

Comparisons of Railroad Track and Substructure Computer Model Predictive Stress Values and In-Situ Stress Measurements

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ABSTRACT:

The purpose of this paper is to compare stress levels at various vertical locations in railroad trackbeds. Various trackbed structural designs and axle loadings are assessed. The computer model - KENTRACK - is used as the analytical predictive procedure. In-situ pressure (vertical compressive stress) measurements were conducted on both heavy-haul CSX Transportation revenue service trackbeds and on the Association of American Railroads Transportation Technology Center test trackbeds.

Pressure measurements were obtained at the rail base/tie plate and tie plate/tie interfaces using specially designed Tekscan matrix-based force sensitive sensors. Pressure measurements were obtained at the tie/ballast, ballast/subballast, and subballast/subgrade interfaces using Geokon earth pressure cells.

The predictive pressure from the KENTRACK program and in-track measurements utilizing Tekscan sensors and earth pressure cells compare very favorably. These comparisons are illustrated for a variety of trackbed designs and conditions and axle loadings. The findings further validate the KENTRACK procedure as a means to design and analyze railroad trackbeds for a wide variety of loading configurations and trackbed designs. Typical data and comparisons are included.

INTRODUCTION

Railroads have been used extensively for transport for around 175 years and during this period, track structure, train speeds, annual gross ton-miles, and axle loads have changed significantly. For example, on United States' railroads, heavy axle locomotives are commonly used. Peak axle loads have increased to 36 tons. The average annual gross ton-miles continue to set new records each year. All those changes serve to increase revenue and also require premium track structures and components. Due to the insufficiency of traditional track structures, many problems have developed. These can be categorized into two failure groups.

The first one is the failure of the subgrade. This occurs when the existing pressure on the top of the subgrade is higher than the maximum subgrade bearing pressure. Mathematically, the maximum subgrade bearing pressure can be expressed as a function of soil properties, such as shear modulus, Poisson's ratio, density, water content, plasticity, etc. However, in most cases, maximum subgrade bearing pressure is determined based on field tests or laboratory tests from collected samples. When a subgrade failure occurs, it adversely affects the railroad track geometry and is expensive and difficult to remedy. Preventing subgrade failure is one of the major objectives of railroad trackbed design, construction and maintenance.

The other one is the failure of railroad track structural components. This commonly happens after components such as rail, tie plate, fastener, tie, ballast and subballast are in service for a period of time. It is common knowledge that the failure of track structural components will affect the geometry of the track, which is closely related to the safety issues. Periodic replacement of track structural components cannot be avoided (Lopresti, Davis and Kalay, 2002); however, increasing components service life should be considered since it is an effective way to reduce maintenance costs.

The solution for subgrade failure involves a combination of reducing the pressure on the top of the subgrade, improving drainage (effectively improving the properties of the subgrade), adding thickness to the trackbed, or utilizing higher quality/load bearing trackbed components. Hot Mixed Asphalt (HMA) trackbed has been successfully applied in the United States. The solution for minimizing structural failure is designing and selecting reasonable fasteners and track components so that an optimum track structural support stiffness can be achieved. To find the optimum track structural support stiffness, it is necessary to determine the pressure at different levels in the track such as at the rail base/tie plate, tie plate/tie, tie/ballast, ballast/subballast, and subballast/subgrade interfaces. By knowing the pressure of above interfaces, track stiffness can be determined. Also, another advantage of determining the pressures at different interfaces of track structures is that it will be beneficial for designing the tracks' structural components. Herein, two types of measurement methods were applied and a computer model was developed to determine the pressures at previously mentioned interfaces by verification of the data from in-track measurements with the data predicted from the computer model.

BACKGROUND

Two types of railroad trackbeds are utilized in the United States. The most common is the traditional all-granular ballast trackbed. The HMA trackbed has been developed and tested for the past twenty years and has been successfully proven for numerous advantages over traditional ballast trackbed (Rose, Brown and Osborne, 2000). Two HMA trackbed designs have been evaluated. One called underlayment, where ballast is laid between asphalt and the track panel and the other one is overlayment, where the track panel is placed directly on the top of HMA. In practice, underlayment is more commonly accepted since there is a ballast layer between the tie and asphalt. This provides a protective cover for the asphalt by blocking sunlight, draining water, and maintaining a relatively constant temperature and environment. Also, it permits easy adjustment of track geometry and level. Therefore, only underlayment is covered in this paper. Figure 1 shows the cross sections for the three trackbeds. Figure 2a shows a layer of HMA being laid over the subgrade during the construction of an underlayment HMA trackbed and Figure 2b illustrates the details of the structural components used in an underlayment HMA trackbed.

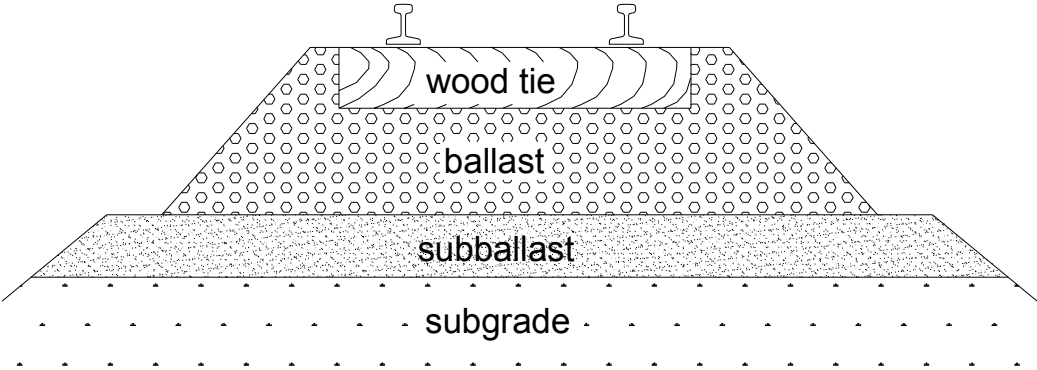
IN-SITU TEST SYSTEMS

The two measurement devices utilized in this research are the Tekscan matrix-based force sensitive sensors -- used to measure the pressures at the rail base/tie plate and tie plate/tie interfaces, and the Geokon earth pressure cells -- used to measure the pressures at the tie/ballast, ballast/subballast, and subballast/subgrade interfaces. The details of the two measurement systems are described as follows.

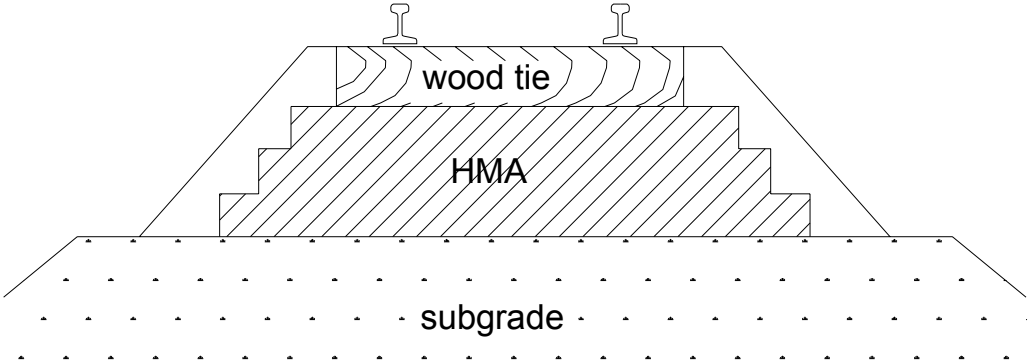
Tekscan Pressure Sensors

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 (approximately 40 mil thick) matrix-based sensor consisting of two flexible polyester sheets with silver conductive electrodes printed on them. One sheet has semi-conductive ink printed in rows while the other sheet has the semi-conductive ink printed in perpendicular columns. The two sheets of polyester

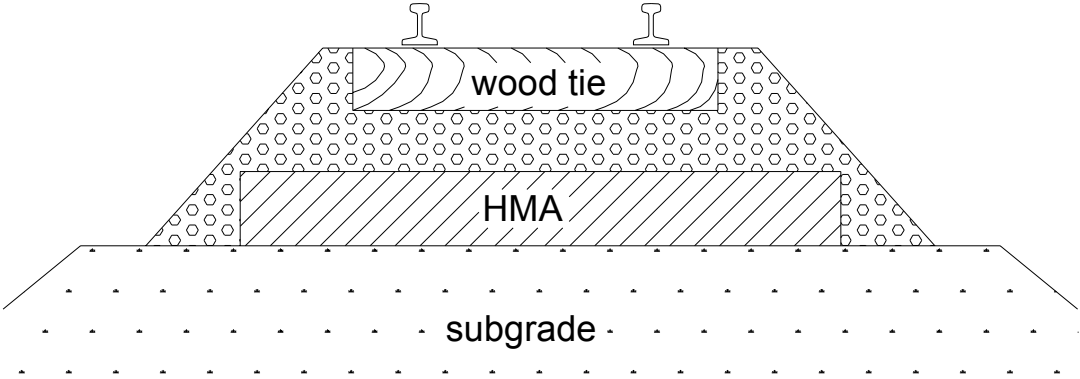
are then glued together along their periphery. The illustration in Figure 3 shows a basic Tekscan sensor and its components.



all-granular ballast trackbed



overlayment HMA trackbed



underlayment HMA trackbed

Figure 1. Sections of Three Types of Trackbed Designs



Figure 2a. Placing an HMA Underlayment on Subgrade during the Construction of a Second Track next to an Existing Ballast Track



Figure 2b. Exposed HMA Underlayment in Trackbed with Ballast and Wood Tie Track

The ink is pressure sensitive and its conductivity varies with applied force, similar to the components of a strain gauge. By applying force to 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. When force is distributed over the sensor, this process is repeated for all the rows and columns and the distribution of force over the active area is determined (Tekscan, Inc., 2003).

Saturation of the cell occurs when the pressure reaches the capacity of that particular sensor. Sensors are manufactured for various pressures. The Tekscan sensors are an 8-bit system, which means

that the cells record a raw value from 0-255. The cell is considered saturated when it reads 255 (Stith, 2004). The sensor that was used for the railroad pressure measurements had a capacity of approximately 1200 psi, thus providing a 6 psi resolution for the readings.

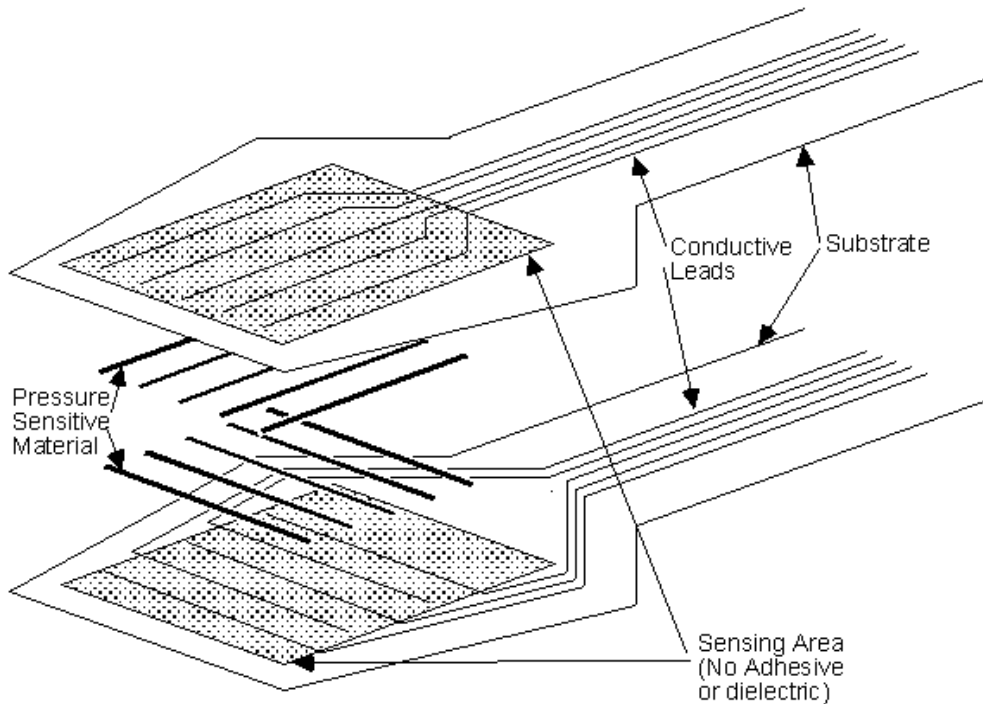


Figure 3. Basic Tekscan Sensor Schematic

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 a strip on the sensor. The handle has pogo pins that tightly clamp to the sensor. Those pogo pins make individual contact with each of the silver leads that connect to the columns and rows of ink (Stith 2004). The handle's wire is then attached to a Magma Box that houses a cardbus-to-PCI expansion system. This box is necessary to transform the output from the handle to a form that the computer can input.

The final piece of equipment is a computer with the I-Scan Software installed. I-scan is the computer program developed by Tekscan that enables the user to record and analyze data. Figure 4 is a schematic view of the setup of the Tekscan system for in-track tests. Figure 5 shows an in-track view.

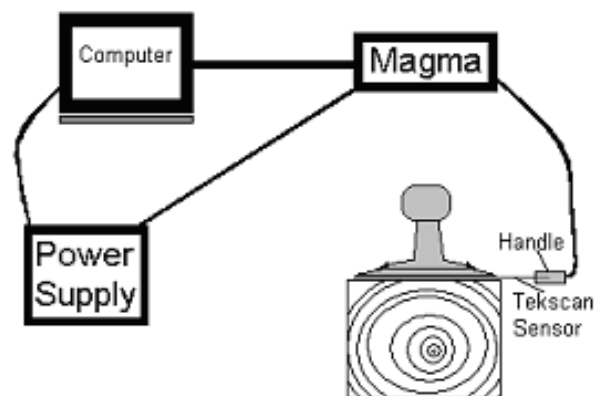


Figure 4. Tekscan Measurement Configuration



Figure 5. In-track view of Test

Geokon Earth Pressure Cells

In order to measure the pressure exerted by a train on the supporting materials in the track structure, Geokon Model 3500 Earth Pressure Cells were used. The portion of the cell that receives the load consists of two slightly convex stainless steel circular plates that are 9 inches in diameter welded together at their edges. Between the two plates, a small void is filled with a de-aired hydraulic fluid. When a load is applied to the plates, the load compresses the fluid and forces it down a short length of high-pressure stainless steel tubing. This tubing connects to a pressure transducer, which converts the pressure of the compressed fluid into an electrical signal. From the pressure transducer, the electrical signal is transmitted through a signal cable to the readout location (Rose, Li and Walker 2002). The Geokon Pressure Cells used in the field to determine pressures in the trackbed have a 100 psi limit. This was sufficient to gather the data needed.

In addition to the pressure cell, a computer and junction box are required to determine pressures. The junction box has pressure cells connected to it, which is in turn connected to the computer. A 12-volt battery provides power for the electrical signal. In this manner, the junction box acts as a hub through which all components are connected. It also provides multiple ports for additional pressure cells, thereby allowing for multiple pressure readings to be recorded simultaneously. Snap-Master is the data acquisition system used for obtaining the pressure measurements for in-track measurements. The program allows the user to record the electrical signal from the pressure cell in real time. Figure 6 is a schematic view of the pressure cell configuration for in-track tests. Figure 7 is a view of an in-track test.

Each Geokon Pressure Cell is calibrated prior to shipping. This is done to provide a calibration factor, which converts voltage readings to actual pressure values. The procedure involves developing a plot of recorded voltages for known vertical pressures. From this plot, the inverse of the slope is determined, which is the calibration factor. The calibration factor is then multiplied by the voltage reading to determine pressure.

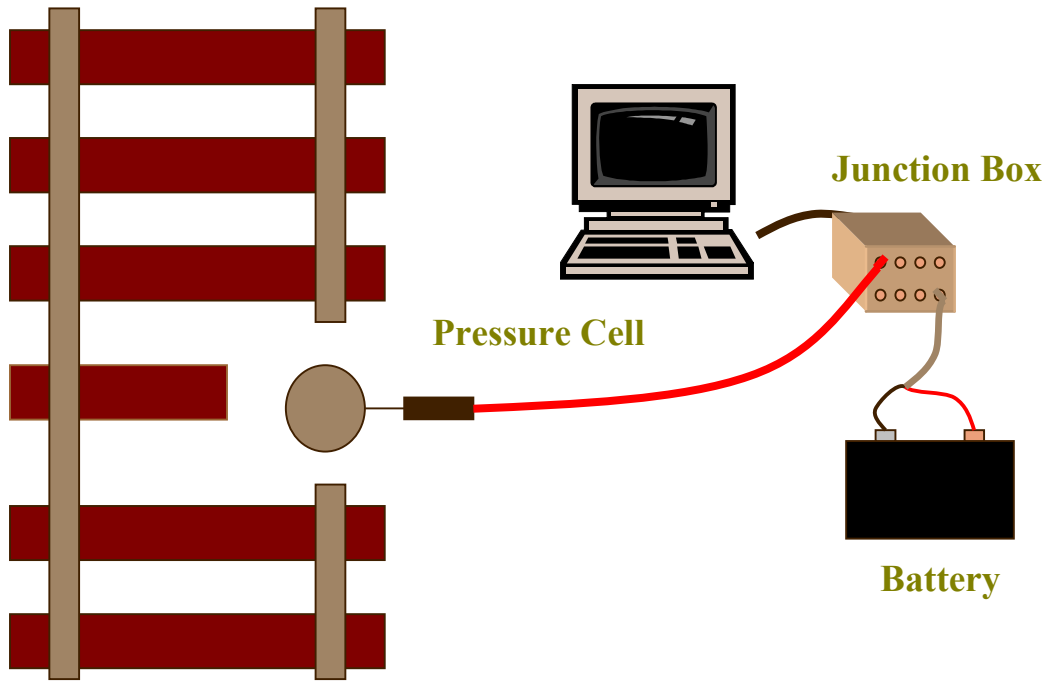


Figure 6. Pressure Cell Measurement Configuration



Figure 7. In-Track View of Pressure Cell Testing

PREDICTIVE TEST SYSTEM

A structural design computer program, KENTRACK, was developed for analyzing railroad trackbeds by the Department of Civil Engineering, University of Kentucky in early 1980s (Huang, Lin, Deng and Rose, 1984). Recently, this program has been modified from a previous version that utilized a

Disk Operating System (DOS). The modification permits the user to change various properties of the track structure much easier than previously when values were entered by DOS. A user-friendly Window's based interface, Graphical User's Interface, containing four descriptive forms (or screens), allows the user the option to enter varying values for the track structure components. Only a brief description about this computer program is contained herein. More details about KENTRACK and its applications can be found in related reference (Rose, Su and Long, 2003).

The railroad track structure typically consists of rail, fastener, tie and a multi-layered support system from top to bottom, as shown in Figure 8. Among them, the multi-layered support system consists of trackbed, subgrade and bedrock. The trackbed is normally composed of two layers ---- the top one is ballast or slab and the bottom one is granular material such as subballast or bound material such as asphalt mix. When several loads are applied to the rail, the stress, strain and deflection of rail and tie can be obtained by superimposing the effect of each load. Computations of the stress and strain in rail and tie were based on the finite element method in KENTRACK. Rail and tie can be classified as beam elements and the spring element is used to simulate the tie plate and the fastener between rail and ties. For KENTRACK, only four layers are used ---- ballast, subballast or HMA, subgrade soil and bedrock ---- from top to bottom. The details of multi-layered system solution method can be found in a related reference (Huang, 1993).

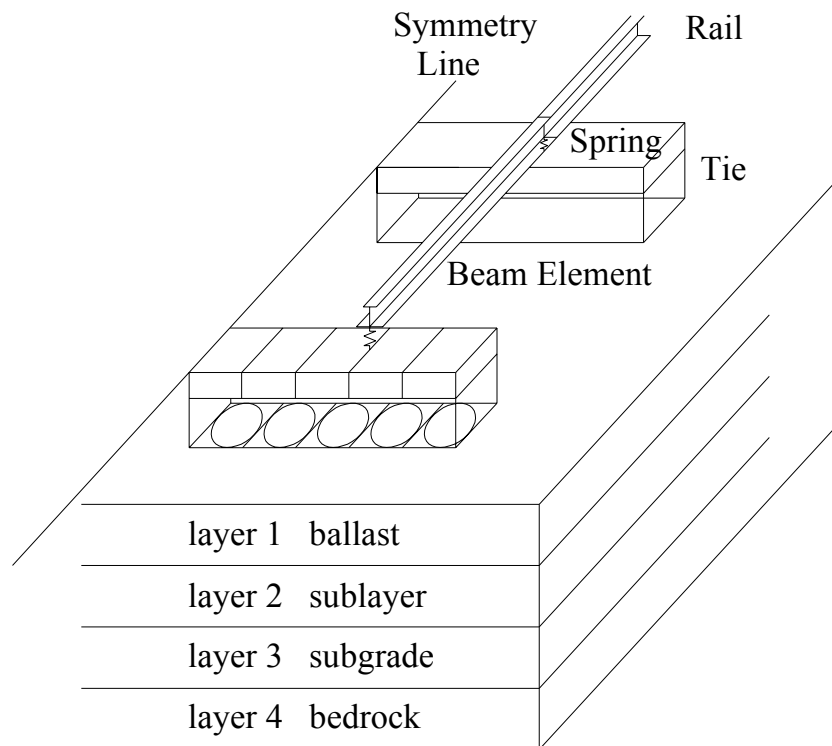


Figure 8. Sketch of Railroad Track Model

An HMA railroad trackbed is composed of three different materials. They are ballast, HMA and subgrade soil. Although all of them are considered as elastic materials, different kinds of numerical equations are used to describe them due to their different inherent properties. Ballast can be considered as either a non-linear or linear material. When a railroad trackbed is recently constructed and has not been compacted, ballast always behaves non-linearly. Whereas, if the trackbed has been used for a period and the ballast has become compacted, it is more reasonable to use the linear model rather than the nonlinear model for calculating the resilient modulus.

HMA is a temperature dependent material. Its dynamic modulus can be calculated by using the method developed by the Asphalt Institute (Hwang and Witczak, 1979). Note that different temperatures should be used for different months or seasons.

Subgrade soils are always considered as linear elastic materials regardless of the type. However, the program permits using different kinds of soil to composite the total subgrade with different Poisson's ratios and elastic modulus values. In the bottom layer, the program will consider it as an ideal material -- - bedrock --- which has an infinite elastic modulus (incompressible) and 0.5 for Poisson's ratio.

Damage analysis, a function provided by KENTRACK, can predict the service life of the railroad trackbed because a prediction function has been integrated into the program based on the Minor linear damage analysis criteria. Note that in the KENTRACK program, two failure criteria are utilized due to the different properties of materials. For HMA, it is the tensile strain on the bottom of asphalt that controls asphalt life to prevent excessive cracking. For subgrade soil, it is the vertical settlement that controls subgrade life to prevent excessive deformation, which is determined to adversely affect track geometry. The service life of the track structure is governed by the lesser one, either tensile failure of the HMA layer or vertical permanent deformation of the subgrade.

TEST SITES

Two open track test sites were selected; one is on a CSX Transportation revenue line in Conway, KY and the other is the Transportation Technology Center Inc. (TTCI) test facility. Figures 9 and 10 show the track section in Conway, KY and TTCI respectively. The specific parameters for the two tracks are given in Table 1.

DATA PRESENTATION AND DISCUSSION

Tekscan sensors were positioned between the rail and tie plate to determine the pressure under the rail, which assists in understanding the reaction forces under different rail seats for particular wheel loads. This is beneficial for track related calculations, such as analyses of tie and rail deflection. Tests were conducted at Conway, KY. A set of wheels for a truck of a 6-axle locomotive was used, which represents the typical locomotive in the United States. The wheel position along the track is shown in Figure 11. Tekscan sensors were used to measure the pressures under the rail from tie number 1 to 21. As expected, peak pressures were found at ties number 3, 7 and 11, under the wheels. Figure 12 shows the pressure distribution under tie number 7. It can be found that the total reaction force under the rail at position tie number 7 is 27730 lbs. Also, it is interesting to note the load distribution along the rail by plotting the reaction forces at each tie position and it is shown in Figure 13. Based on this figure, it can be found that the reaction forces distribution along the track are almost symmetrical to the center wheel load (at tie number 7). Also, it should be noted that the track dead load will cause a reaction force of about 2248 lbs, which is an approximate value measured at tie number 21. By observing Figure 13, note the reaction force curve between tie number 14 and number 21 is very flat, which means the reaction forces above these ties change very little. Therefore, an initial conclusion can be drawn that the "effective" load distance is about 15 tie spacings (from tie number -1 to 14). The locomotive has three sets of wheels, therefore, by using superposition principle, it can be found for each single wheel load, the effective distance is about 10 to 12 tie spacings. This is a very important finding because it confirms the effective distance for a single load and it will be used when applying KENTRACK for calculating stresses in the track structure.

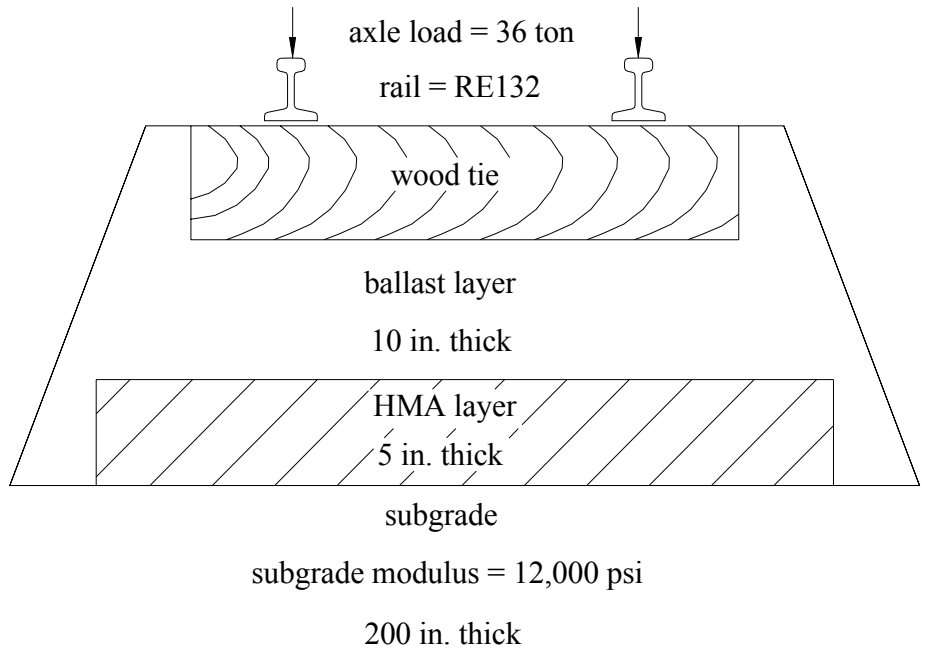


Figure 9. Section of HMA Trackbed on CSX Transportation Revenue Line in Conway, KY

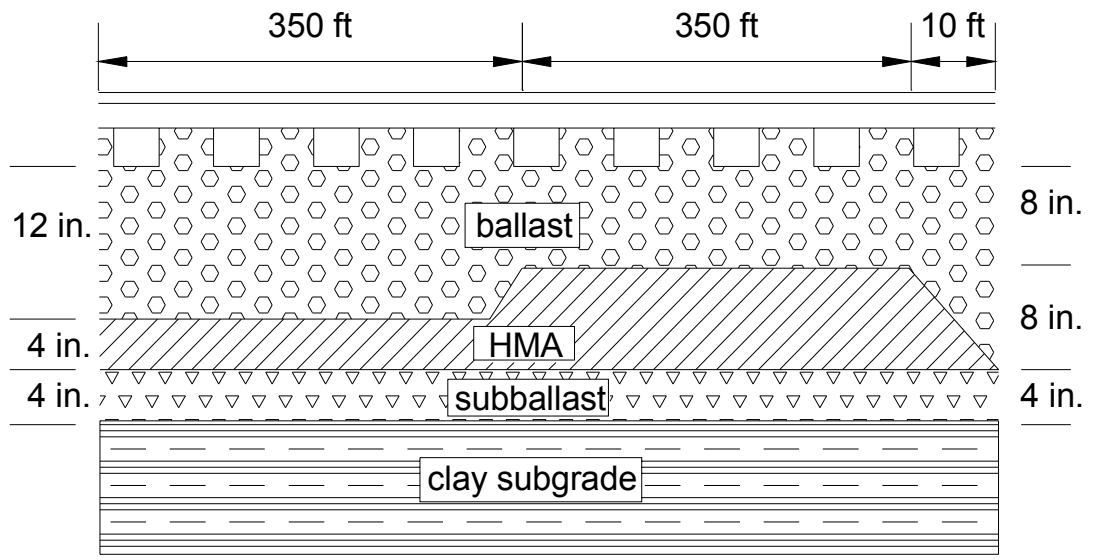


Figure 10. Longitudinal Section of Test HMA Trackbed at TTCI

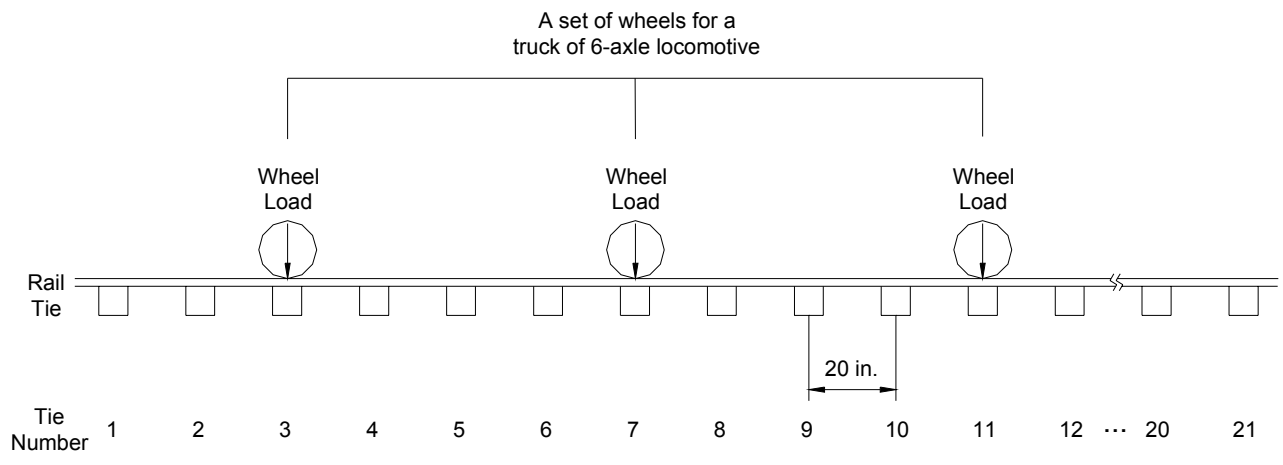


Figure 11. Truck Position along the Track

Table 1. Details of Track Parameters for Conway, KY and Ballast Trackbeds

Parameter Name	Conway, KY	TTCI
Wheel Load (lbs)	36000	
Rail Size	RE132	
Tie Type (Fastener Type)	Wood Tie (Spike)	
Tie Spacing (in.)	20	
Tie Dimension (in.)	102×7×9 (length×thickness×width)	
Ballast Modulus (psi)	46412	
Poisson's Ratio for Ballast	0.3	
Ballast Thickness (in.)	10	8 – 12
Subballast Thickness (in.)	N/A	4
Poisson's Ratio for Subballast	N/A	0.35
HMA Thickness (in.)	5	4 – 8
Poisson's Ratio for HMA	0.45	0.45
Temperature for HMA (°F)	50 (spring) 63 (summer) 37 (autumn) 19 (winter)	
HMA Modulus (psi)	698000 (spring) 372000 (summer) 1250000 (autumn) 2250000 (winter)	
Volume of Voids for HMA (%)	5.7	5.7
Volume of Bitumen for HMA (%)	13.5	13.5
HMA Viscosity at 21 °C (poise)	2500000	2500000
Subgrade Modulus (psi)	11600	5800
Subgrade Thickness (in.)	200	
Poisson's Ratio for Subgrade	0.4	
Poisson's Ratio for Bedrock	0.5	
Traffic Volume (MGt)	50	35

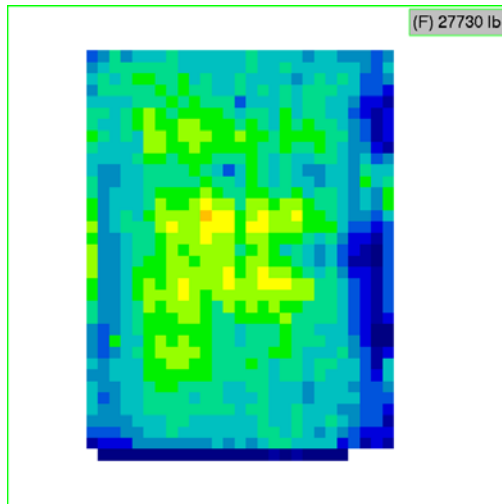


Figure 12. Pressure Distribution Under Tie Number 7

Predictive data, shown in Figure 14, depicts the vertical compressive stress distribution under the tie. According to this figure, a non-uniform vertical compressive stress distribution was obtained. Peak pressure was found under the rail seat and zero pressure was found at the edge of the tie. Also, the predictive pressure distribution from a traditional ballast trackbed was plotted in Figure 14. It can be noted that for the same load, the vertical compressive stress distribution curves for two types of trackbeds are different. For a HMA trackbed, peak pressure under the rail seat is higher than the one in ballast trackbed. Whereas for the pressure in the center of the tie, pressure in the HMA trackbed is lower than the one in ballast trackbed. Although the two curves have a different shape, the areas enclosed by the each curve are the same and this is reasonable since the area represents the total reaction force. Note that at the center of the tie, the vertical compressive stresses were 11.7 psi and 3.4 psi for ballast and HMA trackbed respectively, only about 25% and 5% of peak value under the rail seat in corresponding trackbed. This information is particularly valuable for tie design calculations.

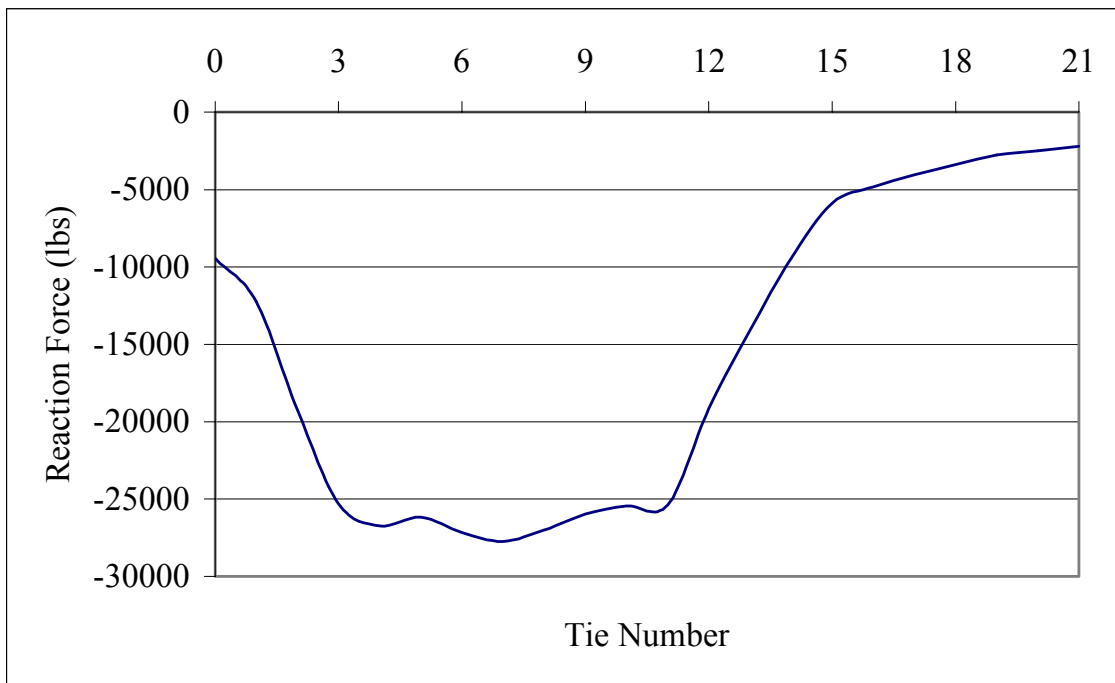


Figure 13. Load Distribution along the Track

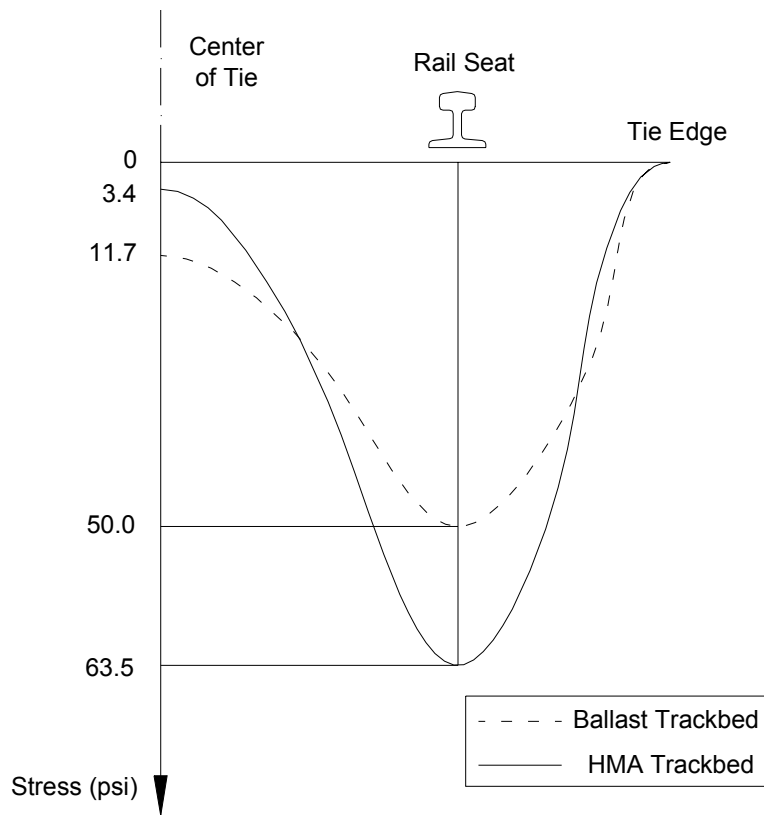


Figure 14. Predictive Vertical Compressive Stress Distribution under the Tie for Ballast and HMA Trackbeds

Vertical compressive stresses over the HMA layer were also measured using earth pressure cells and the results were checked with the predictive values from KENTRACK. For the CSX track in Conway, KY, measured vertical compressive stresses were 16 psi in 5 in. thick HMA trackbed and 15 psi in 8 in. thick HMA trackbed as shown in Figure 15. Predictive values from KENTRACK for these two cases were 21 psi and 22 psi. Also, for the track at TTCI, measured values were 15 psi in both sections, shown in Figure 16. KENTRACK predictive values were 12 psi for the 4-in. HMA section and 22 psi for the 8-in. HMA section. Differences are noted when comparing predictive values with measured values. To explain this, it is necessary to understand HMA performance. HMA is a visco-elastic material and based on the existing experience, it fails by cracking at the bottom of the layer due to excessive tensile strain rather than due to vertical compression. Thus, the KENTRACK model was developed primarily for calculating the tensile strain on the bottom of HMA rather than the vertical compressive stress. Therefore, predicted values for vertical compressive stress may not be accurate. It should be noted that even higher predicted vertical compressive stress could be tolerated by HMA and would not affect performance.

Subgrade vertical compressive stress is an important issue since it is closely related to the performance of the track. In-track measurements were conducted on the 8-in. HMA section in TTCI test track for a dynamic case. Test results were shown in Figure 16. Based on Figure 16, it can be noted that the vertical compressive stress over subgrade is about 8 psi. Meanwhile, vertical compressive stress over subgrade in a 4-in. HMA section was also recorded and it is 7.7 psi. The KENTRACK predictive values for these two cases are 8.3 and 8.2 psi, very close to the actual measurement. For comparison, a traditional ballast trackbed was selected in TTCI. It has a 18-in. thick ballast layer. The vertical compressive stress measured from this track is around 11.6 psi, whereas KENTRACK gives a value of 11 psi.

Tables 2a and 2b contain all the KENTRACK Predictive Values (KPV) and In-Track measured Data (ITD) for the Conway and TTCI tests. The comparisons have been discussed previously in the text.

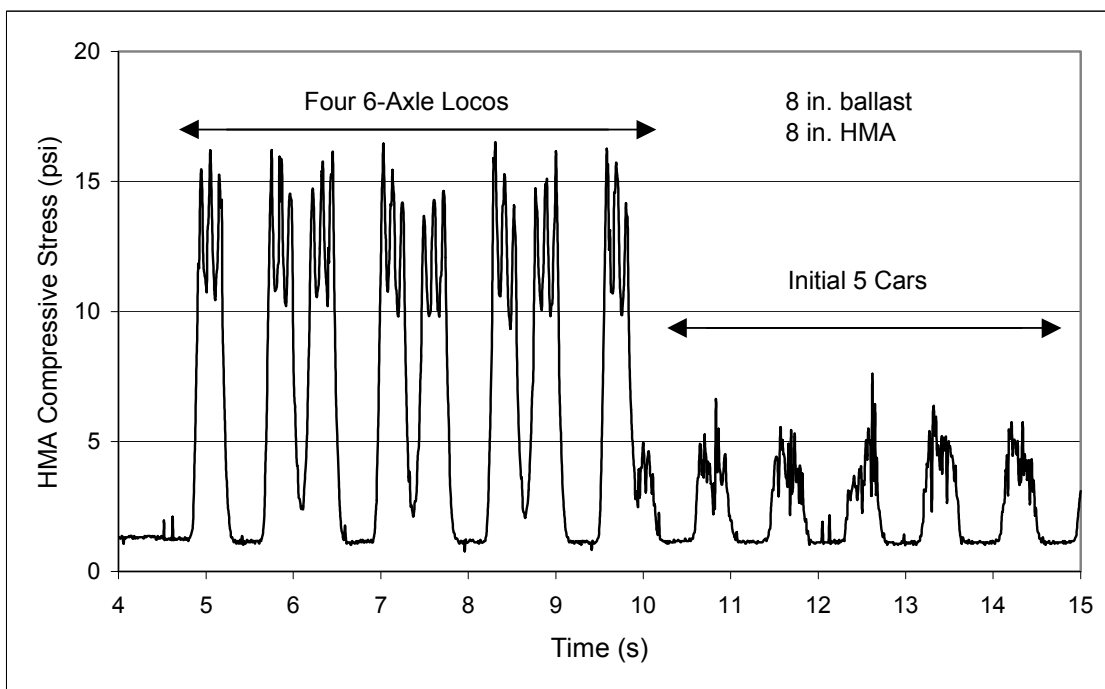
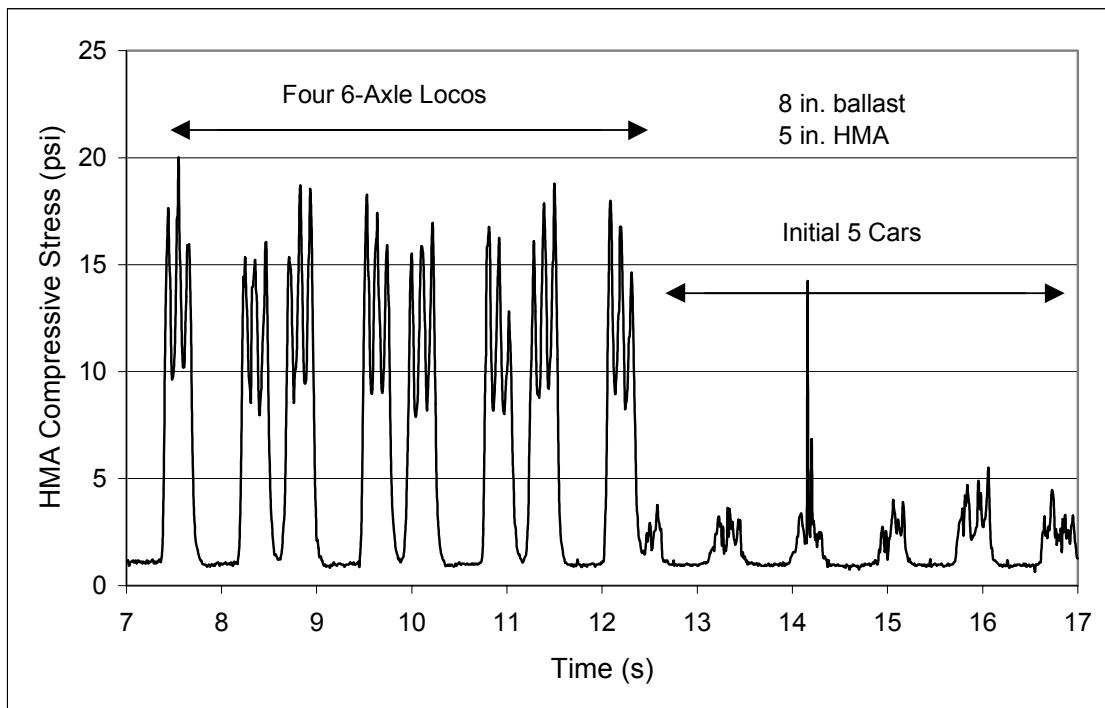


Figure 15. Representative Dynamic Compressive Stress on HMA Layer Measured for Empty Coal Train on CSX Transportation Mainline at Conway, KY

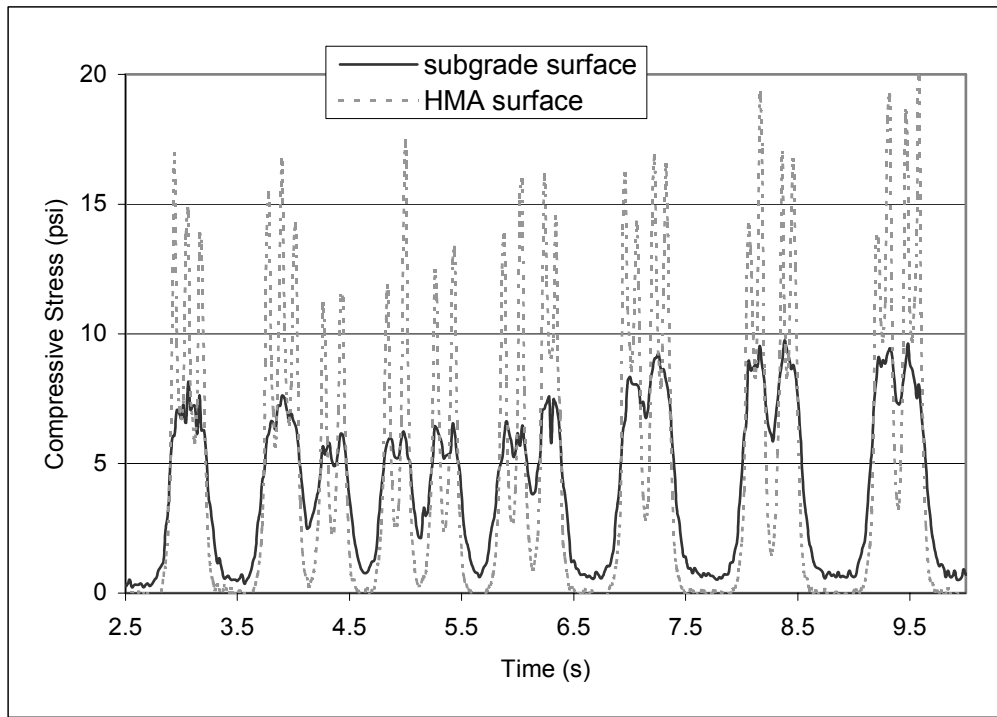


Figure 16. Dynamic Compressive Pressures Measured on TTCI Test Track

Table 2a. Comparison of the KENTRACK Predictive Values (KPV) Versus In-Track Data (ITD) for the CSX Mainline at Conway, Kentucky

Thickness Ballast/HMA inches	Vertical Compressive Stress on Ballast KPV/ITD, psi	Vertical Compressive Stress on HMA KPV/ITD, psi	Vertical Compressive Stress on Subgrade KPV/ITD, psi
10 / 5	47.9 /	21 / 16	13.6 / -
10 / 8	48.7 /	22 / 15	11.7 / -

Table 2b. Comparison of the KENTRACK Predictive Values (KPV) Versus In-Track Data (ITD) at TTCI in Pueblo, Colorado

Thickness Ballast/HMA inches	Vertical Compressive Stress on Ballast KPV/ITD, psi	Vertical Compressive Stress on HMA KPV/ITD, psi	Vertical Compressive Stress on Subgrade KPV/ITD, kPa
12 / 4	43.5 / -	11.7 / 14.9	8.3 / 8.0
8 / 8	47 / -	21.9 / 14.9	8.2 / 7.7

FINDINGS AND CONCLUSIONS

Stresses at several critical interfaces in the railroad track structures and foundations have been predicted and measured and results compare favorably. Geokon earth pressure cells and Tekscan sensors provide methods for direct measurements of trackbed pressures.

The KENTRACK computer program, based on finite element method and multi-layered theory, has been utilized to predict stresses in the track structure and foundation. The program is capable of analyzing both traditional ballast trackbeds and HMA trackbeds. In-track measurements confirm the predictive values from KENTRACK thus providing this program a measure of credibility.

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