

In-Situ Test Measurement Techniques Within Railway Track Structures

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ABSTRACT

Recent changes in national transportation needs have placed increased burden on railroad infrastructure. To meet the increased demand for efficient freight transport, the railroad industry has increased traffic volume and maximized axle loadings. Increased axle loads have forced railroads to reevaluate existing infrastructure to ensure their ability to accommodate the additional traffic loads. It is imperative to design and maintain tracks such that they can withstand high volume and increasing axle loads over an extended service life, considering the track structure is the most significant capital expense for railroad companies. It has been desirable for years to develop non-intrusive procedures to directly measure pressures and stresses at various levels and interfaces in the railroad track structure in order to optimize track designs and improve subsequent track performance.

Methods for measuring both pressures and deflections have been presented in recent research focusing on assessing the performance of trackbeds with increased track modulus, primarily through the addition of asphalt underlayment. These studies involve instrumenting HMA trackbeds with earth pressure cells and displacement transducers to measure pressure levels and distributions within the track structure and rail deflections under moving trains.

Additional test methodologies have been developed to include pressure readings at interfaces like the rail/tieplate interface and the tieplate/tie interface using very thin pressure sensitive Tekscan sensors. The Tekscan Measurement System uses a piezoelectric film sensor composed of a matrix-based array of force sensitive cells, similar to mini strain gauges, to obtain accurate pressure distributions between two surfaces in the track. The procedure appears applicable for a wide variety of specific track related measurements to include: 1) analyzing pressure distribution patterns at the rail base/tie plate/tie interfaces to minimize wear and eliminate pressure points, 2) validating and optimizing horizontal curve geometric design criteria relative to superelevation, 3) assessing crossing diamond, other special trackwork, and bridge approach impact pressures, and 4) evaluating the advantages/disadvantages of various types of tie plates, fastenings, and tie compositions with the objective of equalizing pressure distributions over the interface areas.

Results of testing are presented in detail for test installations on CSX Transportation heavy tonnage mainlines and at the Transportation Technology Center (Pueblo) low track modulus heavy tonnage test track.

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INTRODUCTION

Railways have served as a prominent transportation mode in this country for nearly two centuries. Throughout the late nineteenth and early twentieth centuries it was the primary mode for both freight and passenger transport. After experiencing a significant shift in freight transport from rail to highway throughout most of the twentieth century, recent increases in fuel costs and highway congestion have shifted the trend back to railways. In response to the increased traffic demands, freight railways have increased train speeds, gross ton-miles, and axle loads. The latest Association of American Railroads statistics (AAR, 2006) indicate that in 2005 an all-time record 1.7 trillion ton-miles of freight was carried over the nation's nearly 141,000-mile (227,000 km) railroad network. The average freight car weight has increased to 129 tons (117 metric tons) with most new cars having gross weights of 143 tons (130 metric tons).

The importance of developing and specifying premium track structures and components to adequately carry the increased tonnage is a current reality of the industry. Failure of the track structure and components results in difficulty maintaining track geometric features necessary for efficient and safe train operations. Maintenance costs and track outages increase due to frequent maintenance and renewal cycles.

TYPICAL TRACKBED FAILURE MODES

Failure types within the track structure in response to the imposed loadings can be categorized as either subgrade or trackbed structural component failure. **Subgrade** failure occurs when the pressure transmitted to the subgrade is greater than the inherent bearing capacity of the particular subgrade. The subgrade soil's ability to accommodate loading pressures is a function of its shear strength, cohesion, plasticity, density, and moisture content. A well-compacted subgrade soil that is confined and maintained reasonably dry will normally perform adequately for an indefinite period of time. A possible exception is a highly compressible soil such as peat. Subgrade failures adversely affect track geometry and are normally difficult and expensive to correct.

The second type of trackbed failure occurs when one or more of the **trackbed structural components** fail to perform satisfactorily for a reasonable period of time. This is commonly manifested by the subballast, and particularly the ballast, becoming clogged (fouled) with excessive quantities of fine size material. This lowers the shear strength of the ballast and bearing capacity of the subballast. Fouling is normally due to degradation of the ballast, infiltration of subgrade soil particles, extraneous droppings from hopper cars, or wind-blown fine particles. Track geometry is adversely affected to varying degrees. The geometry is difficult to rectify since it is difficult to manipulate and adjust the fouled ballast with typical trackbed maintenance surfacing equipment.

Periodic replacement of the track components (rails, ties, fasteners, and special trackworks) cannot be avoided (Lopresti, Davis and Kalay, 2002). However, it is desirable to increase the service life of the components. The adequacy of the trackbed structural components supporting the track can have a significant effect on the life of the track components by reducing impact stresses and minimizing deflections of the track.

The solution for minimizing **subgrade** failures 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 structural components, or utilizing higher quality/load bearing trackbed components. The solution for minimizing **structural component** failure is designing and selecting reasonable fasteners and track components so that an optimum track structural support stiffness will be achieved. In order to design optimum track structural support stiffness, it is necessary to determine the pressures at different levels in the track support structure such as at the rail base/tie plate, tie plate/tie, tie/ballast, ballast/subballast, and subballast/subgrade interfaces.

IN-SITU TEST SITES

Two test sites have been utilized to obtain trackbed pressure and deflection measurements. The **Revenue** line is the CSXT 40 MGT (36 MGt) heavy tonnage **Mainline** between Cincinnati, OH and Atlanta, GA at Conway, KY. Two 1,000-ft (305 m) long asphalt underlayment sections, consisting of 5-in. (125 mm) and 8-in. (200 mm) thick layers of asphalt, were placed during 1983. This section of track has remained virtually maintenance free for nearly 25 years and has been subjected to numerous tests and evaluations.

The **Non-Revenue** line is on the **High Tonnage Loop** at the Transportation Technology Test Center (TTCI) near Pueblo, CO. Two 350-ft (107 m) long asphalt underlayment sections, consisting of 4-in. (100 mm) and 8-in. (200 mm) thick layers of asphalt, were placed during 1999 over the soft clayey subgrade portion of the test track. Test trains with 40-ton (36 metric ton) axle load continuously circle the loop to provide accelerated loading (Li, Lopresti and Davis, 2002).

PRESSURE AND DEFLECTION MEASUREMENT TECHNIQUES

Pressures exerted by the wheel loads on the trackbed support materials were obtained with Geokon Model 3500 Earth Pressure Cells. These were imbedded in the track structure above and below the HMA mat. Figure 1a is schematic view of the pressure cell configuration for in-track tests. Figure 1b is a view of an in-track test.

The portion of the cell that receives the load consists of two slightly convex stainless steel circular plates that are 9 in. (230 mm) in diameter welded together at their edges. The void between the two plates 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 (690 kPa) limit.

In addition to the pressure cell, a computer, power source, and junction box are required. A 12-volt battery provides power for the electrical signal. 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.

Each Geokon Pressure Cell is calibrated prior to in-track tests. This provides 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.

Pressures exerted by the wheel loads on the ties and plates were obtained with the Tekscan pressure distribution system. Tekscan Inc., the company that produces the force distribution measurement system, provides sensors, software, and technical support for the product. The measurements are made with a thin (≈ 0.1 mm thick) matrix-based sensor consisting of two flexible polyester sheets with silver conductive electrodes printed on them. One sheet has a semi-conductive ink printed in rows while the other sheet has the ink printed in perpendicular columns. These two sheets of polyester are glued together at the edges. The illustration in Figure 2a shows a basic sensor and its components. Figures 2b and 2c show a typical test setup schematic and a view of an in-track test, respectively (Rose & Stith, 2004).

The ink is pressure sensitive and its conductivity varies with the force applied to it, similar to a strain gauge. By exciting one row and one column at a time the system isolates the location where the row and column meet which completes the circuit. The force applied is determined by measuring the change in resistivity through the

circuit. The process is repeated for all the rows and columns and the distribution of force over the active area is thus determined.

Deflections under the dynamic loadings of the railcars were recorded in conjunction with the pressure measurements using Linear Variable Displacement Transducers (LVDT). An obstacle to using LVDTs to measure track deflections is establishing a fixed point of reference (datum). The fixed datum is achieved by driving a 1-in. diameter steel rod through the track structure and into solid sub-strata. Therefore, the rod is unaffected by the passing of the trains and remains at a fixed elevation. Figure 3a is a schematic view of the LVDT configuration for in-track tests. Figure 3b is a view of an in-track test arrangement. The LVDT consists of a nonmagnetic shell and a magnetic core. The relationship between input and output voltage is related to displacement.

The LVDT is attached to a removable clamp that can be secured to the base of the rail. Two pieces of angle steel are securely clamped to the stationary rod. The LVDT is rotated so that the movable indicator (core) is positioned over a piece of the angle steel and zeroed. Snap-Master is used as the data acquisition system for obtaining the deflection measurements in the real-time domain. A 6-volt battery supplies the power for the LVDT.

Track deflection is considered to be a primary indicator for predicting track strength, life, and quality. Excessive deflection causes accelerated movement and wear of ballast and ties through inter-particle powdering and abrasion. The ideal track structure provides a balance of stiffness and flexibility – not too stiff, not too resilient.

CONWAY, KY (CSXT) TEST RESULTS

Track Pressure Measurements

A variety of trains were measured including a loaded coal train, mixed freight train, and five locomotives in several Tekscan pressure distribution tests. The tests mainly focused on 1) obtaining in-track pressure measurements at the rail base/tie plate interface 2) evaluating the ability of Tekscan to record higher speed trains in a section of open track, and 3) evaluating the effects of different types of plates – machined steel, polyurethane, and rubber. The output from the Tekscan sensors that were placed at the rail base/tie plate interface showed that the force was concentrated over a few small areas of the hot-punched steel plates, producing a few very high pressure peaks. Typical results for pressure distributions at the rail/tie plate interface for a steel, polyurethane plastic, and a rubber tie plate are presented in Figures 4a, 4b, and 4c, respectively (Rose & Stith, 2004). The peak rail base/tie plate interface pressures typically range from 400 to 600 psi (2,800 to 4,200 kPa) provided the pressures were distributed fairly uniformly. It is obvious that rigid objects such as commercially produced plates and rail bases will inevitably have a few high contact points on their supposedly “flat” surfaces. From geometry, it is known that three points define a plane. Therefore, a plate’s three highest points would be the “high plane” of the plate. Assuming the plate does not deform, these three or possibly four high points would assume the entire applied load resulting in very poor pressure distribution. This was precisely what results from initial tests yielded.

Trackbed Pressure Measurements

Figure 5 is a typical plot of the pressures exerted on top of the HMA mat for an empty coal train in the time domain (Rose, Li and Walker, 2002). Vertical pressures imposed by typical 286,000-lb (130-metric ton) locomotives and loaded coal cars range from 13 to 17 psi (90 to 120 kPa) on top of the HMA mat. The average locomotive wheel load is 35,000 lb (16 metric tons). Pressures are reduced to 2 to 4 psi (15 to 30 kPa) under the 63,000 lb (29 metric ton) empty cars, which have an average wheel load of 8,000 lb (3.5 metric tons).

The beam action of the track, which distributes the concentrated wheel loadings over several ties and the confined, high modulus ballast layer, serve to effectively reduce the heavy wheel loadings. By comparison, a 180-lb (82 kg) person will exert about 6 psi (40 kPa) pressure while standing on a level surface. Furthermore, typical tire pressures imposed on highway asphalt surfaces under loaded trucks range from 100 psi (700 kPa) to over 150 psi (1,050 kPa) depending on the magnitude of loading and tire configurations.

Trackbed vertical stress levels on top of the HMA mat under heavy tonnage railroad loadings are very low and only a fraction of those imposed by high-pressure truck tires on highway pavements. The HMA mat should have an extremely long fatigue life at the load-induced pressure levels existing in the trackbed environment.

Trackbed Deflection Measurements

Dynamic track deflections were recorded in conjunction with the pressure measurements using LVDTs referenced to a fixed datum. Figure 6 is a typical plot of rail deflections under 286,000-lb (130-metric ton) locomotives and loaded cars. The deflections average 0.25 in. (6.4 mm) for wood tie track and around 0.05 in. (1.3 mm) for concrete tie track. These are considered optimum for both track types.

Based on the wheel loadings and measured track deflections, the calculated dynamic track modulus (stiffness) values are in the 2,500 lb/in/in (17 MPa) range for wood tie track and around 7,500 lb/in/in (52 MPa) for

concrete tie track. These are also considered optimum. The concrete tie track deflects much less than the wood tie track and is thus much stiffer. This increases pressure within the ballast. The ballast must be properly supported from below so it can develop high shear strength to reduce the higher than normal imposed loading pressures. The high modulus HMA mat provides increased support and confinement for the ballast in concrete tie track.

TTCI (PUEBLO) TEST TRACK RESULTS

Trackbed Pressure Measurements

HMA underlayment sections were placed over a soft subgrade (low track modulus) and subjected to 40-ton (36-metric ton) axle loads. The use of HMA underlayment was intended to reduce load-induced stresses to the subgrade and to provide a waterproof layer over the underlying soil. Since its installation, the performance of this test track has been evaluated in terms of track geometry degradation with traffic as well as the amounts of track modulus increase and subgrade stress reduction compared to conventional granular layer construction (Li, Lopresti and Davis, 2002).

Figure 7 gives the track modulus test results obtained at 92 MGT (83 MGt) and the subgrade stress results under a static wheel load of 20 tons (18 metric tons). As shown, the average modulus values for the two HMA segments are 2,800 lb/in/in (20 MPa) and 3,300 lb/in/in (23 MPa) for the fully consolidated ballast (increased from 2,600 and 2,800 lb/in/in (18 and 19 MPa)), respectively, at 0 MGT (0 MGt). The track modulus for the 18-in. (450-mm) granular track averaged 2,000 lb/in/in (14 MPa). As a result, the measured subgrade stresses were lower for the asphalt trackbeds than for the 18-in. (450-mm) granular track. Under 20-ton (18-metric ton) static wheel load, only 7 to 8 psi (50 to 55 kPa) of subgrade stress was generated under the HMA underlayments, compared to 12 psi (83 kPa) under the 18-in. (450-mm) granular track structure.

To indicate how stresses induced by wheel loads are reduced from the HMA to the subgrade, Figure 8 shows the dynamic stress results under an actual train operation at 40 mph (64 km/hr) measured on the 8-in. (200-mm) HMA surface as well as on the subgrade surface. As illustrated, use of a 8-in. (200-mm) HMA underlayment reduced the subgrade stress by approximately one-half.

In addition, the data in Figure 8 indicates that the dynamic pressures measured on the top of the HMA surface for the 16- to 20-ton (15- to 18-metric ton) wheel loads range from 11 to 19 psi (75 to 130 kPa). These values compare favorably with the 13- to 17-psi (90- to 120-kPa) dynamic pressures measured on top of the HMA mat at the CSXT Conway test site for the 18-ton (16-metric ton) wheel loads, as indicated in Figure 5.

FINDINGS

- The Tekscan system is applicable for railroad trackbed evaluation and can be used to measure pressures within the track components. The non-intrusive nature of the Tekscan sensor makes it ideal for the upper region of the track structure specifically the rail base/plate interface.
- Pressure distributions at the rail base/tie plate interface generally showed a few points of very high pressure.
- Peak dynamic pressures typically ranged from 400 to 600 psi (2,800 to 4,200 kPa) at the rail base/tie plate interface for the 286,000 lb (130 metric ton) locomotives and loaded cars.
- Peak dynamic pressures range from 13 to 17 psi (90 to 120 kPa) on top of the HMA mat under 286,000 lb (130 metric ton) locomotives and heavily loaded cars – only two to three times greater in magnitude than the pressure exerted by an average-size person standing on an asphalt pavement.
- Peak dynamic vertical pressures under similar loading are further reduced to 7 to 8 psi (50 to 55 kPa) under the HMA layer at the subgrade interface.
- Dynamic track deflections for HMA trackbeds under 286,000 lb (130 metric ton) locomotives average 0.25 in. (6.4 mm) for wood tie track and 0.05 in. (1.3 mm) for concrete tie track. These are considered optimum.
- Dynamic track modulus (stiffness) values consistently average 2,900 lb/in/in (20 MPa) for wood tie track and 7,200 lb/in/in (50 MPa) for concrete tie track. These are considered optimum.
- In-track test measurements on HMA underlayment trackbeds obtained on CSXT's heavy-haul revenue line and obtained at TTCI's heavy-haul research test facility are consistent.

CONCLUSIONS

Pressures and deflections at critical interfaces within the railroad track structure were successfully measured. Geokon earth pressure cells and the Tekscan Pressure Distribution System provide methods for direct measurements of pressures within both the trackbed and track. Track deflection measurements were successfully obtained using Linear Variable Displacement Transducers.

ACKNOWLEDGEMENTS

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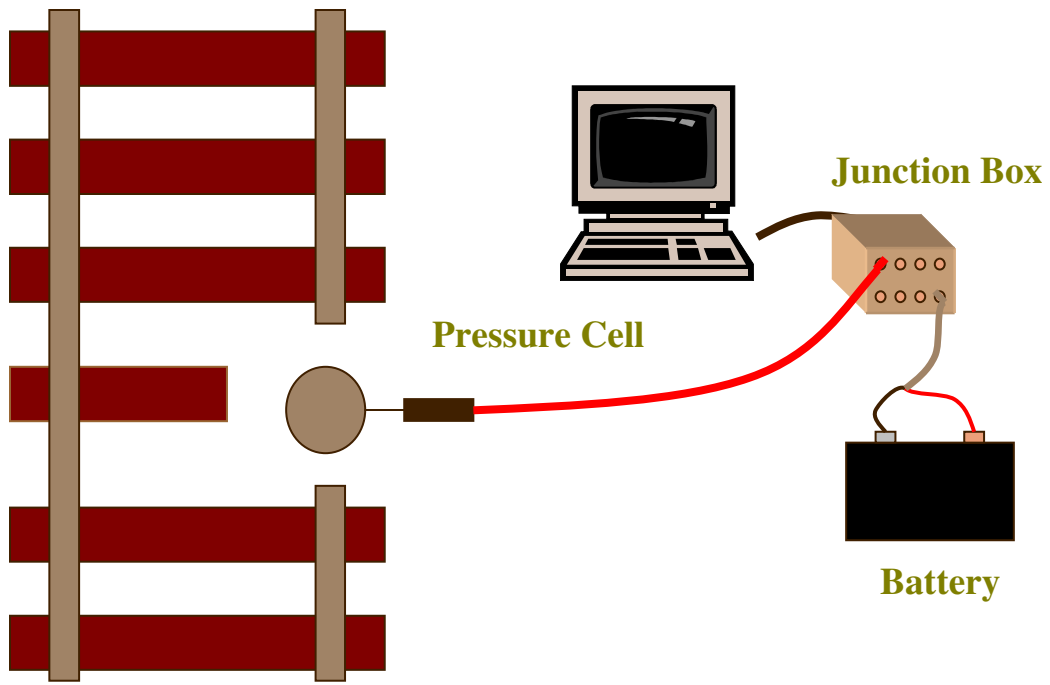


FIGURE 1a. Pressure Cell Measurement Configuration.



FIGURE 1b. In-track View of Pressure Cell Testing.

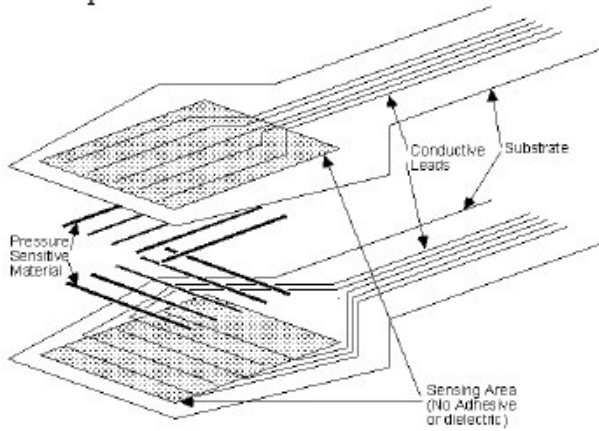


FIGURE 2a. Basic Tekscan Sensor Schematic (www.tekscan.com/technology).

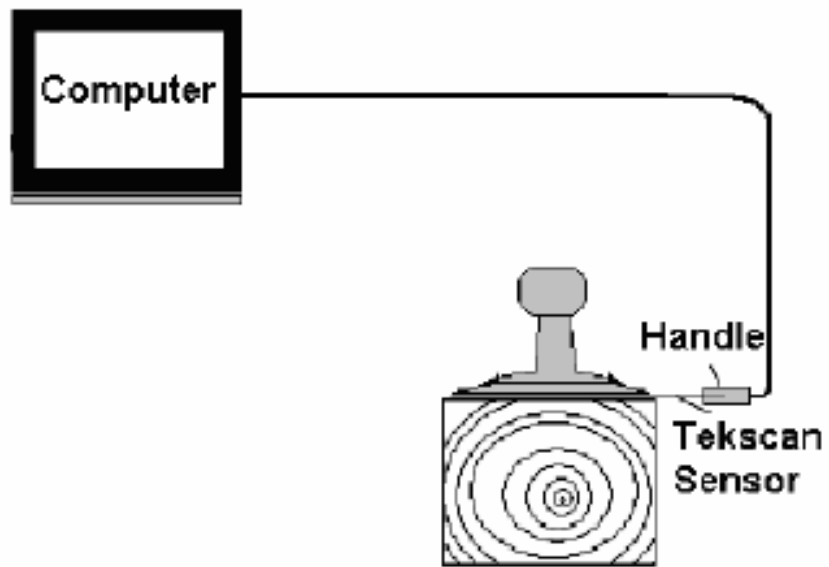


FIGURE 2b. Typical Test Setup Schematic.



FIGURE 2c. In-Track View of Tekscan Pressure Distribution System

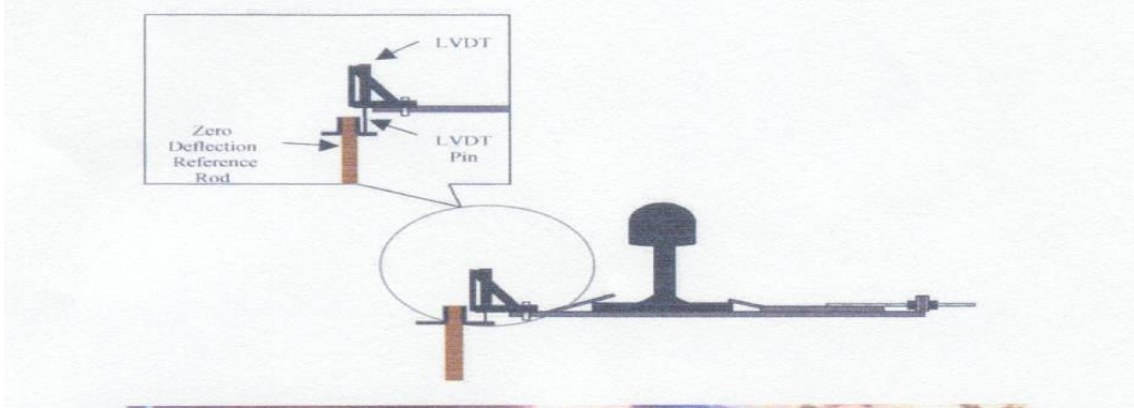


FIGURE 3a. LVDT Measurement Configuration.

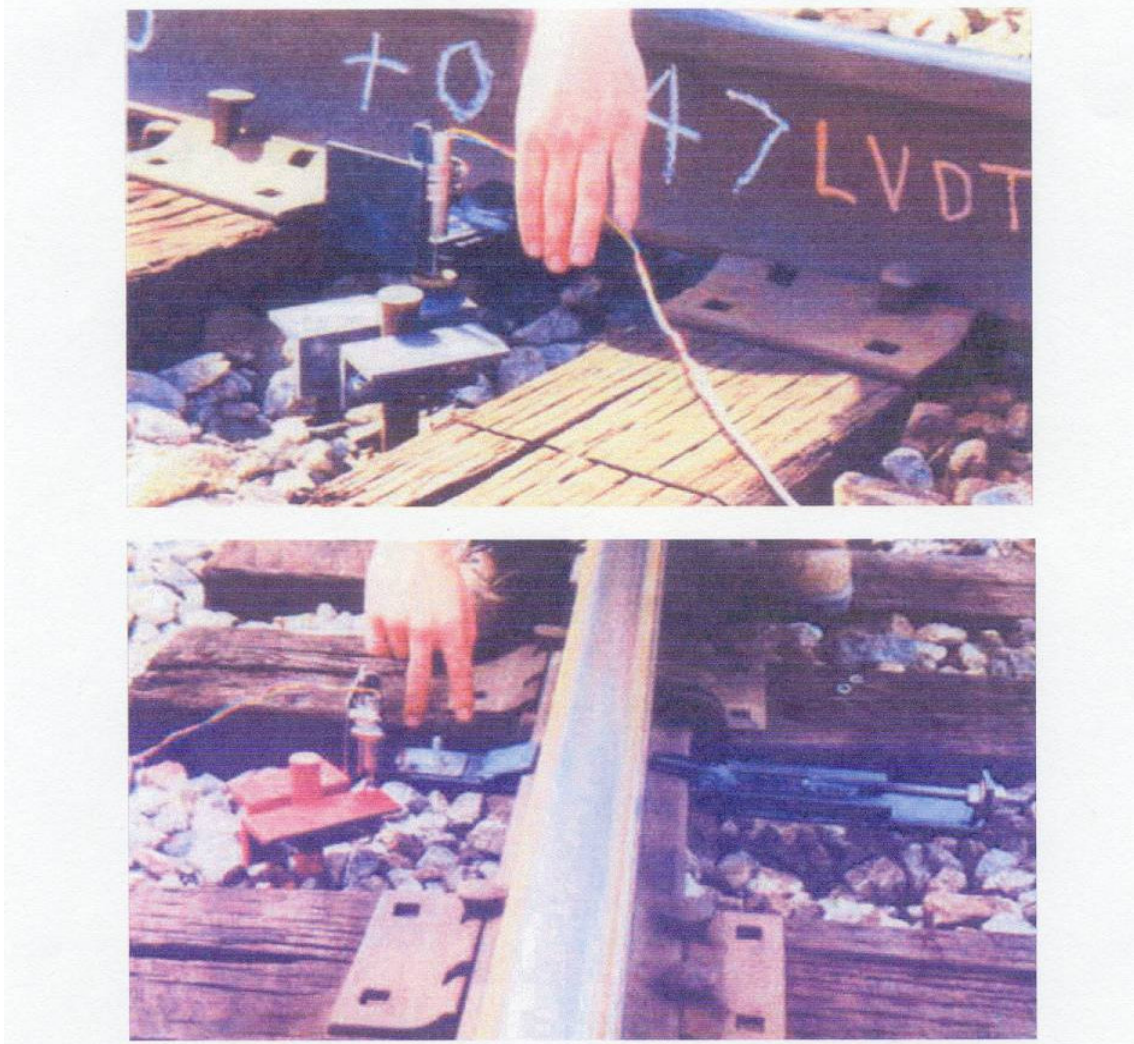


FIGURE 3b. In-track View of LVDT Deflection Testing.

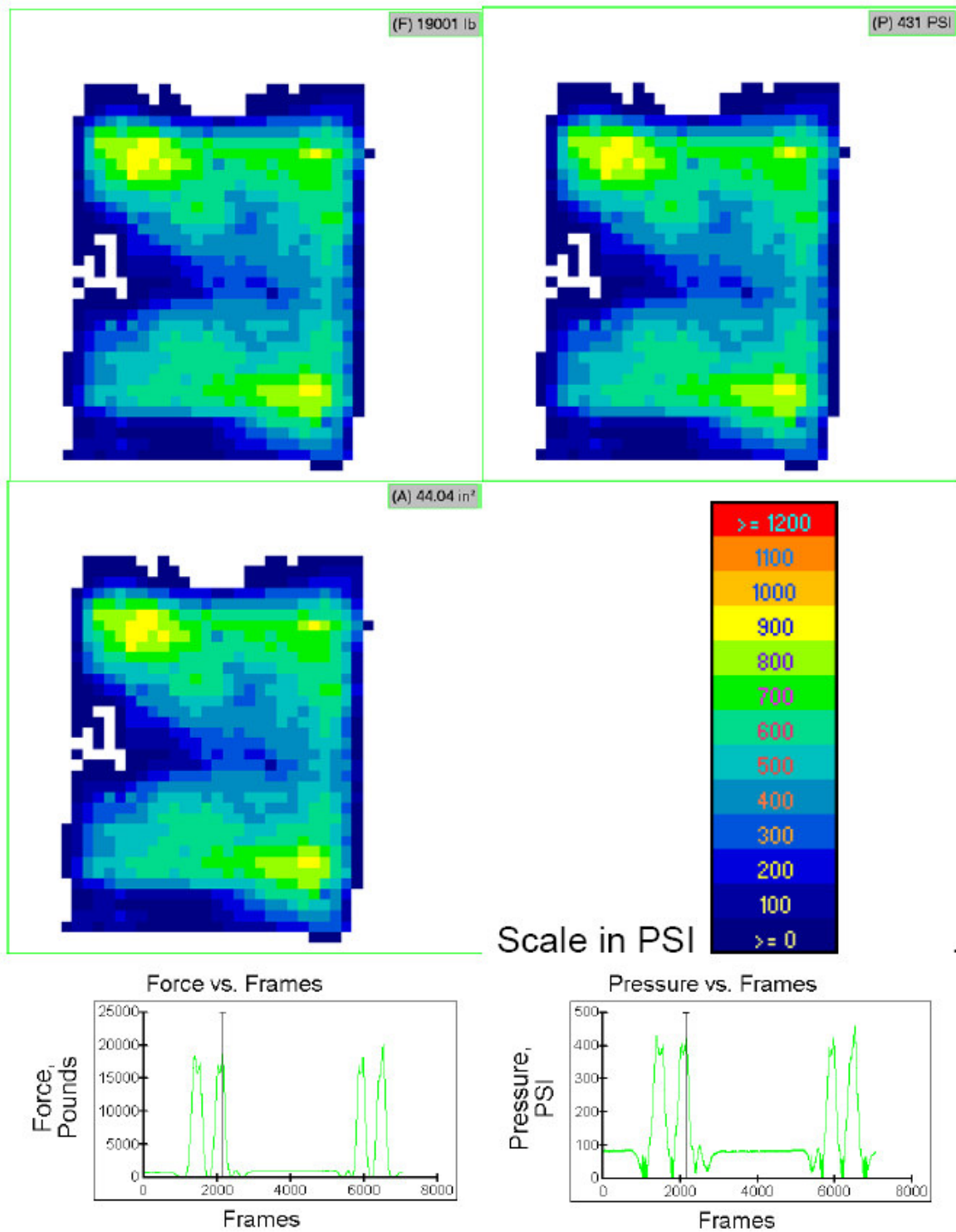


FIGURE 4a. Typical pressure distribution between a machined steel plate and the rail base (Rose & Stith, 2004).

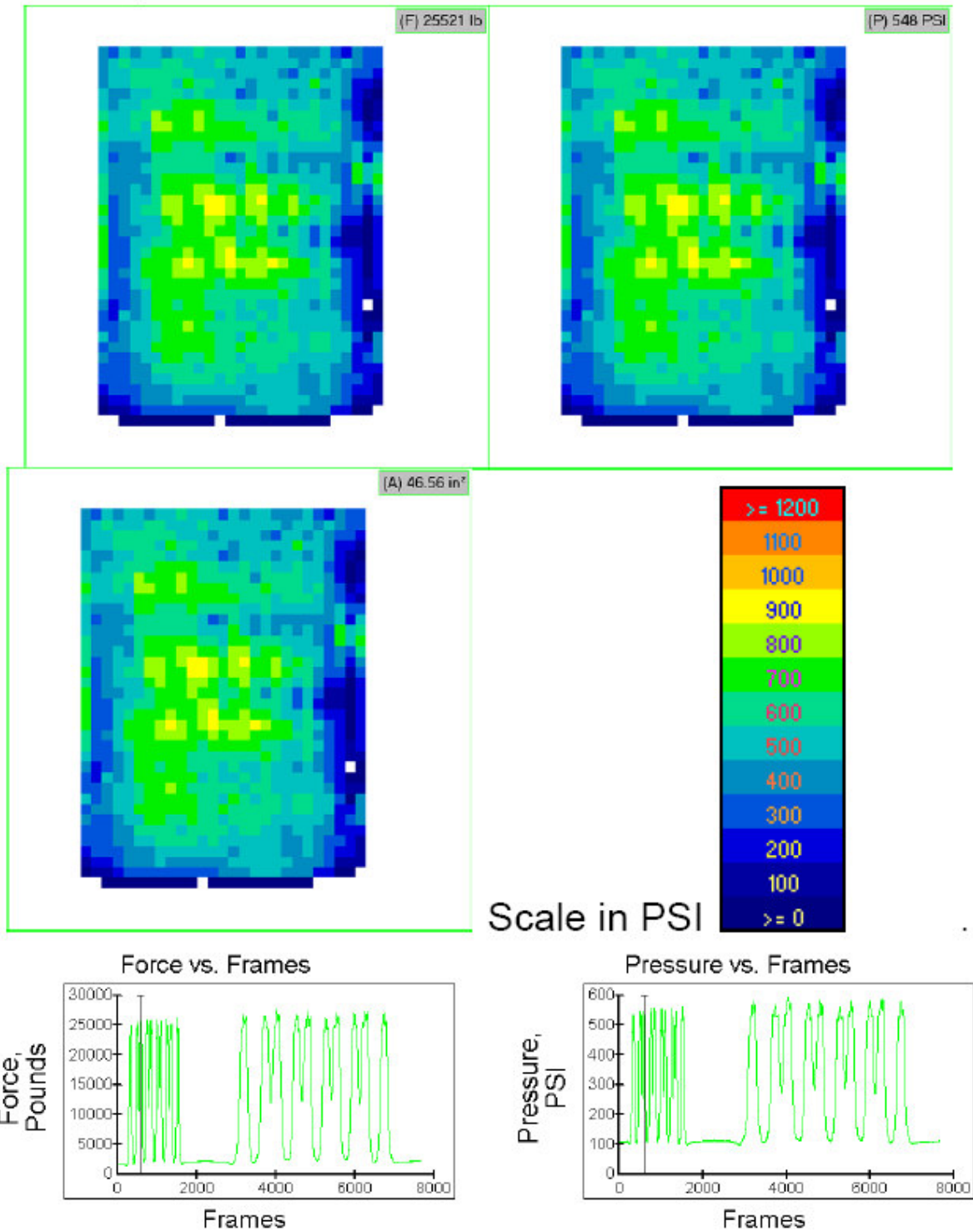


FIGURE 4b. Typical pressure distribution between a polyurethane plastic plate and the rail base. The speed of the train was approximately 30 mph (Rose & Stith, 2004).

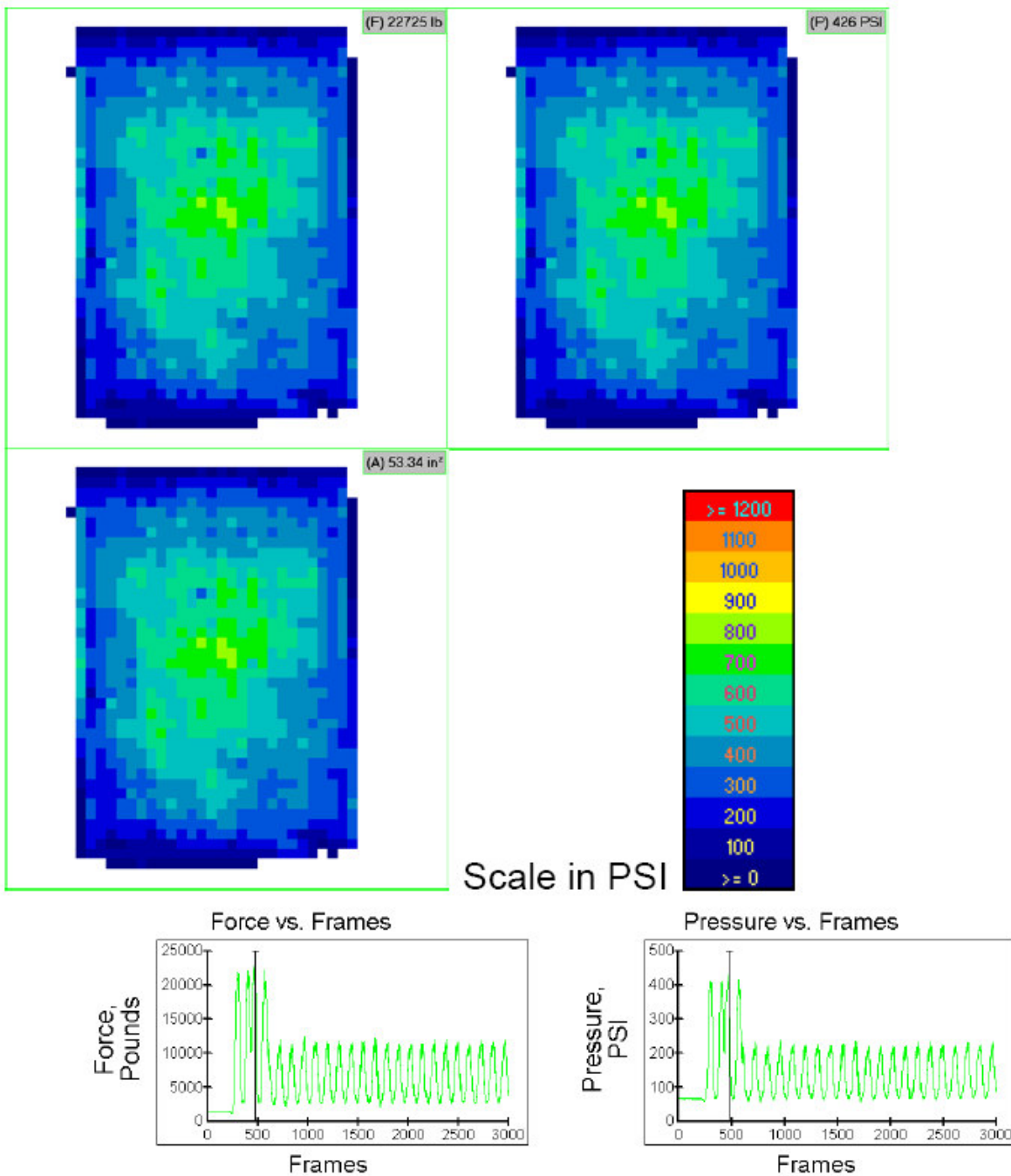


FIGURE 4c. Typical pressure distribution between a rubber plate and the rail base. The lead truck of the second 6-axle locomotive is represented (Rose & Stith, 2004).

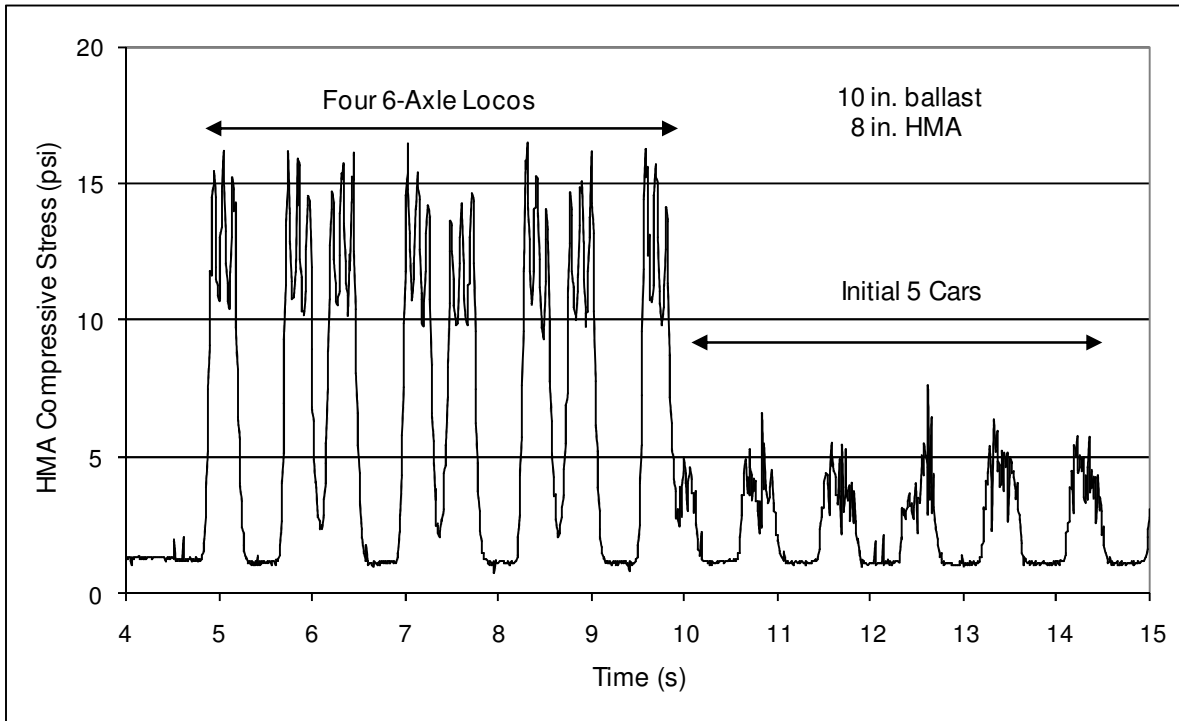
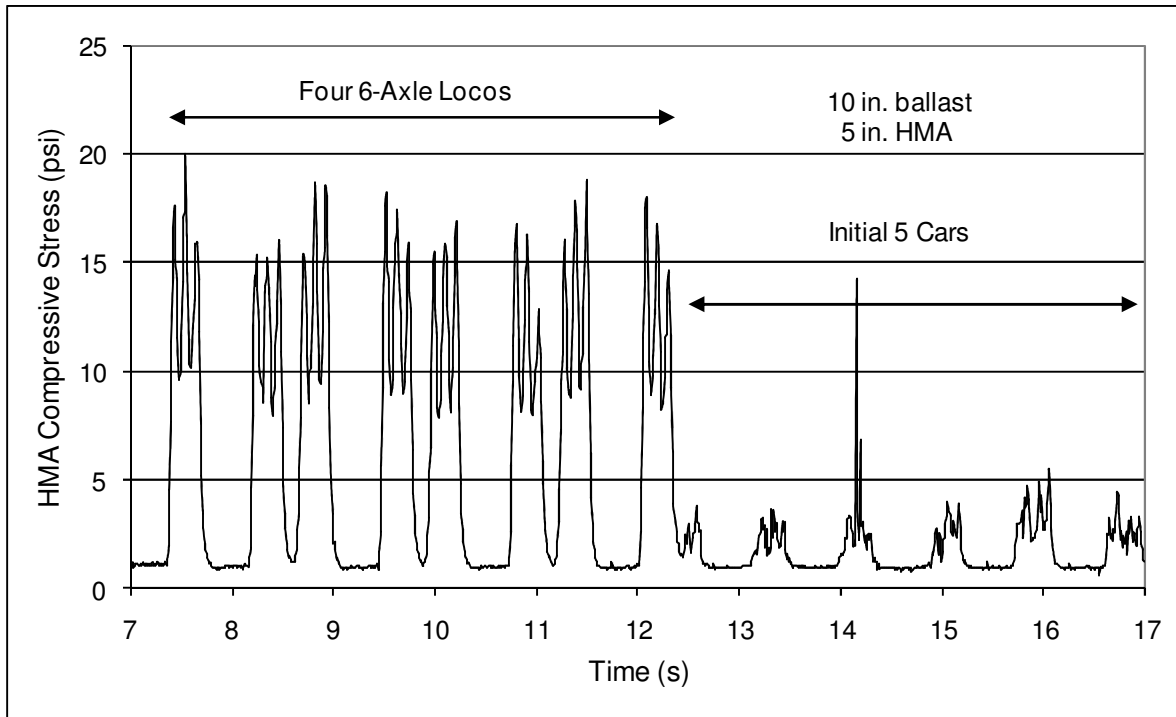


FIGURE 5. Representative Dynamic Compressive Stress on HMA Layer Measured for Empty Coal Train on CSXT Mainline at Conway, KY. (10 psi = 69 kPa and 1 in. = 25.4 mm)

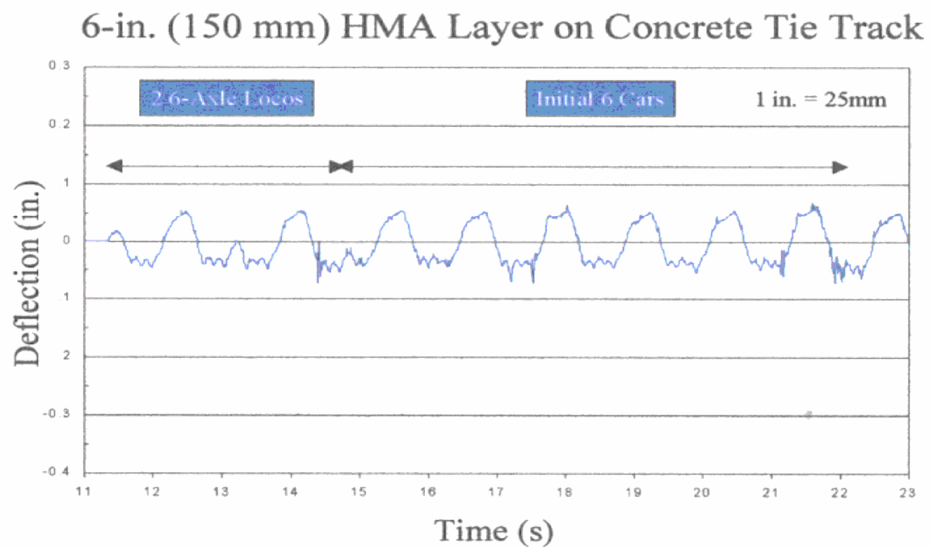
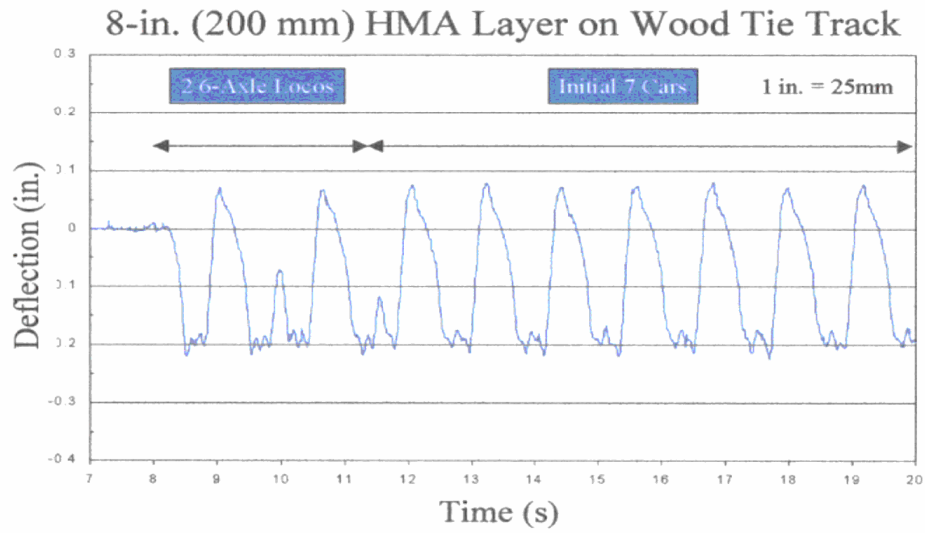
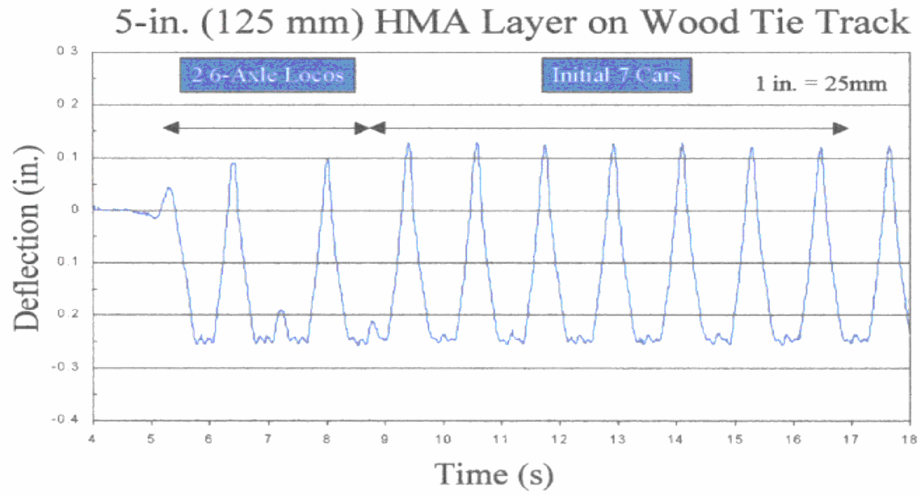
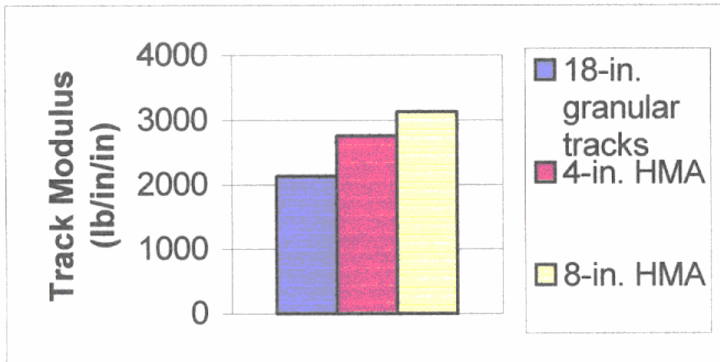
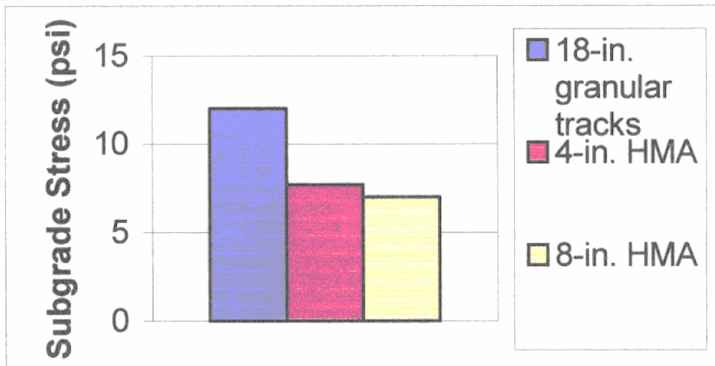


FIGURE 6. Representative Deflections Under Loaded Coal Train.



1 in = 25 mm
 1000 lb/in/in = 6.89 MPa



1 in = 25 mm
 10 psi = 69 kPa

FIGURE 7. Test Results for Track Modulus (Consolidated Ballast) and Subgrade Stress Under 20 ton (18 metric ton) Static Wheel Load.

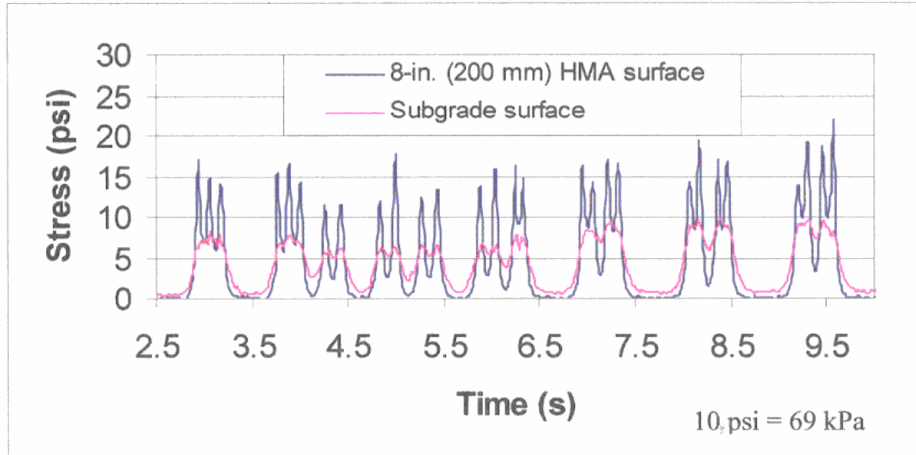


FIGURE 8. Reduction of Dynamic Stresses from 8-in. (200 mm) HMA Surface to Subgrade Surface Under 39 ton (35 metric ton) Axle Cars.