VIRTUAL SENSOR EXPERIMENTAL METHOD

by

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ABSTRACT

Sensor installation in pavement test sections requires extreme care to preserve soil density and moisture so that the soil surrounding the sensors can correctly represent the soil in the rest of the soil layer. In the design of full-scale pavement experiments, it is desirable to have many sensors embedded in the test sections. However, too many sensors may significantly disturb the soil density and moisture, thereby decreasing the reliability of the test results. Under the assumption that stress and strain would reach maximum values at points under the center of the tire path, sensors were installed only at these locations. A method was devised to create a system of virtual sensors that generated detailed contour cross sections of stress and strain without the expense of more sensors and without risking disturbance to the soil layers.

This paper presents an experimental method called Virtual Sensor Method that results in more detailed views of the state of stress and strain in a test section during traffic events. The method involves post-processing and assembly of sensor data obtained during multiple traffic passes conducted with various offset distances from the center of the tire path using only the existing real sensors. With real sensors installed at various depths within a pavement structure, high definition cross sections of stress and strain can be produced as if many more sensors had been installed, but without the expense or the potential disturbance associated with more real sensors.

The Virtual Sensor Method was applied to a full-scale flexible pavement test section instrumented with three-dimensional sets of stress and strain sensors, and trafficked with a heavy vehicle simulator. High definition vertical, longitudinal and transverse contour cross sections of stress and strain measurements were produced at four load intensities using a heavy vehicle simulator.

INTRODUCTION

Accelerated pavement testing (APT) is the application of controlled traffic loads at rapid rate on a representative pavement test section coupled with measurements of pavement performance and mechanical response. Pavement response to the applied traffic loads is defined by measurements of stress, deformation and strain by means of appropriate sensors and a suitable data acquisition system. The experimental designer is often confronted with the need to balance the desire for more sensors that would yield more detailed information versus cost and the potential for artifacts and soil disturbance that may arise from sensor installation. Based on the assumption that maximum values of stress and strain occur at the center of the tire path, typically sensors in pavement test sections have been placed mostly at these locations. This paper presents a method that was used in experiments on a full-scale flexible pavement test section where sets of stress and deformation sensors were installed at the center of the tire path. A heavy vehicle simulator was used to apply the traffic loads. During post-processing of the pavement response data, measurements from individual traffic passes were integrated into simulations of a unified response to one traffic pass to obtain detailed cross sections of stress and strain in the vertical, transversal and longitudinal directions relative to the traffic loads. This method has been named Virtual Sensor Method, and it is the primary focus of this paper.

APT FACILITY

The APT reported in this paper was conducted on a full-scale flexible pavement test section built indoors in the Frost Effects Research Facility (FERF) of the Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire. CRREL is a component of the Engineer Research and Development Center (ERDC), the R&D division of the US Army Corps of Engineers. The FERF APT facility includes a large building that can accommodate several full-scale pavement test sections, a heavy vehicle simulator, and powerful refrigeration and heating equipment, and a close basin system that facilitates temperature and moisture controls. The climate control system is capable of simulating several winters in one year. A pavement structure can be cooled until frost penetrates depths representative of northern US locations.

For the purpose of the experiments reported in this paper, the climate control equipment kept the air and pavement temperatures practically constant at 23˚C (73˚F) throughout the duration of these experiments.

The FERF is equipped with a Mark IV Dynatest heavy vehicle simulator (HVS) (Janoo et al., 2003) capable of applying a range of traffic loads with automatic or manual control of tire wander or offset distances Figure 1 shows the heavy vehicle simulator. For the purpose of the experiments reported in this paper, manual control was used to produce a series of tire path offsets required for implementation of the Virtual Sensor Method.

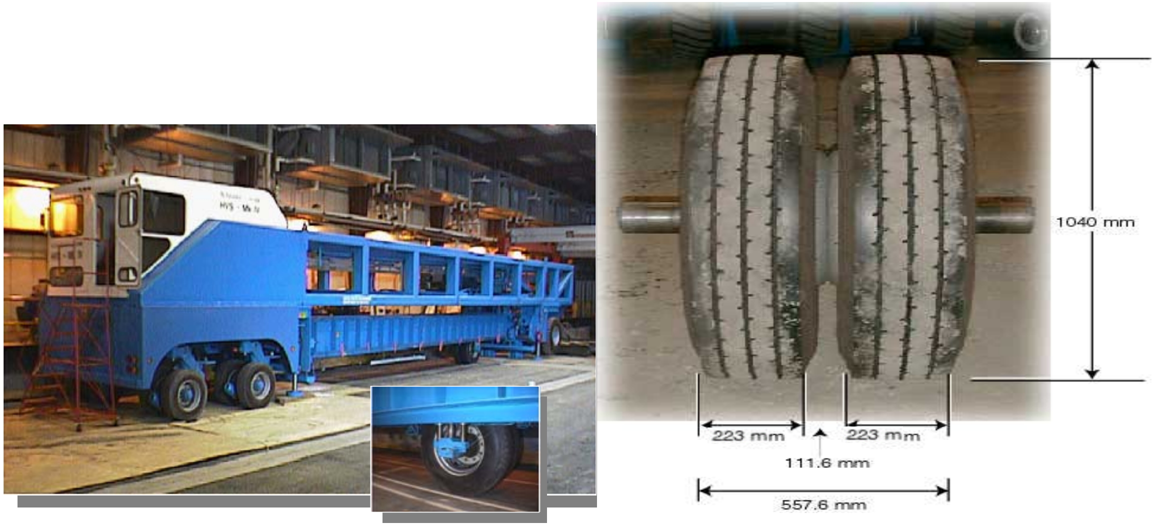

FIGURE 1 Heavy vehicle simulator and dual truck tire assembly.

TEST SECTION

The test section layer structure, from top down, includes a 76-mm (3-in.) asphalt concrete (AC) layer, a 229-mm (9-in.) base course, a 3-m (9.8-ft) subgrade layer, and a thick concrete slab that simulated bed rock. Figure 2 shows a cross section of the test section.

The total thickness of the AC layer was 76 mm (3 in.) built with a 25-mm (1-in.) wearing course over a 51-mm (2-in.) binder course. The hot-mixed asphalt (HMA) in the wearing course conformed to the Type III Vermont specifications. Its maximum aggregate particle size was 13 mm (0.5 in.). Its asphalt binder was PG-58-34 and its binder content was and 5.3 percent. The asphalt concrete binder course was Type II with maximum aggregate particle size of 19 mm (.75 in.) and 4.5 percent of PG-58-34 asphalt binder.

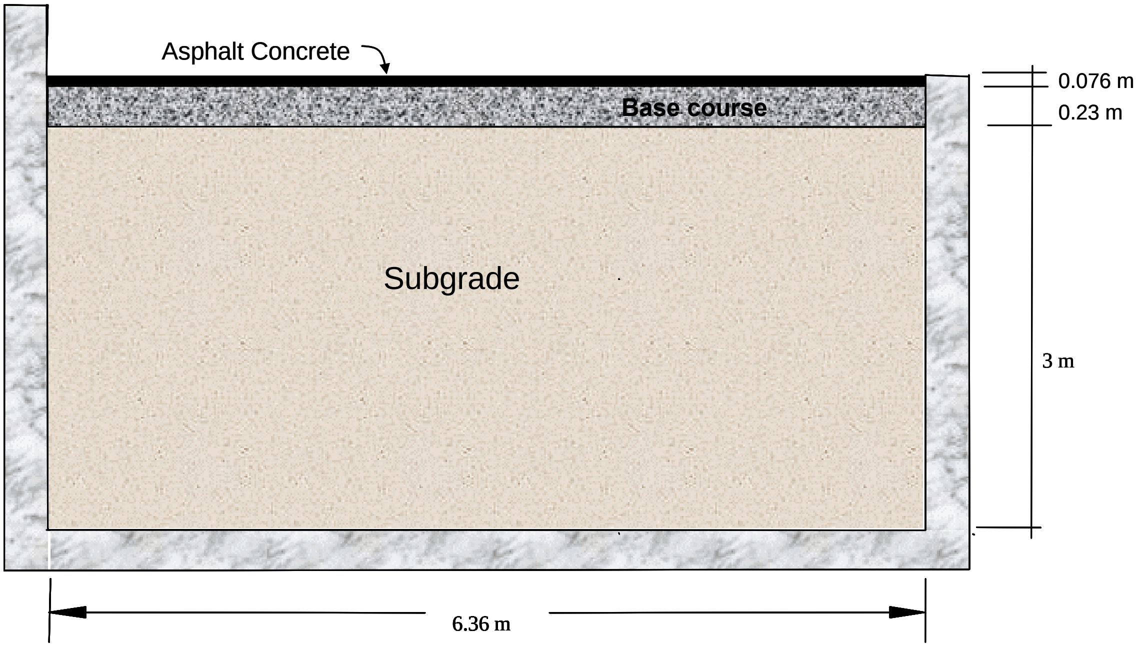

FIGURE 2 Test section cross section.

The base course was made of unbound crushed stone. Its thickness was 304 mm (12 in.). The base course material was classified as AASHTO soil type A-1. According to the Unified Soil Classification System, the base course soil was type GP-GM. This is a mix of poorly graded gravel and silty gravel. The base course material met the New Hampshire specification 304.4 (crushed stone, fine) except for the portion passing the sieve 0.074-mm (#200) that was 11 percent by weight versus the specified limit of 5 percent. The fines were classified as non-plastic. According to the modified Proctor test, the base course maximum density was 2232 kg/m^3 (139.3 lb/ft^3) at optimum moisture content of 6 percent. The crushed stone was obtained from an amphibolite bedrock quarry in Lebanon, NH (Lane and Fish, 2003). The fine soil particles are made of rock dust resulting from the crushing operation.

The subgrade soil was classified as AASHTO type A-7-5. 99.8 percent of soil particles passed the number 200 standard sieve. Its plastic and liquid limits were 21 percent and 55 percent respectively. Its specific gravity was 2.71. As shown in Figure 3, the laboratory California Bearing Ratio (CBR) for this soil at 20 percent moisture content was 53 percent. According to the modified Proctor test, the maximum density of the subgrade soil was 1685 kg/m^3 (105.2 lb/ft^3) at optimum moisture content of 20 percent. The average compacted dry density was 1575 kg/m^3 (98.3 lb/ft^3). This corresponds to 93.5 percent of the modified Proctor maximum density. The test section was built with ordinary, full-size construction equipment. A moisture-density nuclear gauge was used for quality control. The subgrade was built in 152-mm (6-in.) layers. The soil was brought into the test area in a loose condition and at moisture content lower than optimum. Once spread over the test section, the soil was rototilled and moistened until optimum moisture content was achieved. Then, several passes of a steel roller compactor in vibratory mode were applied to compact the soil. The number of roller passes was established by trial and error until the density gain by pass diminished sufficiently.

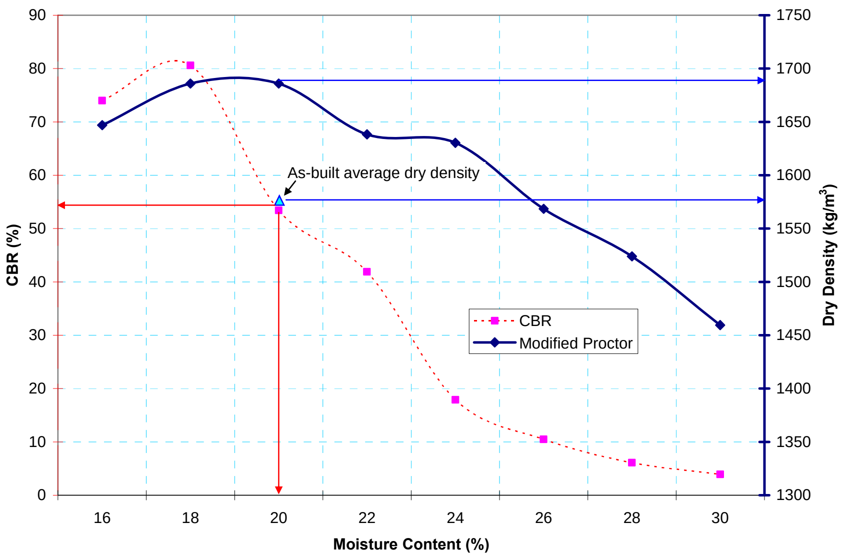

FIGURE 3 CBR and dry density versus subgrade soil moisture content.

The base course was placed in two layers 114-mm (4.5-in.) thick. The material of the base course was moistened until it reached its optimum moisture content according to laboratory modified Proctor tests. The as-built dry density for the base course was 2350 kg/m^3 (146.7 lb/ft^3). This density corresponds to 105 percent of the maximum density obtained in the laboratory by the modified Proctor method.

The test section was 6.4 m (21 ft.) in width and 20 m (66 ft.) in length. Additional length was built to serve as an access ramp during the construction of the test section.

SENSORS AND DATA ACQUISITION SYSTEM

The test section was instrumented with deformation, stress, temperature, and soil moisture sensors. The sensors were carefully installed during the layer-by-layer construction of the test section.

The deformation sensors consisted of pairs of electromagnetic induction coils. These are called εmu coils. Figure 4 shows a set of three εmu coils arranged in coplanar mode. A US dollar quarter coin is included as scale reference. Coil pairs were formed in the coaxial and coplanar modes. The coaxial mode was used to measure vertical deformation, and the coplanar mode to measure longitudinal and transverse directions relative to the direction of traffic. Figure 6 shows a set of three stacks of emu coils used in the experiments reported in this paper. Strain was calculated from inter-pair deformation measurements. To measure deformation with the εmu coil system, one coil is externally energized. A second coil placed at a close distance experiences electromagnetic induction that produces a voltage which varies with the distance between the coils (Dawson, A., 1994). The induced voltage is calibrated against a series of inter-coil distances to produce a correlation as shown in Figure 5.

Figure 4. Set of three εmu coils.

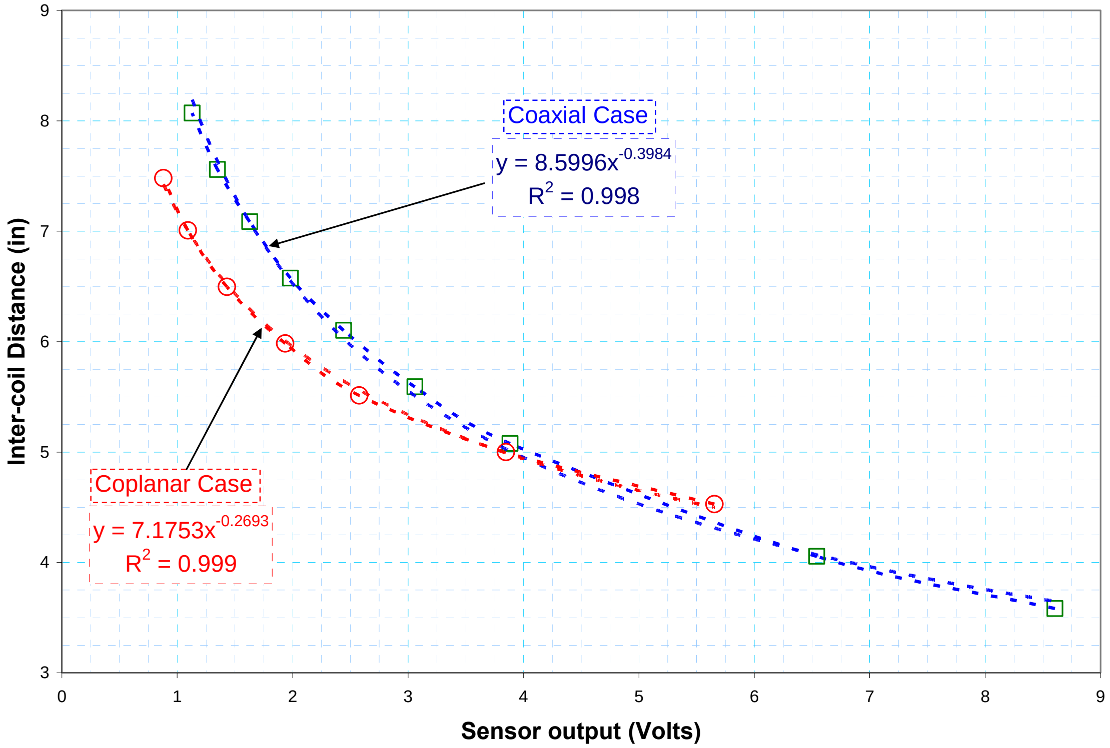

Figure 5. Voltage–distance correlation for εmu coils.

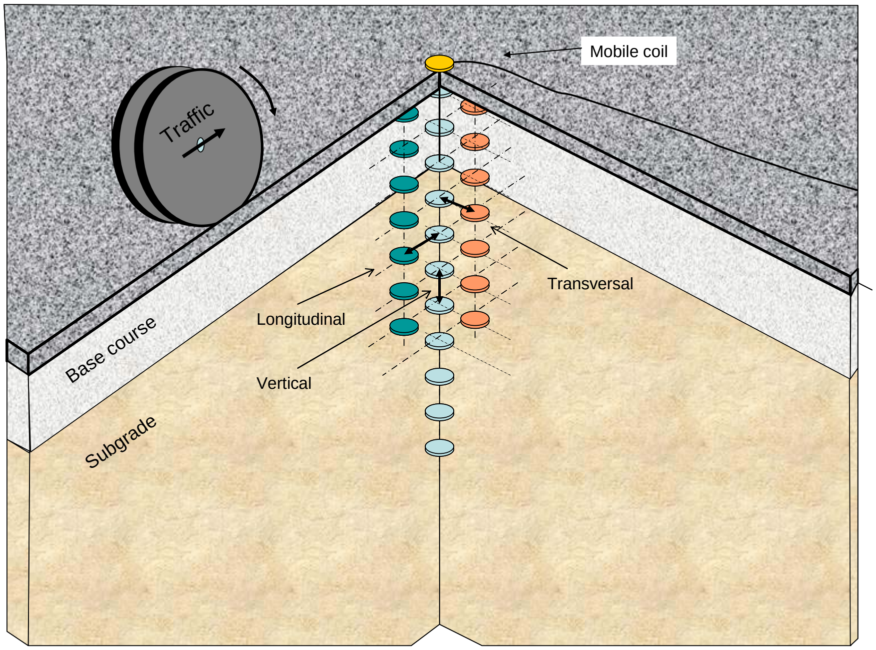

Figure 6. εmu coil stacks.

Geokon® cells were used to measure stress in the vertical, transverse and longitudinal directions. The diameter of the Geokon stress cells used in the base course was 223 mm (9 in.), and the diameter of those used in the subgrade was 100 mm (4 in.) as shown in figures 7 and 8 respectively. All the stress cells were calibrated by the manufacturer.

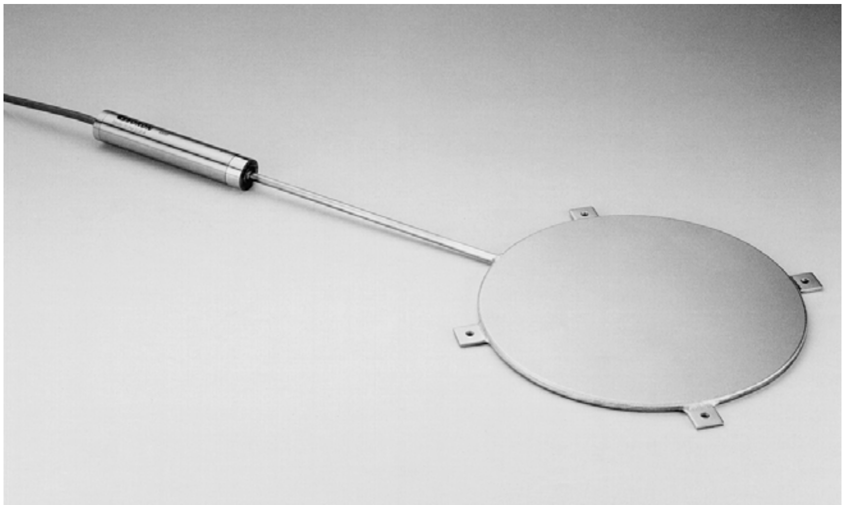

Figure 7. Geokon® stress cell used in the base course.

Figure 8. Triaxial set of Geokon® stress cells in the subgrade.

Soil moisture was measured with Campbell Scientific® reflectometer soil moisture probes model CS615 shown in Figure 9. These sensors measure the oscillation frequency between two rods embedded in the moist soil and correlate this to moisture content via changes in dielectric constant in the soil. Oven-dry measurements during construction and during the forensic evaluation provided a means to calibrate these moisture sensors. Moisture sensors were located at three depths at each of three horizontal locations. Moisture sensors were installed in the middle of the base course and in the subgrade at depths of 15 cm (6 in.) and 61 cm (2 ft) measured from the top of the subgrade.

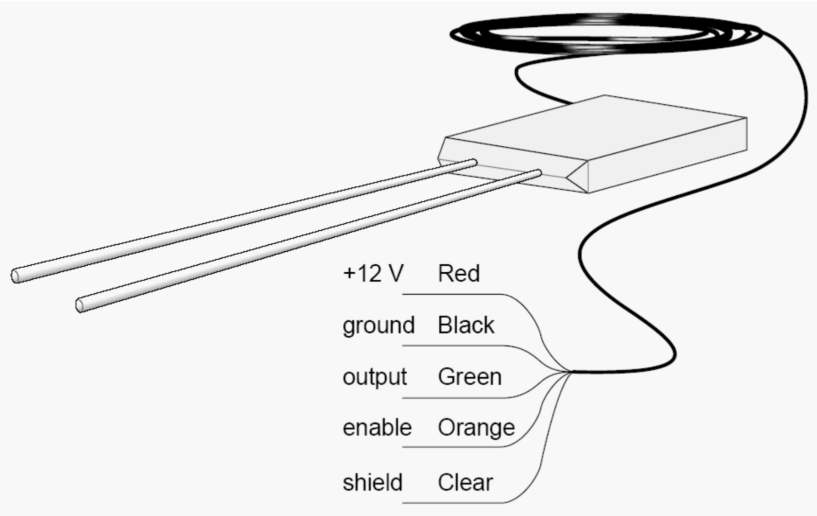

Figure 9. Campbell Scientific® reflectometer model CS615.

Temperature measurements were made with thermocouples that were installed in the air and embedded in the test sections at several depths.

The temperature and moisture sensors were read and recorded with an ordinary data logger. However, due to special requirements of the εmu coil system not met by off-the-shelf data loggers, a custom-made data acquisition system had to be developed. This system also recorded the stress cells signals. The data acquisition system hardware and software were developed at CRREL by an in-house team that included electronic engineers, a LabView® programmer, and pavement engineers. The system, shown in Figures 10a, 10b and 10c, contains signal amplifiers, low-pass and hi-pass filters, bridge balancing adjustments, computer hardware and software, and other components.

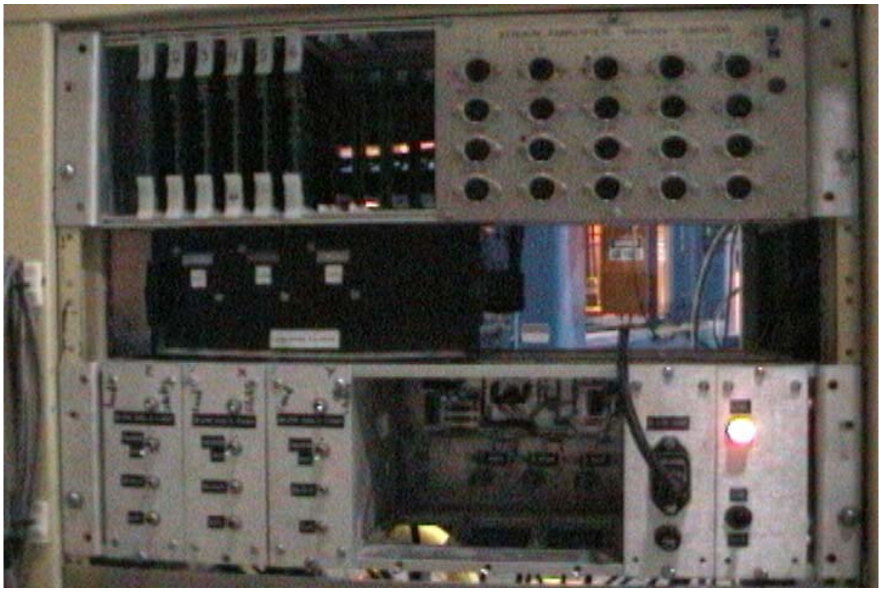

Figure 10a. Signal conditioning hardware in the data acquisition system.

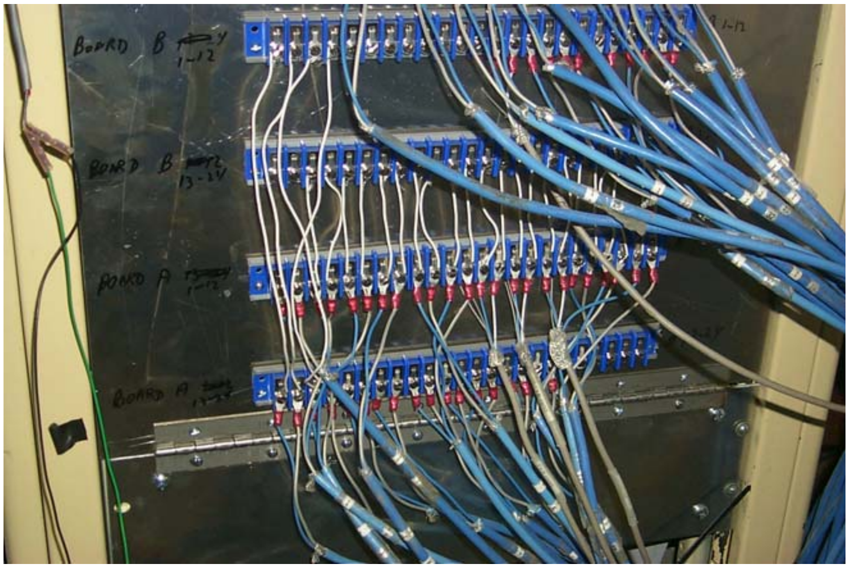

Figure 10b. □mu connections and relay hardware.

Figure 10c. Data acquisition software.

PRELIMINARY TRAFFIC LOADING

For these experiments, traffic was applied with CRREL's HVS equipped with dual truck tires as shown in Figure 1. It must be noted that this test section was subjected to 463,000 HVS traffic repetitions with the equivalent standard axle load prior to the Virtual Sensor measurements presented in this paper. This preliminary traffic caused the test section to develop average total rutting of 4 mm, and no crack was visible. This is relevant because this analysis deals with the resilient component of deformation and strain. Also, the test section had already developed 4 mm of total rutting and no crack was observed. Because the HVS dual tires represented one half of a full truck axle, an HVS load of 89 kN (40 kips) corresponds to an equivalent standard axle load.

VIRTUAL SENSOR METHOD

Sensor installation requires extreme care to preserve the density and moisture of the subgrade soil so that the soil surrounding the sensors can correctly represent the soil in the rest of the soil layer. In the design of full-scale pavement experiments, it is desired to have many sensors embedded in the test sections. However, excessive sensors may significantly disturb the soil density and moisture, thereby decreasing the reliability of a test results. Under the assumption that stress and strain would be largest at points under the center of the tire path, sensors were installed only at these locations. In this paper, we will call these sensors “Real Sensors”, as shown in Figure 11.

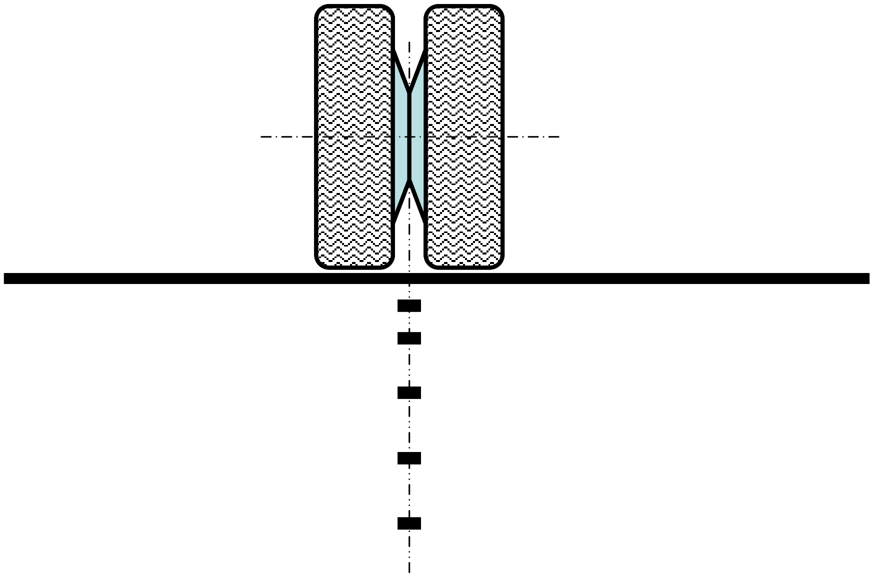

Figure 11. Real sensors.

If cost and installation risks were not important, we would like to have sensors at more locations within the structure of a pavement test section. We will call these non existing sensors: “Virtual Sensors”. Figure 12 shows the real sensors augmented by virtual sensors. In order to obtain measurements from the virtual sensors, we make additional traffic passes with the HVS offset at defined distances from the center of the original tire path, as shown in Figure 13. Notice that the offset between the center of the tire path in Figure 13 and the axis of the real sensors is the same as the offset between the center of the tire path in Figure 12 and the set of virtual sensors located precisely under the center of the tire path in Figure 13. This indicates that the measurements obtained from these two sets of sensors must be the same, provided that the traffic characteristics (the load intensity, speed, etc.) remain the same. The HVS is capable of replicating traffics passes of equal traffic characteristics with negligible variability. The HVS is also capable of producing accurate tire path offsets.

The virtual sensor method is implemented by applying replicate HVS traffic passes at a series of offset distances, and post-processing an assembly of the data from all the offset measurements as if they were measured in one traffic pass with sensors virtually existing at all the offset locations in addition to the real sensors that exist at the center of the original tire path.

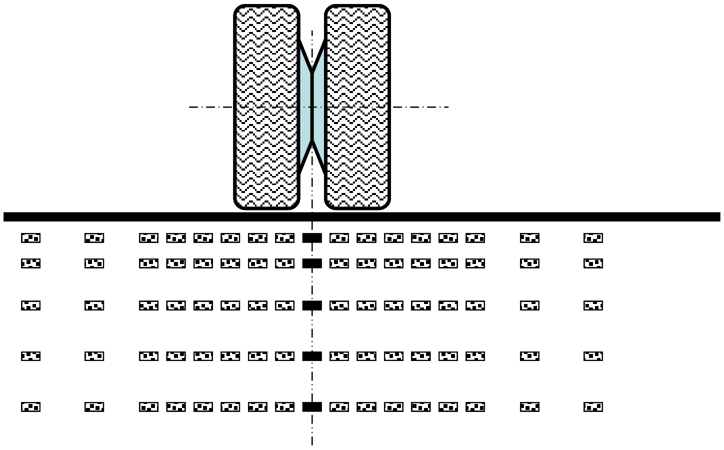

Figure 12. Real sensors augmented with virtual sensors.

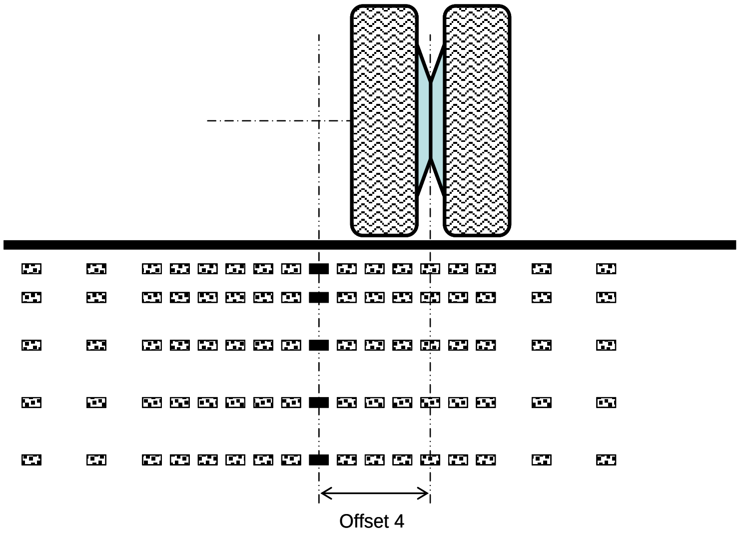

Figure 13. Tires at offset location 4

The virtual sensor method was applied to stress and deformation sensors. As explained before, strain was calculated from the deformations measured between pairs of εmu coils. Figure 14 displays the vertical resilient strain results in a cross section that also shows the depths of the sensors. Figure 15 was built by plotting the same data shown in Figure 13, but now at the spatial location of each sensor, and applying contours of equal strain intensity. Similarly, the resilient strain contours were built in Figure 16 for the transversal and in Figure 17 for the longitudinal directions relative to the tire path.

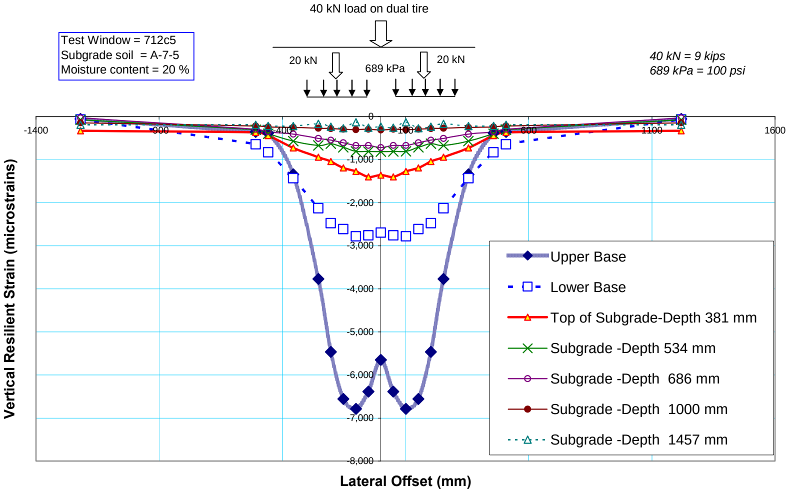

Figure 14. Vertical resilient strain cross section.

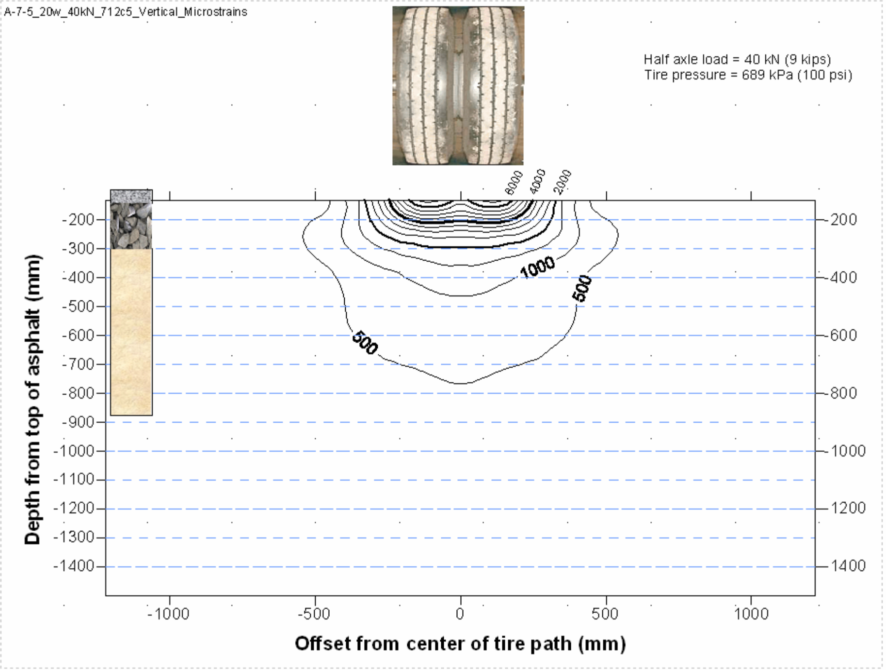

Figure 15. Vertical resilient strain contour cross section.

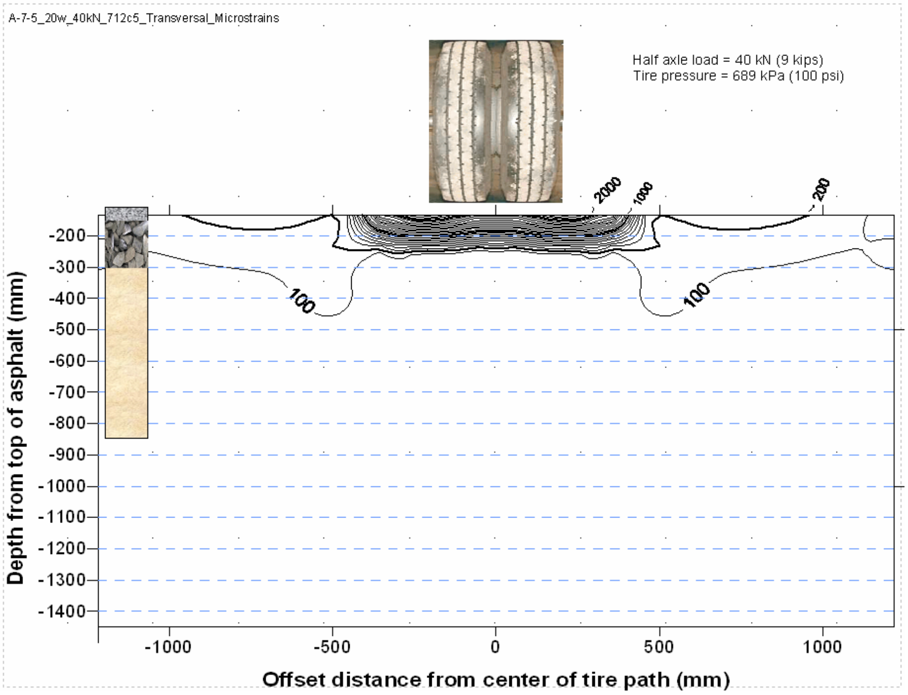

Figure 16. Transversal resilient strain contour cross section.

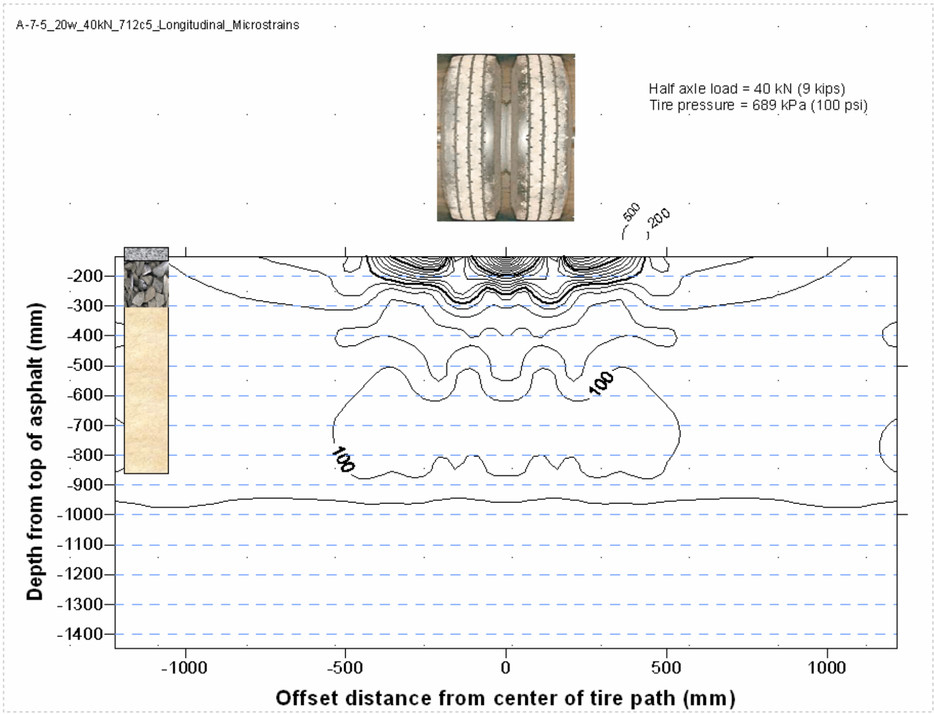

Figure 17. Longitudinal resilient strain contour cross section.

Similarly, contour cross sections were elaborated for the stress measurements in kPa units as shown in Figures 18 through 20.

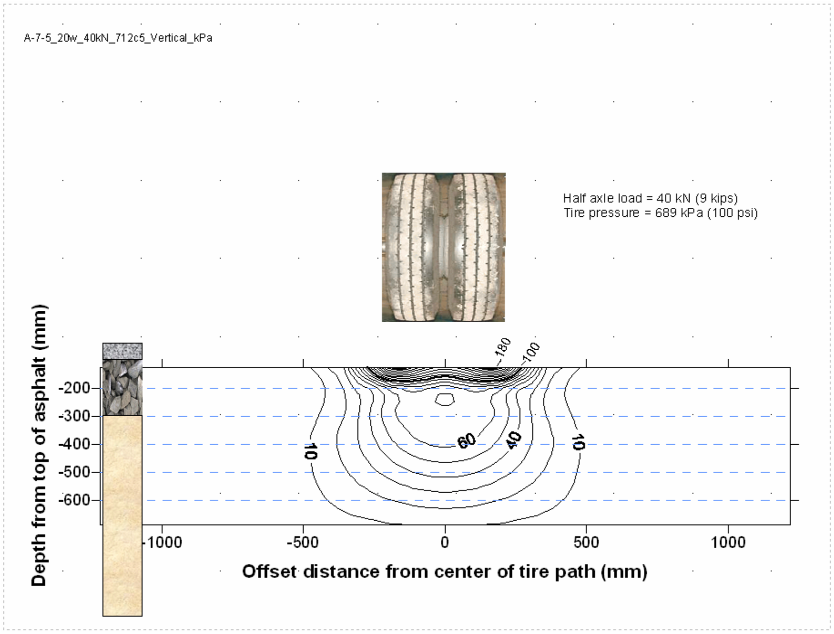

Figure 18. Vertical resilient stress contour cross section.

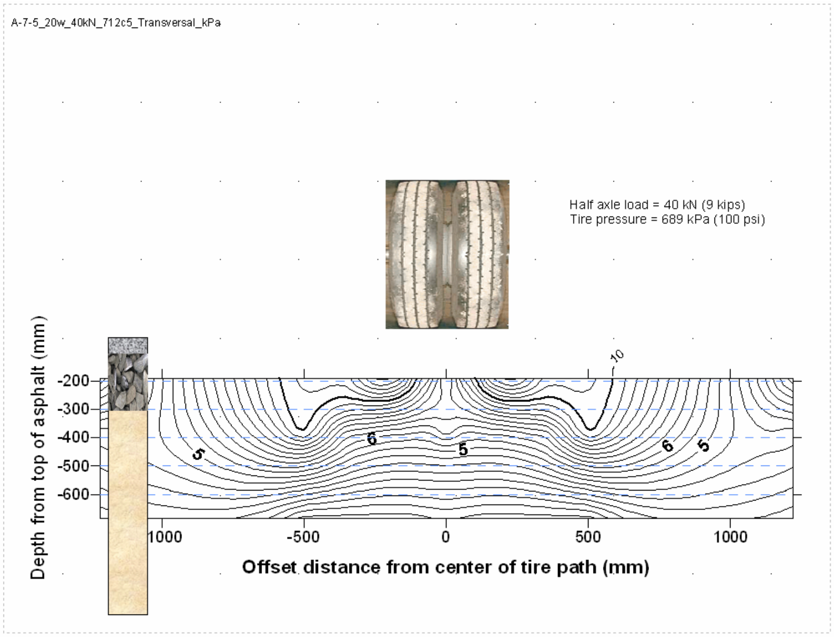

Figure 19. Transversal resilient stress contour cross section.

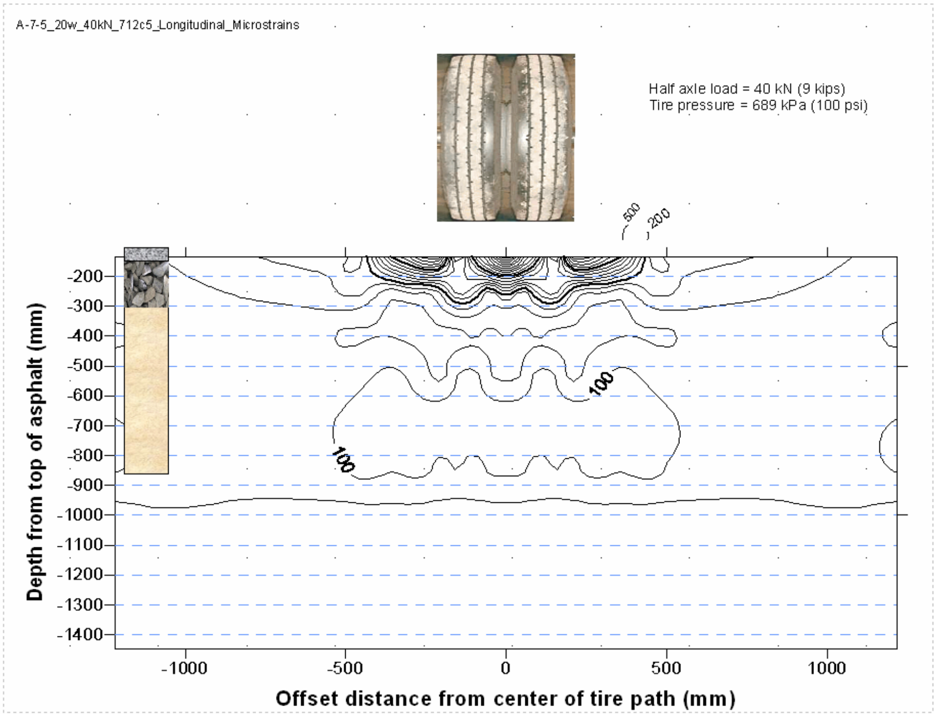

Figure 20. Longitudinal resilient stress contour cross section.

It must be noted that some of the discontinuities shown in the contours such as that for 100 kPa in Figure 20 were caused by the computer software used for plotting, and are not necessarily real. Similar experiments were also conducted at three more load intensity levels. Their results were not included in this paper due to space limitations.

SUMMARY AND CONCLUSIONS

This paper presented an experimental method that can produce more detailed information from stress or strain sensors installed at the center of the tire path in flexible pavement test sections. The method relies on capabilities available with some heavy vehicle simulators that can produce accurate tire path offsets and repeatable traffic load characteristics (load intensity, speed, etc.). The method provides a way to obtain information from non-existing sensors called “virtual sensors” by assembling stress or strain measurement data from a series of traffic passes with varying tire offset distances into an integrated scenario as if the tire path was always centered over the real (existing) sensors.

The outputs of this method are contour cross sections that offer a clearer view of the state of stress and strain during a traffic event. Although the post-processing of the data is laborious, the process can be automated.

ACKNOWLEDGMENTS

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