click OK. An error message will appear, reading "Sensor Misalignment". Ignore this error. It is displayed because the sensor has not yet been connected to the USB handle.

- At this point, take the selected sensor and feed it into the connection on the USB handle, and once the sensor is seated correctly the sensor misalignment error should disappear from the computer display. The green light on the USB handle will remain illuminated to insure the sensor is properly connected. In order to insure the setup is functioning properly, it is desirable to press down on the sensor as it will output the action simultaneously on the computer display.

- After it is confirmed that the sensor is reading, adjustment to the sensitivity can be made. Navigate to Options, and click on settings. Click the Sensitivity tab and choose the desired level. The sensitivity ranges from Low 1 (least sensitive) to High 2 (most sensitive). The selection of the sensitivity is of upmost importance on obtaining accurate results, and will be subsequently discussed in more detail. Figure 4.3 is a screenshot illustrating the range and selection of available sensitivities.


Adjust Sensitivity - Realtime1 (5250:Default)

Adjust options

○ High-2 (Max)

○ High-1

○ Mid-2

○ Mid-1

● Default

○ Low-3

○ Low-2

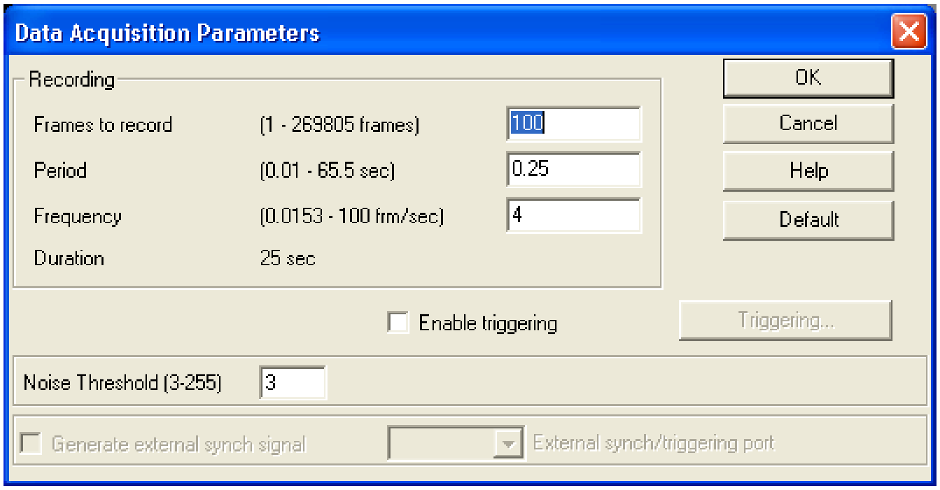
○ Low-1 (Min)

Default

Figure 4.3 Adjust Sensitivity Window

- Additional adjustments that can be made include configuring how movie files are recorded. Figure 4.4 shows where these changes can be made. In the Data Acquisition Parameters window, the options include selecting the number of total frames to record, time period of recording, and the frequency at which frames will be recorded.

- Now the Tekscan system is ready to record measurements. Figure 4.5 shows the completed typical field test setup prior to the testing sequence, using the 2008 Ford Escape vehicle.


Data Acquisition Parameters

Recording

Frames to record	(1 - 269805 frames)	100
Period	(0.01 - 65.5 sec)	0.25
Frequency	(0.0153 - 100 frm/sec)	4
Duration	25 sec	

☐ Enable triggering

Noise Threshold (3-255) 3

☐ Generate external synch signal

External synch/triggering port

Figure 4.4 Data Acquisition Parameters Window

Figure 4.5 Typical Field Testing Setup

4.3 METHODOLOGIES

The initial testing objective was to determine how varying the sensitivity levels would affect the measurements. Previous versions of Tekscan didn't provide for these selections to be made. Therefore this is the first variable that was evaluated for this continuing testing program.

Each test was performed by slowly driving the test vehicle forward and backward across the asphalt pavement and over the selected sensor. In order to keep the variables at a minimum during this initial testing stage, tests were only performed on the test vehicle's right rear tire, with the only variation being the sensitivity levels ranging from High 2 to Low 3. Refer to Figure 4.3 to see the various sensitivity levels from most to least sensitive.

After data was recorded for the aforementioned sensitivity levels with the initial sensor, additional testing was performed using two additional sensors. This provided testing with three different sensors so that the results could be verified as being repeatable between the three different sensors. It also provided verification of which sensor was the most accurate in obtaining measurements.

The results of this initial test sequence follows. In order to decipher the different colors and their meaning, included is Figure 4.6 which is the I-Scan display legend referred to as the Raw Pressure Distribution Color Chart. Figures 4.7 – 4.9 illustrate the effect that the variable of sensitivity selection has on the output of the Tekscan system when the tests are performed using the same specimen and sensor.

It can be seen that the variation in the color palette tends to increase as the sensitivity level is increased. During some tests, it was observed that the output of some cells is red. This color red illustrates the area that is experiencing the highest raw pressure as evidenced by Raw Pressure Distribution Color Chart. Most of the time this will be evidence that the sensor has exceeded the maximum allowable pressure. When the sensor exceeds this level, it is unknown to what extent the actual pressure exceeds this threshold. This uncertainty can cause invalid results because the actual pressure is not measured.

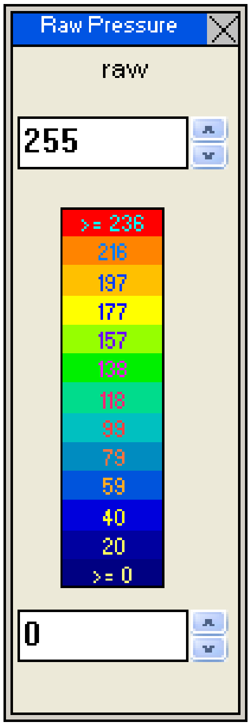


Figure 4.6 Raw Pressure Distribution Color Chart, Raw Pressure Maximum = 255

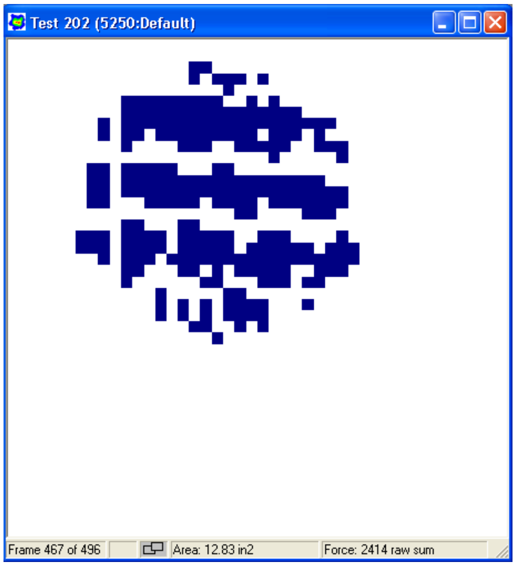


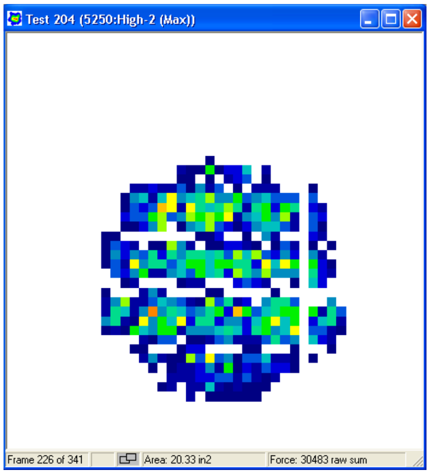
Figure 4.7 Sensor 5250-5, Sensitivity Mid 2, 10/3/08

Frame 304 of 608

Area: 17.47 in2

Force: 9125 raw sum

Figure 4.8 Sensor 5250-5, Sensitivity Default, 10/3/08



Frame 226 of 341

Area: 20.33 in2

Force: 30483 raw sum

Figure 4.9 Sensor 5250-5, Sensitivity High 2, 10/3/08

When observing the data, it became apparent that the issue of displayed cells being saturated was still an issue that needed further explanation. After raising these concerns to Tekscan technical support staff, a method was suggested that would allow for a check on these raw pressures.

Tekscan recommended using the Raw Pressure Distribution Color Chart, and adjust it so that the maximum measured raw pressure would be equal to 254 instead of the default value set at 255. Figure 4.10 shows the adjusted Raw Pressure Distribution Color Chart. This adjusted the scale for not only the red values, but for all ranges of colors. For example, the default setting illustrates values of greater than or equal to 236 to be red. The adjusted scale moves this value down to showing values greater than or equal to 235 as red. Figure 4.11 is the default view with the default Raw Pressure Distribution Color Chart, while Figure 4.12 shows the default view of the same data when the Raw Pressure Distribution Color Chart is adjusted so that the maximum measured raw pressure is equal to 254. This adjustment will effectively allow for the display to show whether or not the cells previously in question of exceeding the maximum measured pressure, are still saturated. If the displayed red cell changes color when the adjustment is made, it will be assumed that the cell in question is within the measurable range. Otherwise, it can be assumed that the red cell is indeed saturated and the data from that particular test is invalid.

Another check can be administered to see whether or not the affected saturated red cells are the result of roadside gravel or debris getting stuck in the tire or underneath the sensor. When in movie mode and using the play function, if the red cell remains in the same place while the tire is rolling over top of it; then it is due to debris on the pavement surface. If the red cell is moving across the screen as the tire rolls across the sensor; then it is due to roadside debris being stuck in the tire.

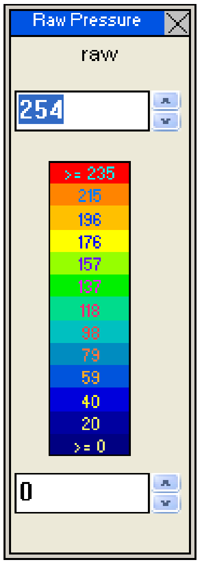


Figure 4.10 Raw Pressure Distribution Color Chart, Raw Pressure Maximum = 254

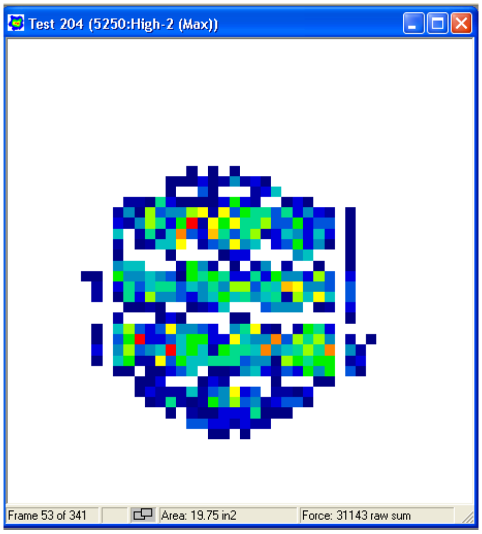


Figure 4.11 Sensor 5250-5, Sensitivity High 2, 10/3/08, Raw Pressure Maximum = 255

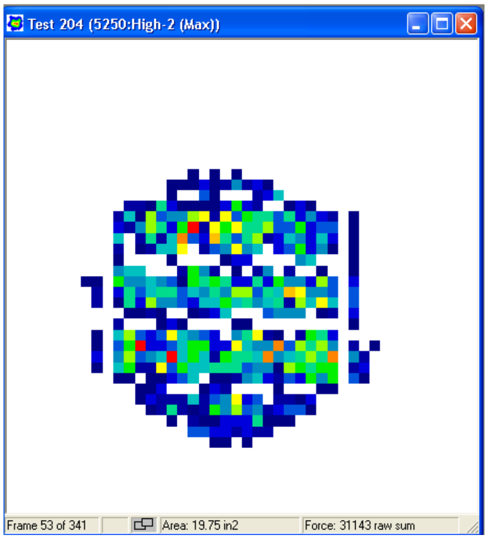


Figure 4.12 Sensor 5250-5, Sensitivity High 2, 10/3/08, Raw Pressure Maximum = 254

4.4 SENSITIVITY AND SENSOR SELECTION

4.4.1 Overview

Once the data was obtained during the initial testing, it was necessary to evaluate and make decisions on what sensitivity and sensors should be used for the remaining testing sessions.

4.4.2 Sensitivity Selection

After visually inspecting the data, it became apparent that different sensitivity settings returned vastly different results. For the same loading condition, it was evident that the lower the sensitivity setting; the lower the raw sum and measured contact area. Inversely, the higher the sensitivity setting; the higher the raw sum and measured contact area.

The first criterion used to select the sensitivity was to see how the measured contact area varied with different sensitivity selections. As previously discussed, the higher the sensitivity setting, the greater the measured area. The tests performed used the same loading procedure and sensor, but had different sensitivity settings. The results of these tests are shown in Figure 4.13. It was then verified that sensitivity does indeed have a direct impact on the measured contact area. Results of this analysis illustrated that Mid 2 sensitivity seemed to be most effective and consistent between trials, but more analysis was needed to insure that the proper sensitivity was selected.

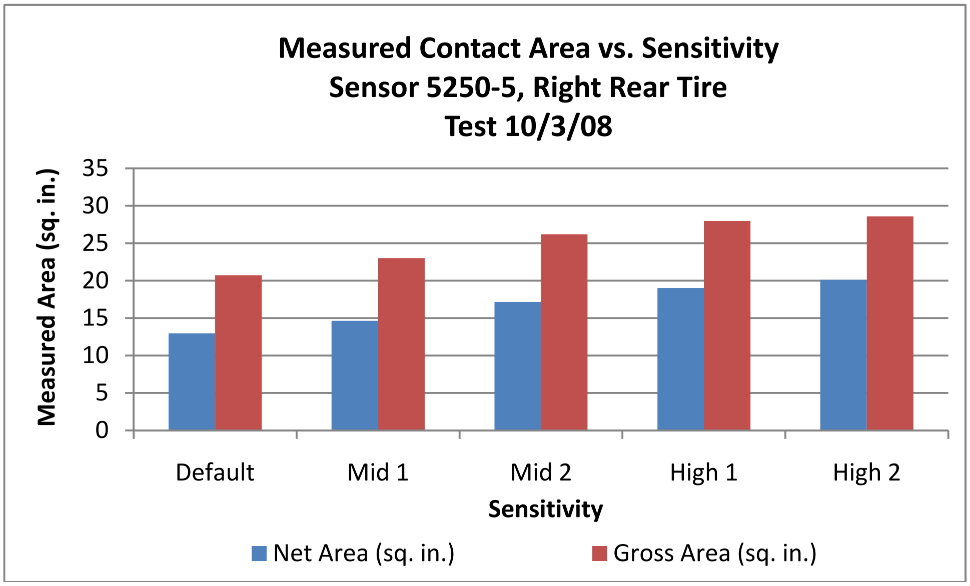


Figure 4.13 Measured Contact Area of Right Rear Tire Based on Choice of Sensitivity

Another important criterion when selecting the sensitivity was to see how closely the measured tire inflation pressure compared to the value of the calculated gross pavement pressure based upon the Tekscan measurement. The assumption was made that the measured tire inflation pressure should be equal to the gross pavement pressure. This assumption was discussed with the Tekscan technical service staff. The decision was, based upon our testing setup, that this would be a valid assumption. Therefore the average gross pavement pressures were calculated for each of the tests used on the right rear wheel of the test vehicle. Each of these tests used the same loading procedure and sensor, but had different sensitivity settings. Figure 4.14 is a chart showing the variation of calculated gross pavement pressures versus sensor sensitivity. From this analysis, both Mid 2 and High 1 seem to most closely represent the measured tire inflation pressure. Although both would seem to yield similar results, it was determined that the heavier loads in the front axle would make Mid 2 the better choice in effectively choosing a single setting for all four tires of the test vehicle.

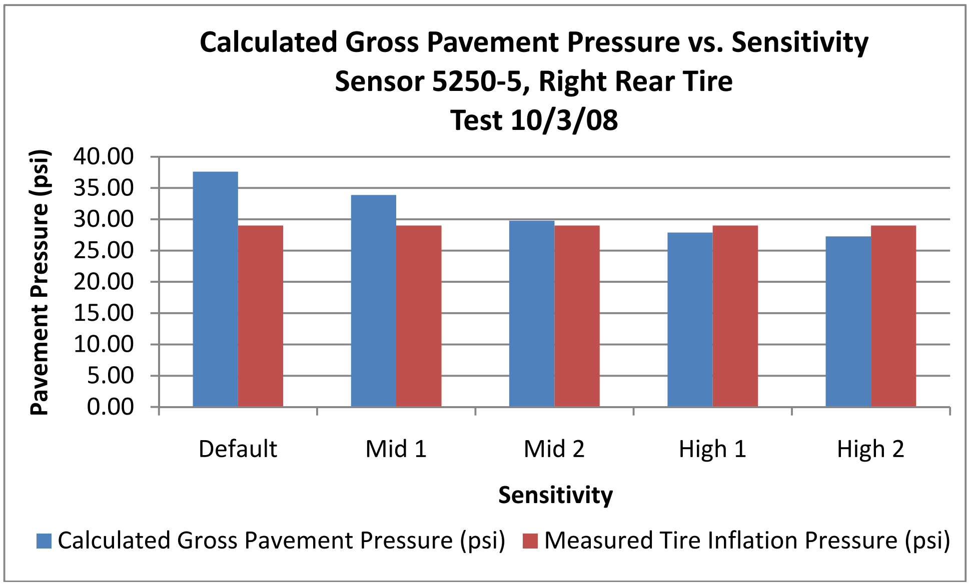


Figure 4.14 Pavement Pressure of Right Rear Tire Based on Choice of Sensitivity.

4.4.3 Sensor Selection

After selection of a sensitivity setting was determined, it was desirable to select the sensor to use for the remainder of the testing. Three identical sensors, designated the 5250 series, were available. These sensors were all used at some point in the testing, but because of time constraints and the need to eliminate this variable, it was desirable to focus most of the testing using only one of the three available sensors.

Further research into selecting a sensor led to the finding that the 5250 sensors have relatively low resolution of 20 sensels per square inch. This compares to other available sensors of similar dimensions that contain up to 277 sensels per square inch. Again this was discussed with Tekscan officials, and the decision was that this would not dramatically change the results based upon the testing scenario used in this research. Therefore because of time and cost restraints only the available sensors were used in this testing.

Analysis of these three sensor maps was then completed during this initial testing to determine which sensor map most effectively measured raw sum and contact area. Therefore, it was determined to compare the calculated pavement pressures of each tire for all three sensors. Figure 4.15 shows the results of the testing, and it is clear that all three sensors measured the pavement pressures of each tire within an acceptable variation. Abbreviations were made to streamline the results in the table and include: right rear (RR), right front (RF), left front (LF), left rear (LR), calculated net pavement pressure (CNPP) and calculated gross pavement pressure

(CGPP). These abbreviations are used in this report when discussing results. As previously mentioned, it was desired to primarily use one sensor for the remainder of testing, and although all sensors would have been acceptable, it was decided to continue using sensor number five of the 5250 series for further testing.

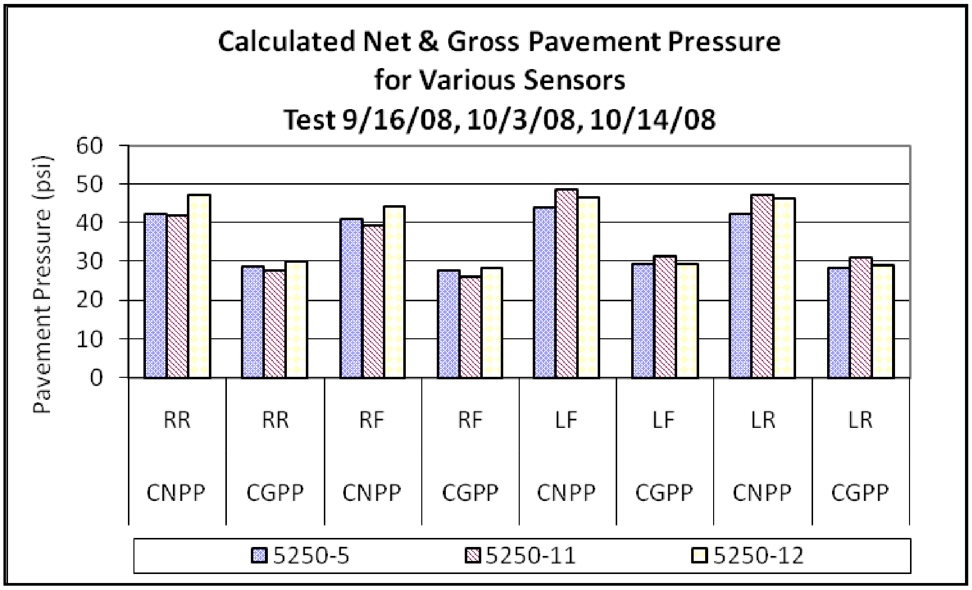


Figure 4.15 Calculated Net and Gross Pavement Pressure Based on Tire and Choice of Sensor

CHAPTER 5. SURFACE PRESSURE MEASUREMENTS

5.1 INTRODUCTION

This section explains how the remaining tests were performed along with analyses for each of them. The initial testing provided the framework for continuation testing. The results of the initial tests yielded the sensitivity setting and particular sensor to be used. This section expands upon the initial results so that more complex analysis can be completed in order to accomplish the objectives.

5.2 REPEATABLE RESULTS

5.2.1 Overview

One of the main objectives of the research was to establish a procedure that provided repeatability and consistency of measurements. The data and results would effectively be useless if the results could not be repeated. In order to test the repeatability, it was determined that two test sessions of repetitive loadings would be conducted. This tested the repeatability of the results over two test dates and also provided a means to check the durability and results of the sensor during each test. It had been observed during initial testing that some of the data seemed to decrease after repeated tests. Further testing had to be performed to determine whether or not this was a function of the sensor beginning to relax over the duration of testing or it was purely coincidental.

5.2.2 Repetitive Loading

In order to measure repeatability of measurements, it was determined that the best way to accomplish this would be to repeatedly drive the test vehicle forward and backward five to ten times (greater than what was typically performed for a normal testing procedure). For example, for testing on October 3rd ten consecutive measurements were taken, while on October 14th twenty consecutive measurements were recorded. All of the repetitive testing was performed on the right rear tire of the test vehicle, with the only variable being the day the test was performed. Figures 5.1 and 5.2 illustrate the results of repetitive loading on the calculated net pavement pressure and on the calculated gross pavement pressure, respectively. The results of the two tests are compared to each other for the first ten measurements, while the remaining measurements are displayed to illustrate that the test was providing results well within acceptable limits.

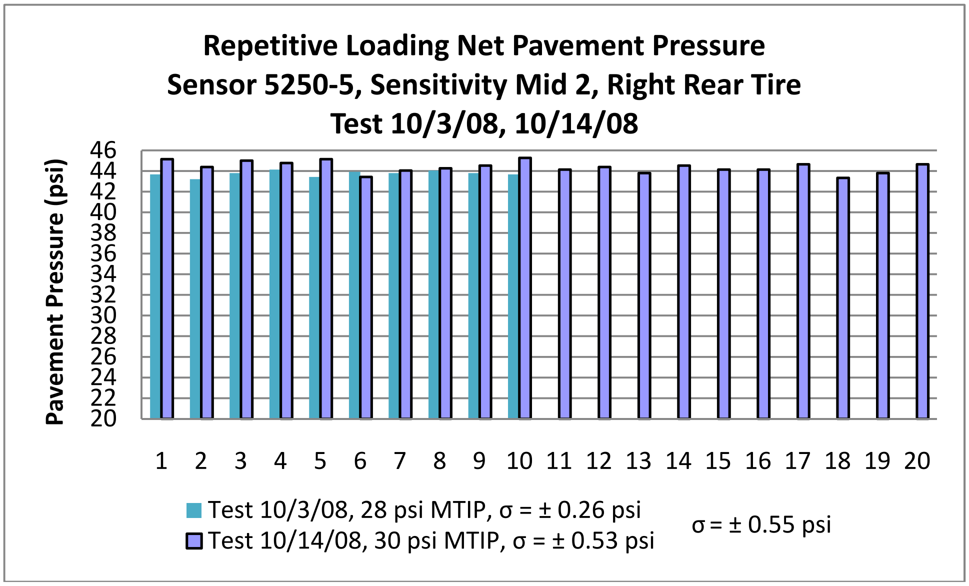


Figure 5.1 Calculated Net Pavement Pressure Based on Repetitive Loading on Right Rear Tire

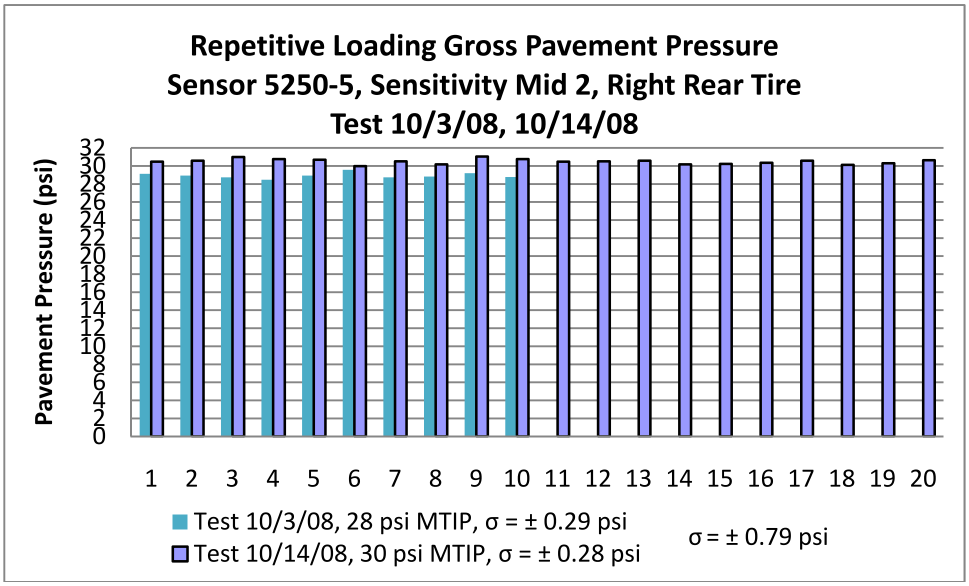


Figure 5.2 Calculated Gross Pavement Pressure Based on Repetitive Loading on Right Rear Tire

Although visual inspection of the repetitive loading data seems to illustrate that the results do not widely vary, it was decided to perform a standard deviation analysis of the results. Standard deviation is defined as the root mean square of the deviations around the mean. The standard deviation was calculated for each day of test data, along with a combined standard deviation of all values that were obtained over the two different days of testing. The standard deviation formula is illustrated in Figure 5.3. In this formula, X bar is the value of the mean, N is the sample size, and X_i represents each data value from i=1 to i=N.

$$s = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N-1}}$$

Figure 5.3 Standard Deviation Formula

The results of the standard deviation computation are shown in Figures 5.1 and 5.2. The standard deviation over both days for the calculated net and gross pavement pressures is equal to ±0.55 psi and ±0.79 psi, respectively. This represents ±1 standard deviation, which accounts for 68.2% of the data in the normal distribution curve as shown in Figure 5.4. An acceptable measure of standard deviation attempts to account for ±2 standard deviations, which results in 95.4% of the data set being included within the acceptable range. If expanded to ±2 standard deviations for the two previous values, then the calculated net and gross pavement pressures would be equal to ±1.10 psi and ±1.58 psi, respectively.

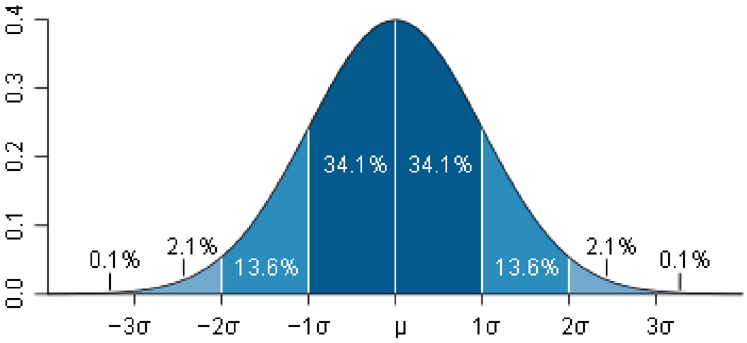


Figure 5.4 Normally Distributed Standard Deviation Curve

5.2.3 Sensor Repeatability

Although previous testing reflected that all sensors performed admirably, further testing began to illustrate a difference between the repeatability of the results when different sensors were utilized. It was important to ensure that all results were repeatable and as illustrated in Figure 5.5 it is clear that the three different sensors returned varying calibration factors for each tire of the test vehicle over the period of weeks that the testing occurred. Both sensor number 5 and 12 returned values that remained fairly consistent between the four tires, while sensor 11 had much greater variation. This again reinforces the decision to primarily use sensor number 5 for the testing.

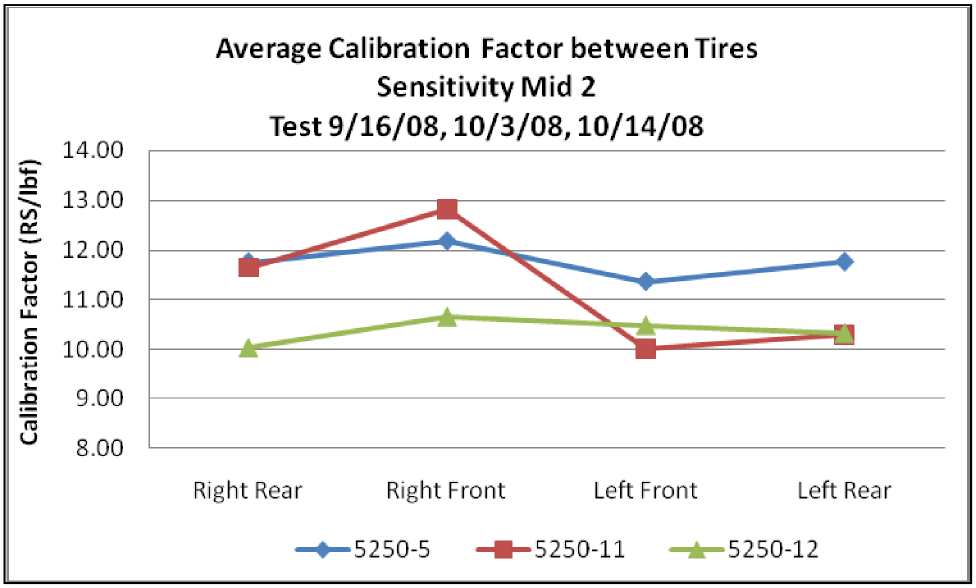


Figure 5.5 Calibration Factor of Each Sensor at Different Tire Locations

A factor that assists in explaining differences in calibration factors over time is the previously discussed phenomenon of sensor drift. Drift was tracked over the time that the research was completed. Past Tekscan research had found that drift caused sensors to report a wide variety of values (Ray, 2007). The recorded drift can be found in Figure 5.6. It must be noted that the tire pressures varied slightly in each days test, and this may contribute to the lower calibration factors during later testing as the tire inflation pressure was slightly increased by two psi. Overall, it was found that drift had little effect on the final results.

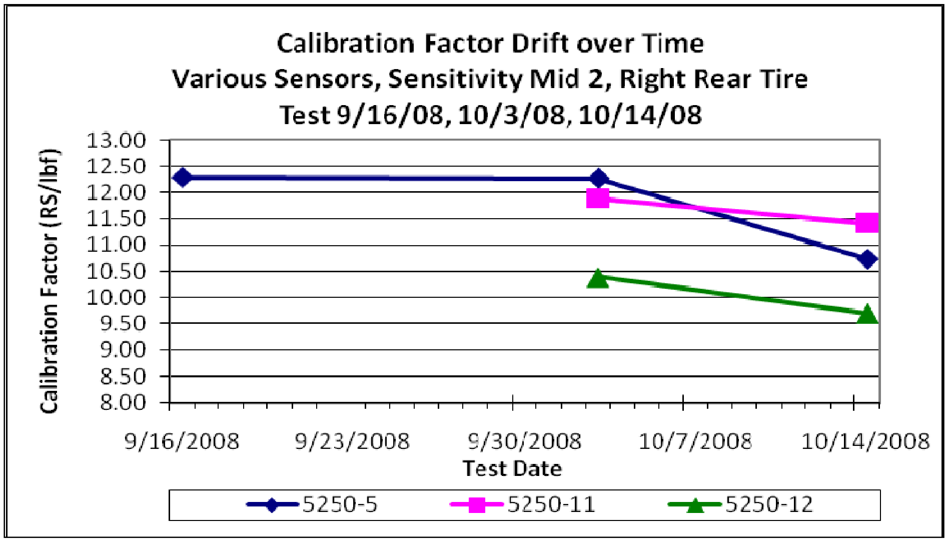


Figure 5.6 Calibration Factor Drift Over Time

CHAPTER 6. ANALYSIS OF DETAILED TEST DATA

6.1 INTRODUCTION

6.1.1 Overview

In order to accomplish the basic objectives, initial testing had to evaluate the effects of controllable variables. Decisions were based upon this testing so that the proper sensitivity levels and sensors were selected insuring that the detailed tests would be accurate. This section analyzes the data collected from the detailed testing that followed the initial testing sessions.

6.2 WHEEL LOADS

The ability to measure the wheel loads at the facility was fairly simple due to the open availability of a commercial grade truck scale at the facility. However, in most instances measuring the load that an individual tire exerts on the pavement is not an easy task. The data collected is analyzed in such a way that will allow for the individual wheel loads to be calculated based upon the individual test data and an established calibration factor.

In order to complete this task, a calibration factor must first be established for the particular sensor and sensitivity setting. As previously discussed, it is generally accepted practice to re-calibrate the sensor each day that testing is performed in order to eliminate any variability that may be present. Calibration involved using a known loading condition with similar properties to the test loading condition and measuring the number of Tekscan raw sum for that test. For this testing phase, the known load was precisely the measured weight of each tire obtained from the commercial vehicle scale. This sequence eventually yields a calibration factor which is simply the number of measured raw sum (RS) per known force (lbf) and is represented as RS/lbf.

This calibration factor is then used in conjunction with the measured data obtained from the other three tires that weren't used in the known loading test when establishing the calibration factor. It is then possible to calculate or predict the wheel load for these three remaining individual wheel locations. The predicted wheel load is calculated by taking the measured raw sum at the tire and dividing it by the calibration factor established from the known load. This is repeated for all four wheels so that results can be compared against one another. Both Figures 6.1 and 6.2 use this methodology to calculate the wheel loads at each individual tire. It appears that the calculated wheel load at each tire compares favorably with the measured wheel load established through the use of the facility's scale.

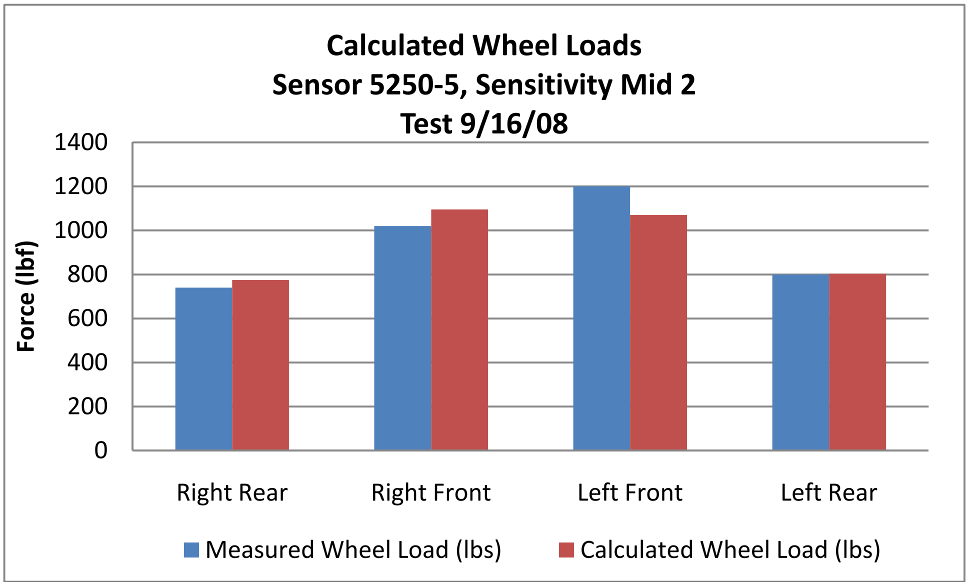


Figure 6.1 Measured Wheel Loads versus Calculated Wheel Loads for Different Tires, 9/16/08

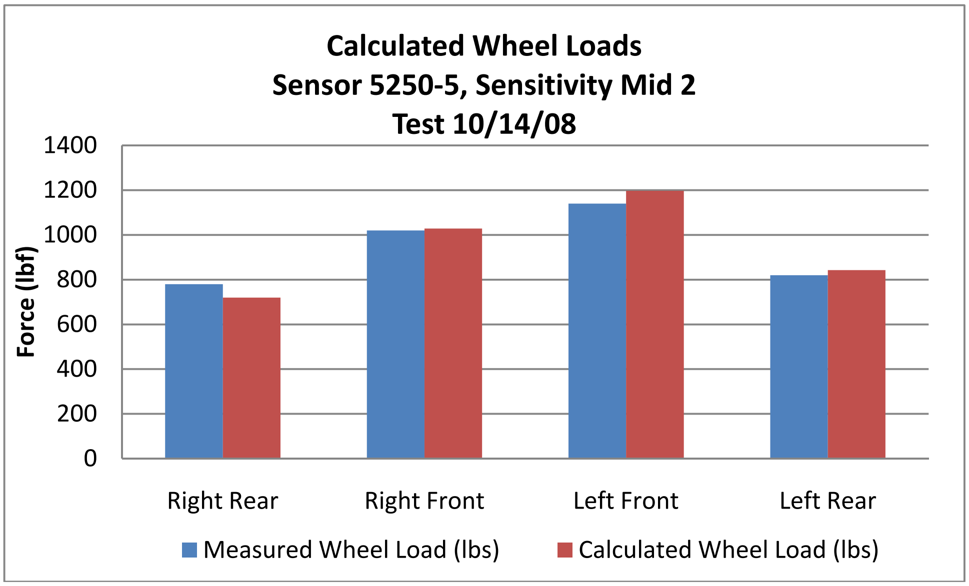


Figure 6.2 Measured Wheel Loads versus Calculated Wheel Loads for Different Tires, 10/14/08

6.3 PAVEMENT PRESSURES

6.3.1 Direct Pavement Pressure

Pressure was initially calculated by using a calibration factor for each individual tire. This computation assumes that each wheel had a known load (measured from scale), and when combined with Tekscan results at each respective wheel, a calibration factor can be computed for each of the wheel locations on the test vehicle. This calibration factor (RS/lbf) is then divided by the (RS/in2) to obtain a pavement pressure (lb/in2). Therefore because this is performed for each wheel load, it is referred to as a direct measure of the pavement pressure.

As illustrated in Figures 6.3 and 6.4, the direct calculated gross pavement pressures are very comparable to the measured tire inflation pressures for all wheels and testing series. This again can be attributed to the gross view more closely illustrating how the tire inflation pressure is actually performing while on the inside of the tire. The gross view spreads the load more uniformly and is more closely related to the uniform surface on the interior of the tire.

Another important aspect of the results is the differences between the recorded net and gross pavement pressures. The calculated net pavement pressure is always much higher than the calculated gross pavement pressure for each of the testing series. The data shows that the net view results in higher pressures because the measured contact area is always much less. Pressure is a measure of load divided by area; therefore, by recognizing this basic relationship, it is apparent that a smaller contact area with a constant load will produce a greater pressure. Inversely, an increase in area, as revealed in the gross view, will yield a pressure that is less when the load is maintained constant.

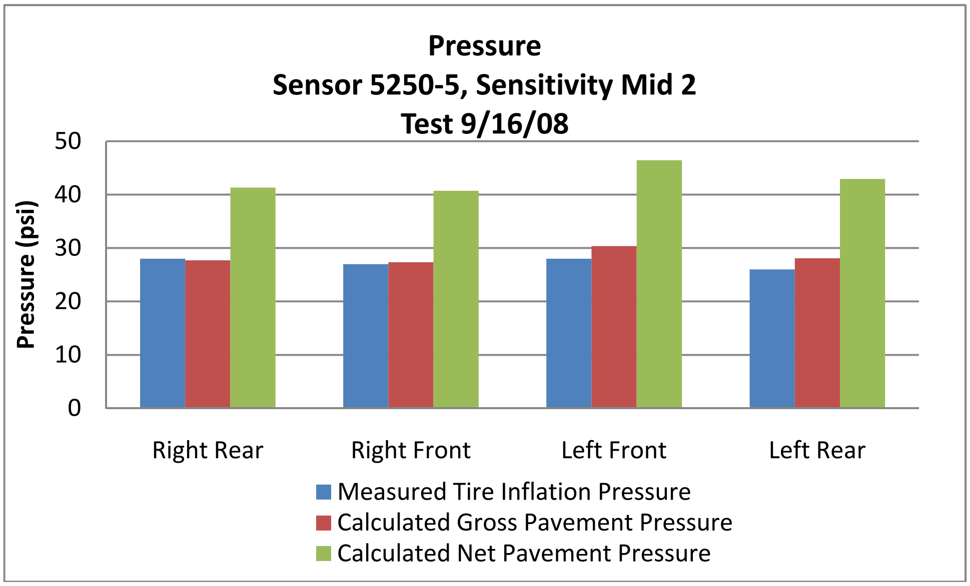


Figure 6.3 Measured Tire Inflation Pressure compared to Calculated Gross and Net Pavement Pressure for Different Tires, 9/16/08

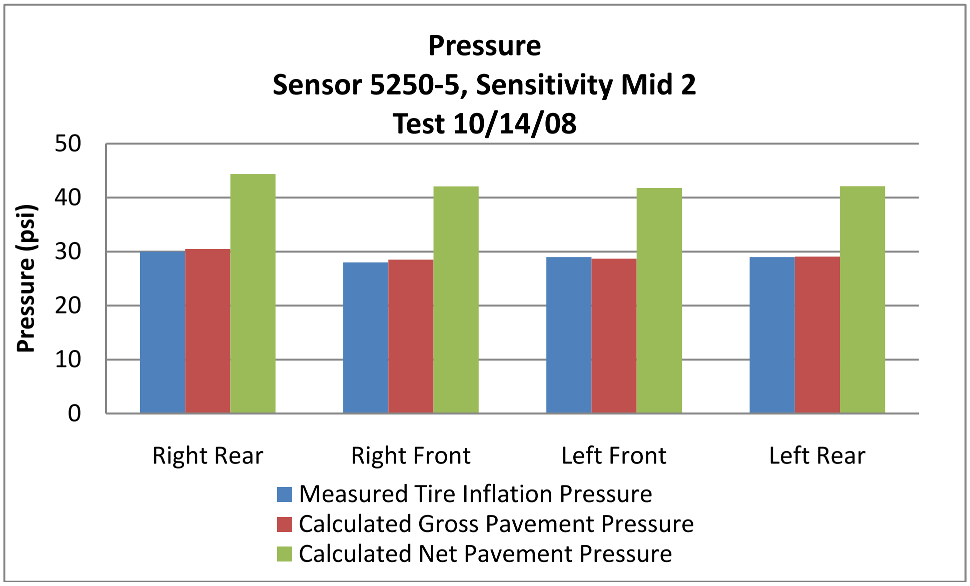


Figure 6.4 Measured Tire Inflation Pressure compared to Calculated Gross and Net Pavement Pressure for Different Tires, 10/14/08

6.3.2 Indirect Pavement Pressure

Pressures also were calculated indirectly. This permits a check on the calculated pressures at each wheel. The method of directly computing the pavement pressure based upon multiple calibration factors is effective, but eliminating the need for multiple calibration factors assists in streamlining the calculations. The indirect method of determining the pavement pressure uses one established calibration factor, and then uses only Tekscan measurements to calculate the pavement pressure at the corresponding wheels on the test vehicle. This method essentially eliminates the need for the vehicle scale because as long as a reliable calibration factor is established for the sensor and sensitivity setting, a measure at each wheel to obtain the known load is not necessary.

This method is nearly identical as the one previously used when the wheel loads were calculated. For example, one wheel load is set as a known and a calibration factor is then computed from that. This calibration factor is then established and is used for the data at the other tires to create a predicted pressure at each tire without a known load. The difference between the previously discussed method of calculating wheel loads is that the first load couldn’t be calculated because it was already known. In this case, the pressure is not immediately known and must be computed from the calibration factor and the data obtained. Therefore, four computations can be made for each calibration factor, unlike the previous example where only three wheel loads can be predicted because the first load is set as a known value. Figures 6.5 and 6.6 illustrate the results of the indirect testing on two different testing dates. Visual inspection of the data concludes that all predicted gross pavement pressures at each wheel are closely related to the measured tire inflation pressure at each respective wheel.

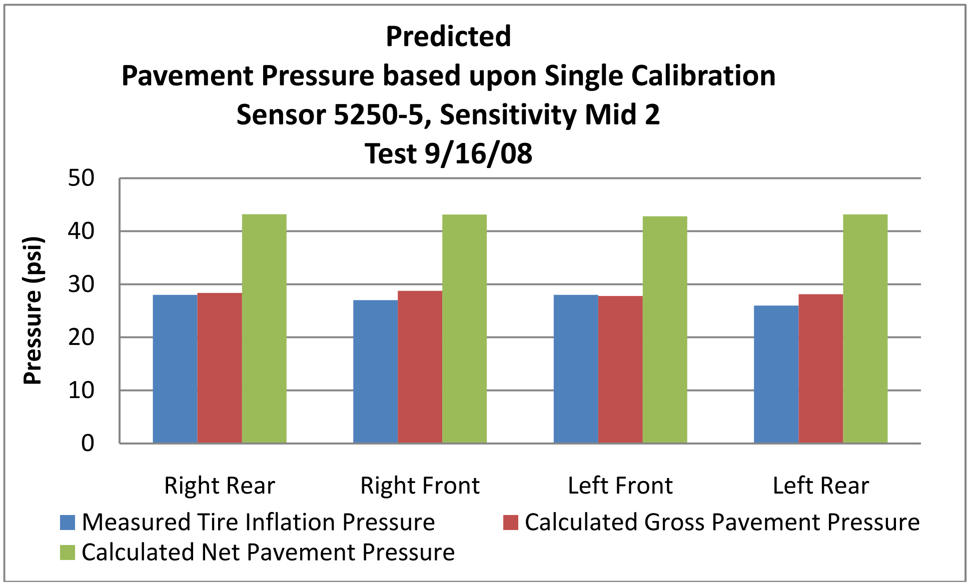


Figure 6.5 Measured Tire Inflation Pressure compared to Predicted Gross and Net Pavement Pressure for Different Tires, 9/16/08

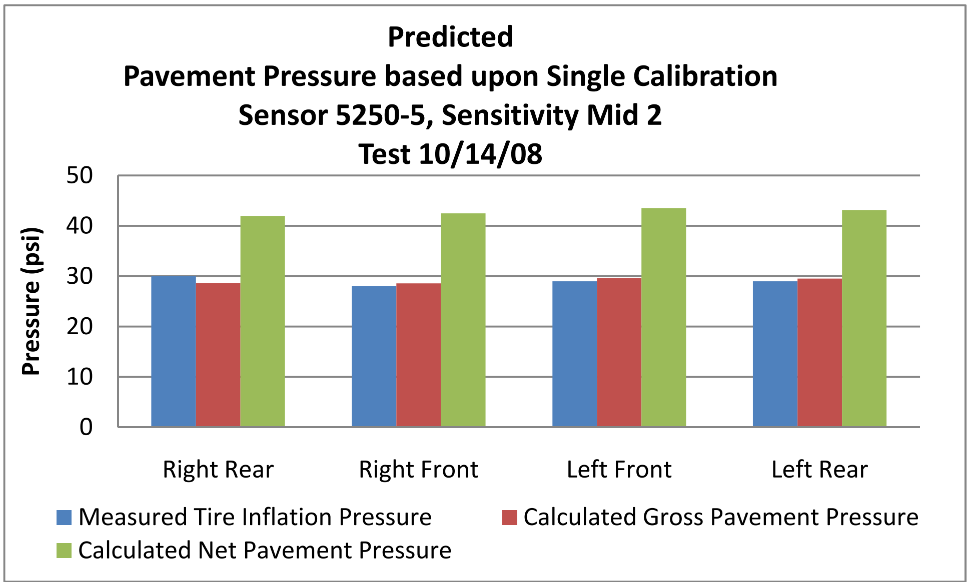


Figure 6.6 Measured Tire Inflation Pressure compared to Predicted Gross and Net Pavement Pressure for Different Tires, 10/14/08

6.4 VARIABLE TIRE INFLATION PRESSURE EFFECTS

6.4.1 Contact Area

Tests were also performed at varying tire inflation pressures. This test procedure followed the established procedure for obtaining data using Tekscan, but instead of holding the tire inflation pressure as a constant, it was varied. All other components of the test, even the test (tire) wheel were held constant.

The test was completed over two testing periods so that results could be compared against one another. On the first day of this testing, the tire inflation pressure was lowered in order to take readings until a low point was reached. At that point, the tire inflation pressure was increased and additional readings were taken at predetermined intervals. During the second day of testing the opposite was done. The tires were overinflated at the beginning of the test and the pressure was slowly released so that tests could be performed at predetermined intervals.

A clear example of what the contact area looks like at different measured tire inflation pressures is provided in Figure 6.7. Graphs of measured contact area versus measured tire inflation pressure are shown in Figures 6.8 and 6.9. It is clear from the graphs that as the measured tire inflation pressure increases, the measured net and gross contact areas will decrease. Inversely, as the measured tire inflation pressure increases, the measured net and gross contact areas will decrease. This is due to the fact that the tire will relax and the sidewalls will flatten and cause a larger imprint when this tire inflation pressure is decreased. This phenomenon is more pronounced at low tire inflation pressures and is more evident when observing the gross measured contact area in most instances.

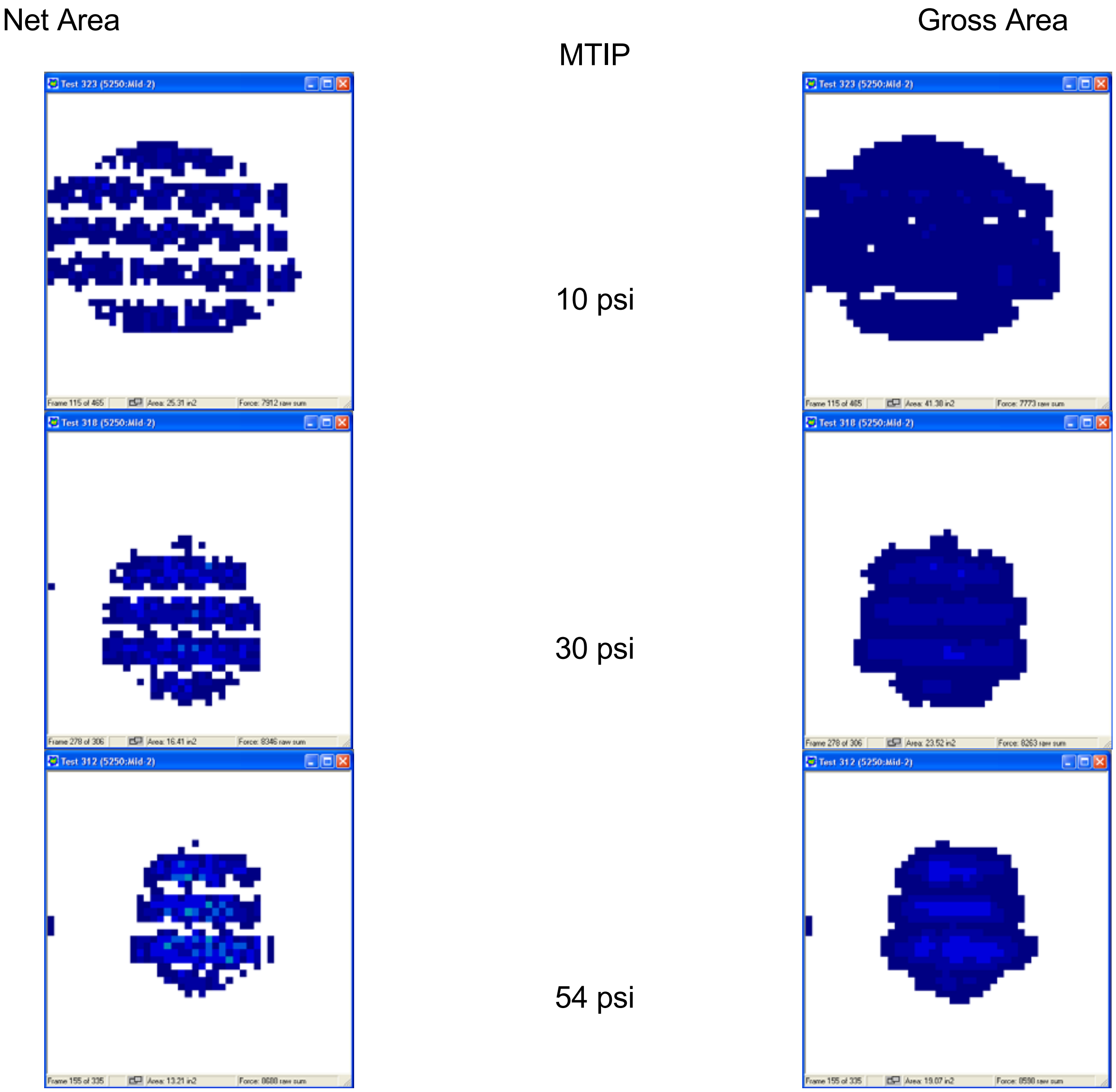


Figure 6.7 I-Scan Views due to Variation of MTIP

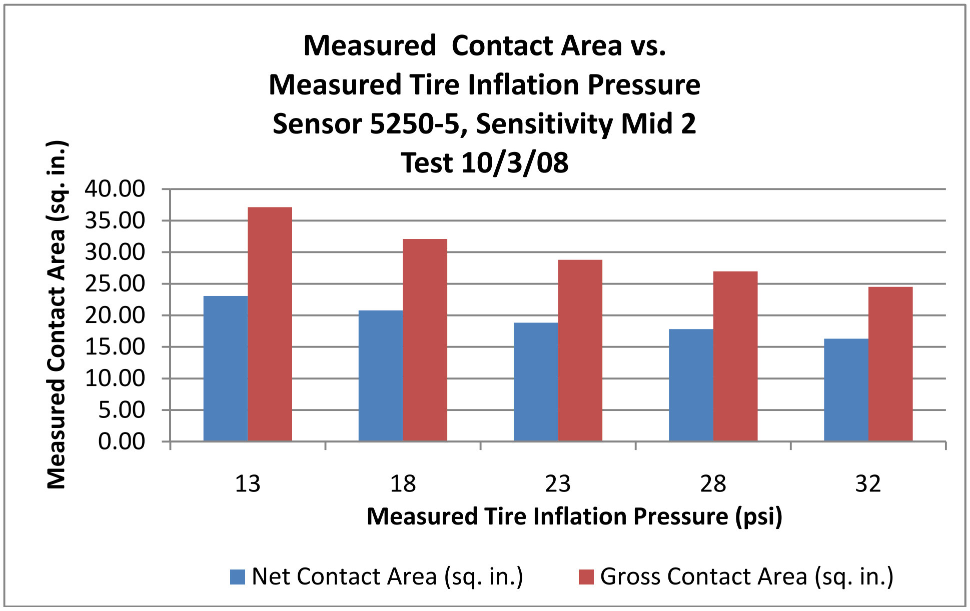


Figure 6.8 Measured Contact Area compared to Different Measured Tire Inflation Pressures for the Right Rear Tire, 10/3/08

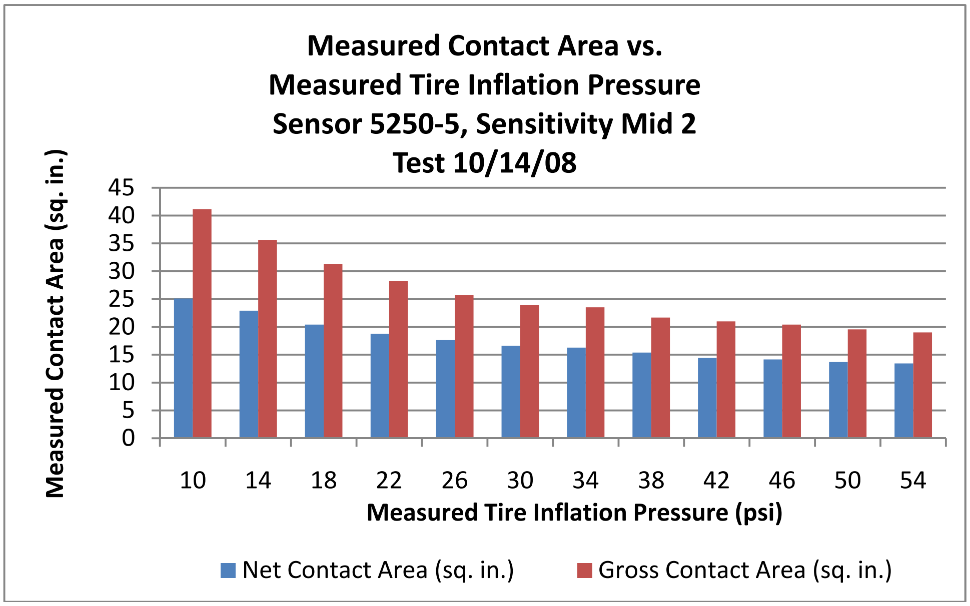


Figure 6.9 Measured Contact Area compared to Different Measured Tire Inflation Pressures for the Right Rear Tire, 10/3/08

6.4.2 Mathematical Relationships

Careful observation of the data recorded during the testing of varied measured tire inflation pressures provided further analysis. The graphs in Figures 6.8 and 6.9 clearly illustrate trends within the data. It was decided to examine this data in order to see whether or not it conformed to an actual mathematical relationship. Therefore the data was plotted as shown in Figure 6.10. Analysis of both the net and gross contact areas yielded both linear and polynomial trends with high confidence values. Although the relationship was tested with linear, polynomial, power, and exponential trends, the polynomial to the second order provided the most accurate result. The R2 confidence value of the net and gross contact area data provided values of 0.9906 and 0.9852 respectively, indicating high correlations.

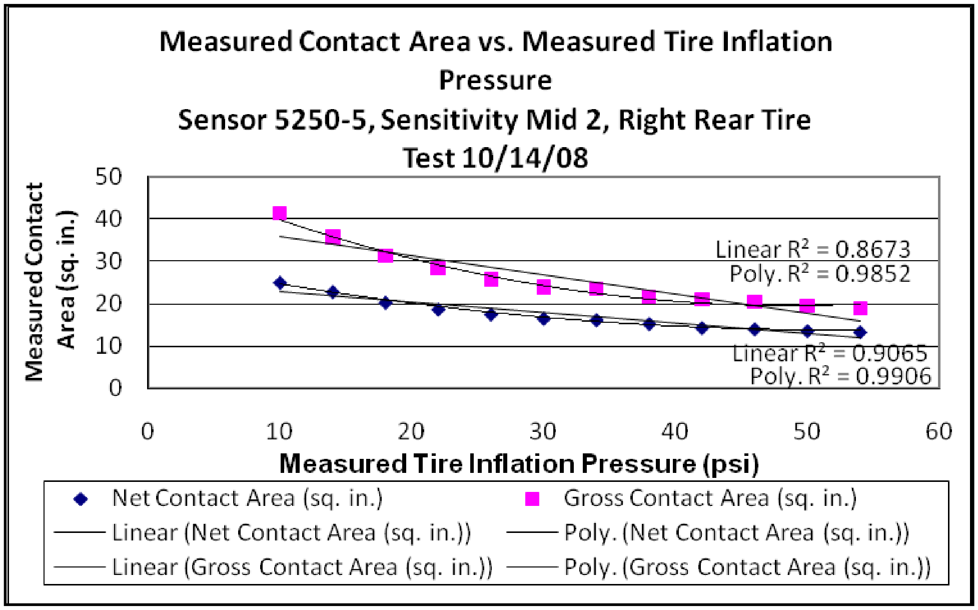


Figure 6.10 Trend Illustrating Measured Contact Area versus Measured Tire Inflation Pressure

CHAPTER 7. FINDINGS AND CONCLUSIONS

7.1 REVIEW

This study examined the following objectives, but each of these objectives relied heavily on the successful use of the Tekscan Pressure Measurement System.

- Review and summarization of previous graduate student research focusing on Tekscan, especially that by Shawn Ray and Justin Anderson;
- Development of procedure to select proper sensitivity setting;
- Assess the ability of the system to predict wheel loads and pavement pressures; and
- Evaluation of effect of tire inflation pressure on pavement pressure and contact area.

This research closely observed the changes that were made to the system after the recent upgrade, especially the sensitivity settings. Previous research using Tekscan didn’t account for the sensitivity changes that could now be instituted. Therefore, advances were made in developing a more user-friendly procedure for selection of sensitivity based upon the expected loading.

7.2 ACCOMPLISHMENTS

7.2.1 Initial Field Testing

The initial field testing consisted of developing a procedure for selecting an optimum sensor and an appropriate sensitivity. Findings based upon these tests include:

- Adjustment of sensitivity can be completed directly in the Tekscan I-Scan software;
- Calibrations should be completed the day of testing;
- Calibration factor values will increase as the sensitivity is increased;
- Measured raw sum increases as the sensitivity is increased;
- Data manipulation can check the validity of the saturated red cells;
- The value of the gross pavement pressure should be approximately equal to the measured tire inflation pressure;
- The measured contact area will increase for the same load conditions as the sensitivity is increased; and
- Sensors with higher resolution are available but may not dramatically improve results of this research.

7.2.2 Subsequent Field Testing

After the initial field testing was complete, it enabled the testing of the pavement surface under the wheel loads and led to procedures that would directly and indirectly calculate pavement pressures and wheel loads of the test vehicle. Findings based upon these tests include:

- Repeatable results could be achieved with Tekscan sensors with little variation;
- Repetitive loads didn't negatively affect the sensor's memory;
- Repeatability depends on calibration factors remaining stable or being accounted for;
- Sensor drift was observed but was minimal in affecting results;
- Wheel load pavement pressures can be accurately computed;
- Pavement pressure can be accurately computed both directly and indirectly; and
- Net pavement pressure is higher than gross pavement pressure.

7.2.3 Variation in Tire Inflation Pressure

An extension to this research investigated the effects of variations of the tire inflation pressures. Findings include:

- As measured tire inflation pressure increases, the measured net and gross contact areas will decrease;
- When tire pressure isn't near the optimum level as set by manufacturer, the gross pavement pressure becomes more difficult to predict and results aren't nearly as close to values of measured tire inflation pressure as shown in previous testing; and
- The relationship between measured contact area and measured tire inflation pressure can effectively be modeled as a 2nd order polynomial.

7.3 CONCLUSIONS

Many conclusions can be drawn from the findings of this research. Most notably advances were made in utilizing sensor variable sensitivity to more effectively measure surface pavement pressure. Conclusions include:

- Adjustment of sensitivity is a simple process to provide accurate data and flexibility for use of sensors;
- Selection of sensitivity should be based upon the concept that the optimal measured tire inflation pressure is equal to the calculated gross pavement pressure;
- In order to obtain accurate data, calibration factors should be computed on the same day of testing;

- The results of each testing sequence can be repeated with consistency;

- Accurate results can be obtained through indirect and direct means when calculating wheel loads and surface pavement pressure; and

- Tire inflation pressure has a direct effect on measured contact area between the surface and the tire.

7.4 RECOMMENDATIONS FOR FUTURE RESEARCH

Although many advances were made, the need for future research still exists. Areas of improvement could begin with the purchase of sensors that can capture a larger area and display a higher resolution. This would allow for greater flexibility in measuring tires with larger contact areas such as larger trucks while the higher resolution may produce more accurate results. The need remains for testing to be performed on a variation of loadings including those of heavier and lighter vehicles. These tests could also include different loadings on a bogie of a large truck in attempts to determine how the load varies between the wheels. These further investigations using varying loads would also allow for a check of the sensitivity selection criteria reported herein. Tekscan is a research tool and will continue to be an important area of emphasis for future research.

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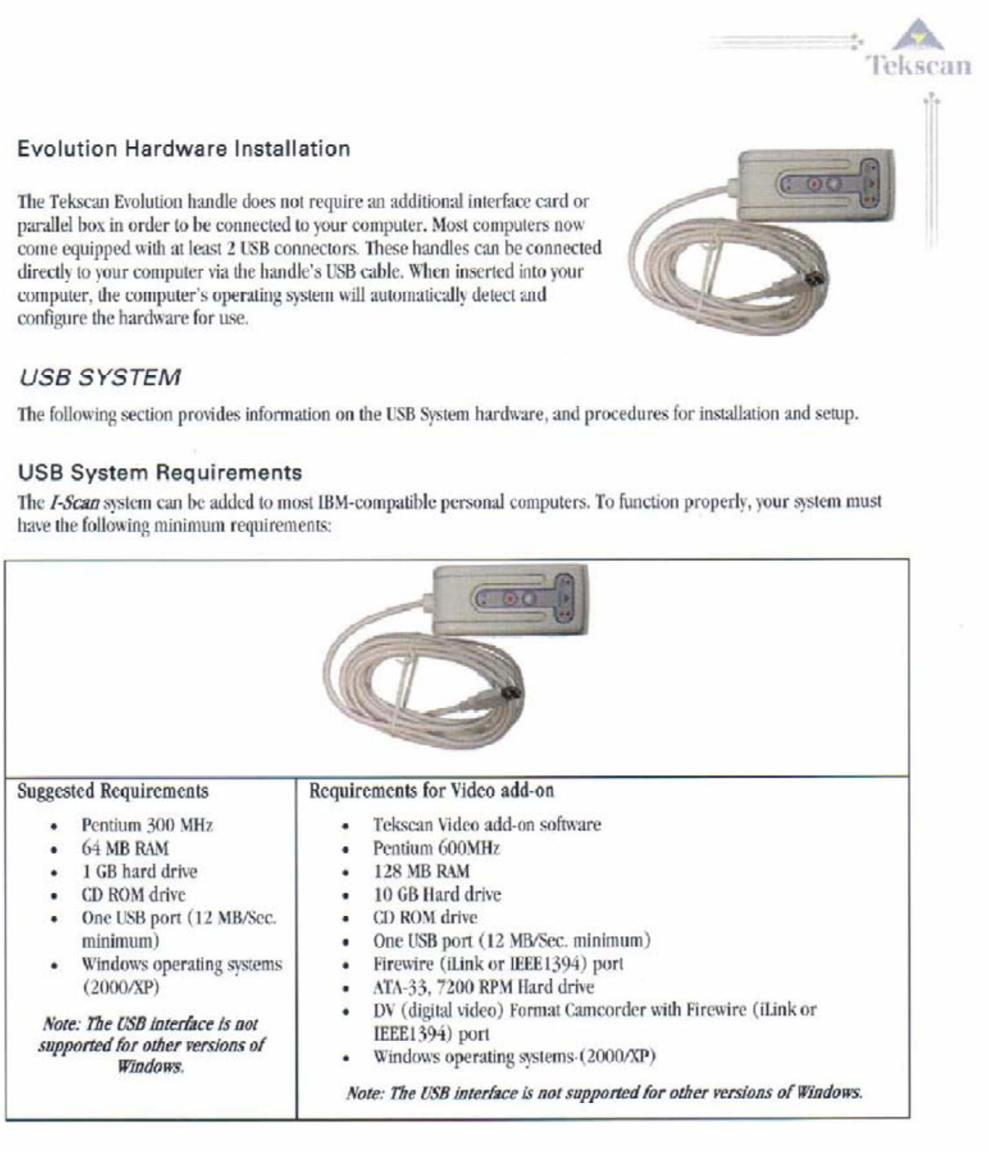
APPENDIX A: TEKSCAN USB EVOLUTION HANDLE SPECIFICATIONS



Tekscan

Evolution Hardware Installation

The Tekscan Evolution handle does not require an additional interface card or parallel box in order to be connected to your computer. Most computers now come equipped with at least 2 USB connectors. These handles can be connected directly to your computer via the handle's USB cable. When inserted into your computer, the computer's operating system will automatically detect and configure the hardware for use.

USB SYSTEM

The following section provides information on the USB System hardware, and procedures for installation and setup.

USB System Requirements

The *I-Scan* system can be added to most IBM-compatible personal computers. To function properly, your system must have the following minimum requirements:

Suggested Requirements	Requirements for Video add-on
• Pentium 300 MHz • 64 MB RAM • 1 GB hard drive • CD ROM drive • One USB port (12 MB/Sec. minimum) • Windows operating systems (2000/XP) *Note: The USB interface is not supported for other versions of Windows.*	• Tekscan Video add-on software • Pentium 600MHz • 128 MB RAM • 10 GB Hard drive • CD ROM drive • One USB port (12 MB/Sec. minimum) • Firewire (iLink or IEEE1394) port • ATA-33, 7200 RPM Hard drive • DV (digital video) Format Camcorder with Firewire (iLink or IEEE1394) port • Windows operating systems (2000/XP) *Note: The USB interface is not supported for other versions of Windows.*

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USB

User Manual

Also Included:

Tekscan I-Scan "family" Sensor(s) -- Depends upon application.
Sensor Carrying Case *(Part ZCAS-4850)*

Type CF equipment

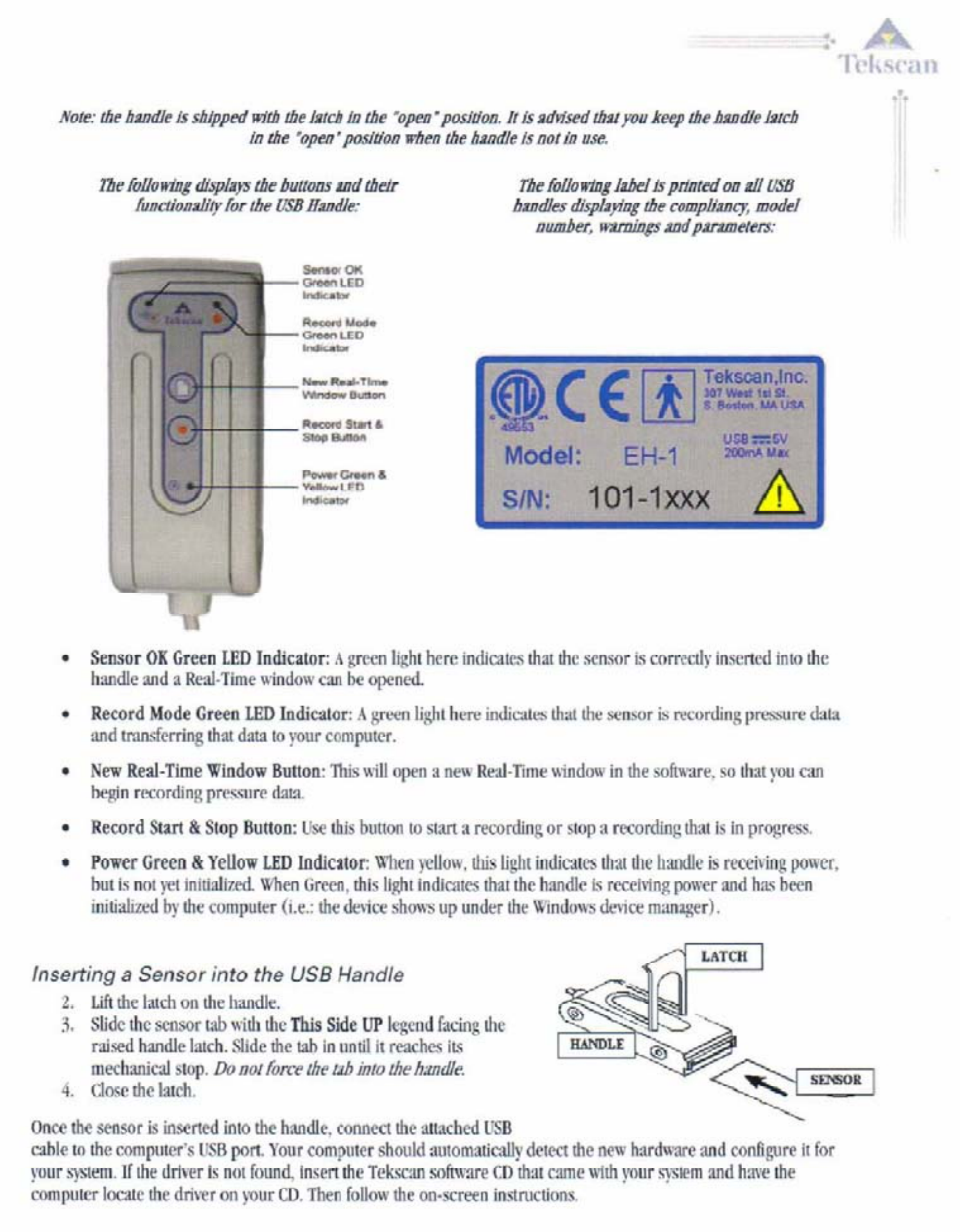
F-type applied part which provides a higher degree of protection of electric shock than that provided by type BF applied parts.

♥

USB Handle

The USB Sensor handle gathers the data from the sensor and processes it so that it can be sent easily to the computer. The buttons on the sensor handle may also be used to start or stop a recording. This function is referred to as '**Remote Recording**'.

The handle has a latch on its topside. In the 'Up' position, the latch retracts the contact pins inside the handle to allow insertion of the sensor tab. The sensor tab is placed into the sensor handle. The handle's attached USB cable is then connected directly to your computer via the USB port.



Note: the handle is shipped with the latch in the "open" position. It is advised that you keep the handle latch in the "open" position when the handle is not in use.

The following displays the buttons and their functionality for the USB Handle:

The following label is printed on all USB handles displaying the compliancy, model number, warnings and parameters:

- **Sensor OK Green LED Indicator:** A green light here indicates that the sensor is correctly inserted into the handle and a Real-Time window can be opened.
- **Record Mode Green LED Indicator:** A green light here indicates that the sensor is recording pressure data and transferring that data to your computer.
- **New Real-Time Window Button:** This will open a new Real-Time window in the software, so that you can begin recording pressure data.
- **Record Start & Stop Button:** Use this button to start a recording or stop a recording that is in progress.
- **Power Green & Yellow LED Indicator:** When yellow, this light indicates that the handle is receiving power, but is not yet initialized. When Green, this light indicates that the handle is receiving power and has been initialized by the computer (i.e.: the device shows up under the Windows device manager).

Inserting a Sensor into the USB Handle

2. Lift the latch on the handle.
3. Slide the sensor tab with the **This Side UP** legend facing the raised handle latch. Slide the tab in until it reaches its mechanical stop. *Do not force the tab into the handle.*
4. Close the latch.

Once the sensor is inserted into the handle, connect the attached USB cable to the computer's USB port. Your computer should automatically detect the new hardware and configure it for your system. If the driver is not found, insert the Tekscan software CD that came with your system and have the computer locate the driver on your CD. Then follow the on-screen instructions.

After following this procedure and starting the ***I-Scan*** software, the message below the real-time window for the sensor should be '**Sensor OK**'. If the message is '**MISALIGNED**', re-insert the sensor using the above procedure. If the '**Sensor OK**' message still does not appear, consult the '**Troubleshooting**' section.

Caution! Do not allow the handle to hang from the sensor. The handle may become damaged, resulting in a misaligned sensor.

USB Handle Maintenance and Care

- The handle cannot be autoclaved.
- Do not let any liquid drip onto the electronics inside the handle. If this occurs, the handle will stop working and must be allowed to dry for 24 hours. You can use your air syringe, however, to significantly reduce this drying time. Do not attempt to dry out the handle using any other method, or you may destroy the delicate electronics.
- To properly clean the device, be sure to wipe down the handle with a 70% Isopropyl Alcohol solution. To do this, slightly dampen a cloth with the alcohol solution, careful not to soak or saturate the cloth. Then wipe the handle after each use.

USB Handle Specifications

COMMUNICATION/DATA ACQUISITION:	
COMMUNICATION PROTOCOL TO HOST COMPUTER	USB 1.1 or 2.0 Compatible, 12 Mbps
SCAN SPEED	Up to 9.84 Hz.
DIGITAL PRESSURE RESOLUTION	8 BIT
ELECTRICAL:	
POWER SOURCE:	Host Computer's USB BUS
POWER CONSUMPTION:	200mA MAX at 5V
MECHANICAL:	
USB CABLE:	
LENGTH in (mm)	180 (4572) - Standard
WEIGHT lbs (kgs)	0.40 (0.18)
HANDLE ENCLOSURE:	
SIZE LxWxH in (mm)	5.42x2.25x1.88 (137.7x57.2x47.6)
OPEN LEVER HEIGHT in (mm)	4.30 (109.2)
WEIGHT lbs (kgs)	0.40 (0.18)
AMBIENT OPERATING CONDITIONS:	
TEMPERATURE: °F (°C)	14 to 131 (-10 to 55) Prolonged use at high Temperatures should be avoided
HUMIDITY: %	0 to 90 (non condensing)
PRESSURE: psi (kPa)	1.7 to 14.7 (11.6 to 101.3) (sea level to 50,000 ft)
STORAGE AND TRANSPORT CONDITIONS:	
TEMPERATURE: °F (°C)	-4 to 131 (-20 to 55) Short-Term 41 to 104 (5 to 40) Long-Term
HUMIDITY: %	0 to 90 (non condensing)
PRESSURE: psi (kPa)	1.7 to 14.7 (11.6 to 101.3) (sea level to 50,000 ft)

USB Hardware Installation

The Tekscan USB handle does not require an additional interface card or parallel box in order to be connected to your computer. Most computers now come equipped with at least 2 USB connectors. These handles can be connected directly to your computer via the handle's USB cable. When inserted into your computer, the computer's operating system will automatically detect and configure the hardware for use.

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