

# Rut Depth Measurement Method and Analysis at the FAA's National Airport Pavement Test Facility (NAPTF)

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**ABSTRACT:** The FAA developed and modified a truss profiler, which is independent of pavement profiles, that is used to monitor rutting of flexible pavements at the National Airport Pavement Test Facility (NAPTF). The truss profiler was developed to replace the more labor-intensive and time-consuming straightedge measurements. Transverse profiles corresponding to the cumulative number of load repetitions applied during traffic tests were measured using a laser displacement sensor mounted and running on a customized 20.1m (66 feet) -long aluminum truss. The profiler is capable of measuring ruts due to 10-wheel aircraft gear configurations having dual-wheel spacing of 137 cm (54 inches) in two traffic lanes. Maximum transverse measuring width is 18.3 m (60 feet) and upheaval outside the wheel track areas is included in all rutting measurements. The profiles reported in this paper were measured on a flexible pavement test track with a single 12-foot-wide traffic lane. The collected profile data was processed using an FAA developed computer program to calculate the maximum rut depth, upheaval, and straightedge-simulated rut depth measured relative to the initial transverse (baseline) profiles. Trafficked profiles were shifted vertically (and/or horizontally), and rotated to compensate for differences in the setup of the profiler. The method of rut depth measurement is presented and the accuracy of the profiler is reviewed. Possible errors in measurements such as truss fluctuations in temperature, structural curvature, and cross slope of the pavement are identified. Detailed descriptions of the adjustment methods used to correct for the identified errors are presented. The geometric changes of the transverse profiles are shown with increasing number of load repetitions superimposed on the untrafficked baseline profiles. Analysis of the profiles shows the effects of lateral wander, loading induced stress, and tire pressure on a hot mix asphalt pavement surface layer. The processed rutting performance data obtained from the NAPTF test pavements are presented and discussed. Specific discussions include characterization of HMA failures showing tertiary flows from the collected data.

## 1 INTRODUCTION

The Federal Aviation Administration (FAA) operates the National Airport Pavement Test Facility (NAPTF), a full-scale airport pavement test facility located at the William J. Hughes Technical Center near Atlantic City, New Jersey. Both flexible and rigid pavements are constructed and tested at the facility. Permanent deformation test results collected from flexible pavements are presented in this paper. The procedures for data collection and processing by an FAA developed profiling system were used. Monitored accumulation of the permanent deformation corresponding to the number of repeated wheel load passes is analyzed.

The FAA's profiling equipment, which runs on rails at the sides of the test pavement, is operated independently of the test pavement surface and was developed to measure the permanent deformation from wide aircraft gear configurations and wander-

ing under typical airport pavement loading conditions. The rut depths with increasing load numbers, based on the untrafficked baseline profiles at different test conditions, are computed using geometric straightedge simulations on the collected profile lines. The computed rut depths from the simulation showed typical HMA pavement performance, including tertiary flow.

## 2 TEST CONDITIONS

The flexible pavement was constructed on a CH clay subgrade known as DuPont clay. The pavement structure consists of 43 cm (17 in.) of econcrete as a stabilized base (P-306) (FAA 2011) and a 13 cm (5 in.) HMA surface layer (P-401). The HMA layer was placed with two different mix designs. The mixes used the same aggregate and aggregate gradings, but different asphalt binders. One mix had a

straight PG 64-22 asphalt binder and the other had a polymer modified PG 76-22 binder. A hydronic heating system was embedded in the econcrete at its base to control the temperature of the HMA at a temperature representative of high temperature airport operations. The as-constructed dimensions of the high tire pressure (HTP) test pavement structure are 35 m (115 ft.) long and 3.7 m (12 ft.) wide.

Dual tires with 137 cm (54 in.) spacing mounted on one of the loading modules on the NAPTF test vehicle were used for the test loading. The tires were inflated with the dead weight of the module on the tires and with the tires at ambient temperature. Inflated tire pressures were 1.45 MPa (210 psi) and 1.69 MPa (245 psi) for the North and South wheels respectively. Higher tire pressures up to approxi-

mately 1.5 MPa (218 psi) and 1.75 MPa (254 psi) were reached during testing.

Wheel loads were 23.8 MT (52,500 lbs) and 27.8 MT (61,300 lbs) with the load application pattern as indicated in Figure 1. The wander pattern of +18 cm (7 in.) (toward the south), 0 (equal distances from the centerline to each tire), and -18 cm (7 in.) (toward the north) is shown in Figure 1a and the loading pattern is shown in Figure 1b. The loads were applied at a trafficking speed of 0.305 m/s (1 ft/s) from west to east. The module was unloaded at the east end and returned to the west end at 1.22 m/s (4 ft/s), after which the wander position was changed and the loading pattern repeated.

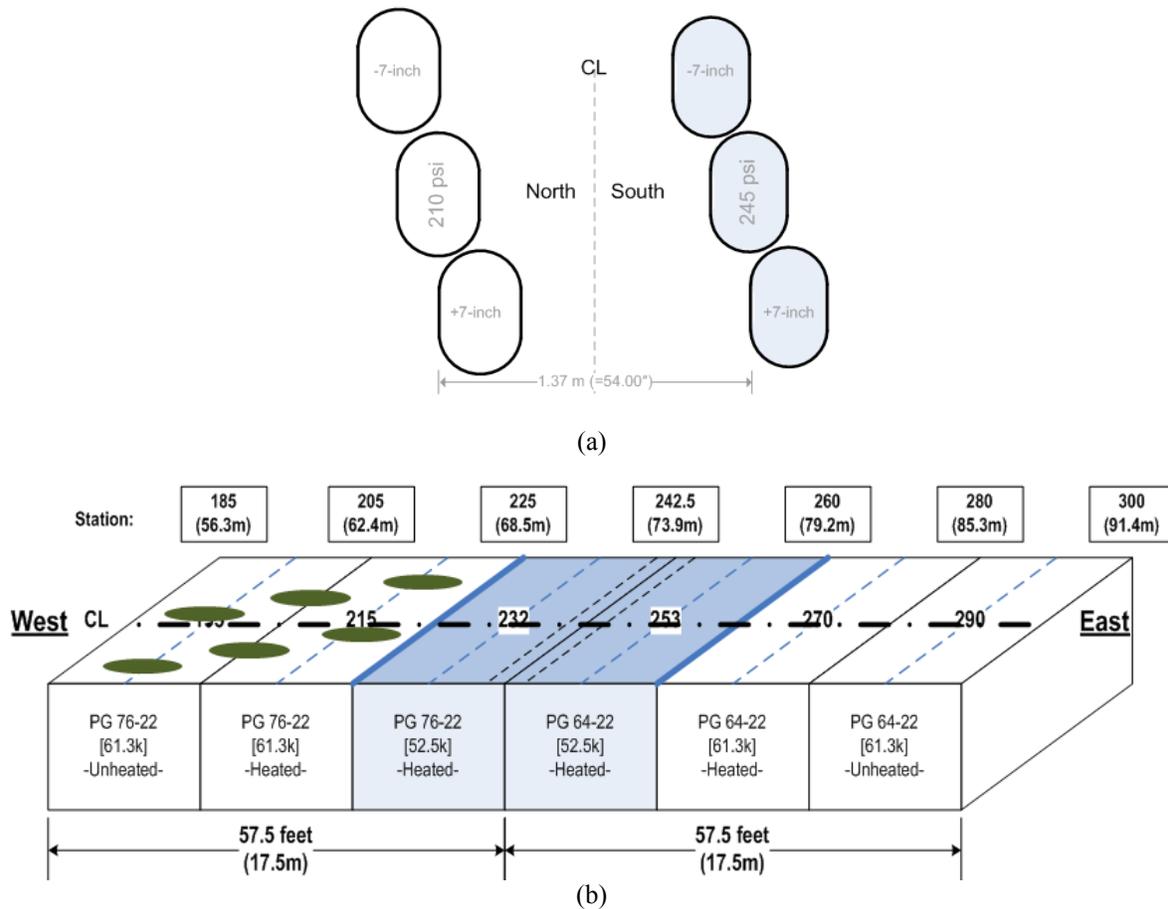


Figure 1. Trafficking conditions for the high tire pressure test area (a) foot prints for wander pattern with 7 inch spacing; (b) loading conditions. The dotted blue lines show the position of the transverse profile measurements.

### 3 DATA COLLECTION

Transverse profiles were measured during trafficking at the middle of each test item, 6.1 m (20 ft) apart, as shown in Figure 1b. The measurements were made at approximately every 21 passes or whenever significant changes were observed.

Since traffic testing at the NAPTF is conducted on a pavement area 18.3 m (60 ft.) wide, the transverse profiles were measured with the FAA's 20 m (66 feet) long truss profiler equipped with a non-contact vertical displacement transducer as shown in Figure 2. The profiler runs on the rail system which is used for supporting and guiding the NAPTF test vehicle. The supporting points of the transverse profiler located on the rail are capable of maintaining the same vertical reference points for the transverse

profiles with pavement surface condition changes. This vertical reference point minimizes any possible profile distortions from the lateral locations of the profiler placed within the depression or upheaval areas.

The truss profiler is operated by moving an infrared laser to monitor the vertical displacement of the pavement, and an incremental rotary encoder as a distance measuring instrument (DMI) on a trolley rolling along the steel flange of an aluminum truss type beam. The laser footprint is oval in shape and the size is approximately 2.5 mm (0.1 in.) × 5 mm (0.2 in.). The laser adopted for the profiler has a measuring range of 100 mm (3.94 in.) to 1,024 mm (40.4 in.) with a stand-off distance of 390 mm (15.4 in.) to 1,200 mm (47.3 in.) (LMI, 2011). The signal acquisition box is assembled to collect data using a USB digital data acquisition unit and software (MCC 2011).

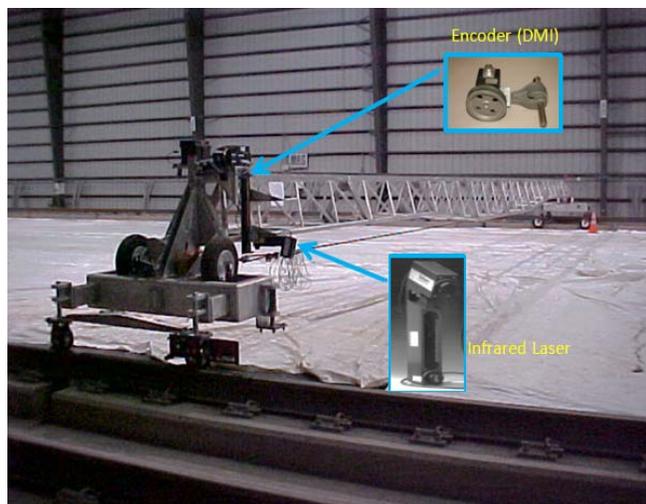


Figure 2. Laser mounted truss type FAA transverse profiler.

#### 4 DATA PROCESSING

The collected profile data is processed using software developed by the FAA. A screen shot of the program is presented with an example transverse profile in Figure 3.

Reference profile lines were taken at a designated calibration section without any load applications. They were used as an input parameter for a subroutine in the program to compensate for any unexpected vertical deformations from environmental condition changes. The pavement profiles before loading were used as base profile lines for each pavement test section to compute rut depth. The rut depth accumulation started from the baselines is mathematically computed to depict HMA pavement performance. The straightedge simulation is performed on each profile line to compute the amount of maximum depression and upheaval in the pavement section. Specific sections of the profiles were cut and rotated for geometric comparisons.

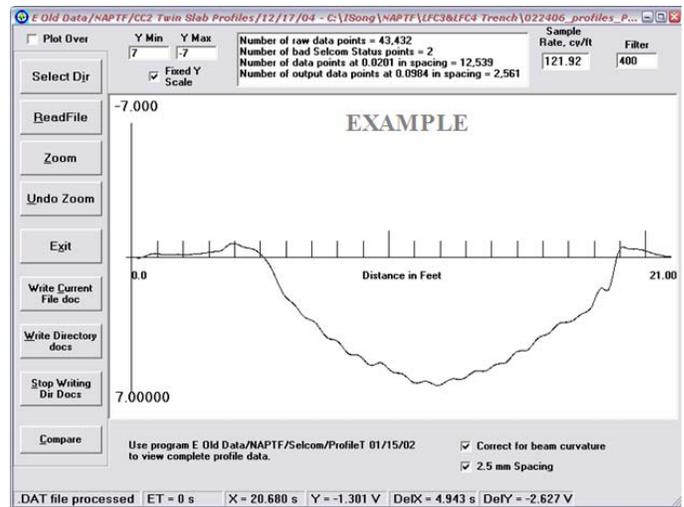


Figure 3. Screenshot of the FAA profile processing software with a transverse profile example.

#### 4.1 Calibration of beam curvature for baseline profiles

Since the FAA customized truss profiler is made from a steel rail on an aluminum truss structure, the different metal expansions at the top and bottom of the profiler leads to a “sagging” shape as shown in Figure 4.

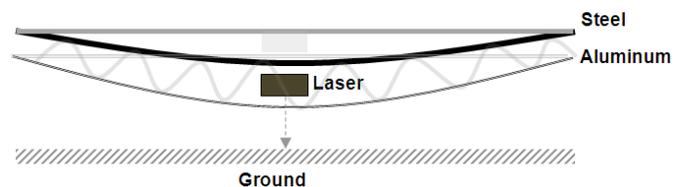


Figure 4. Temperature induced profiler shape changes.

The  $\delta_T$  in Equation 1 is the thermal deformation due to the thermal expansion coefficient,  $\alpha$ , metal length,  $L$ , and temperature changes,  $\Delta T$ , from a reference point. In general, the thermal expansion coefficient is approximately  $13.0 \times 10^{-6}$  m/m K ( $7.3 \times 10^{-6}$  in/in °F) and  $22.2 \times 10^{-6}$  m/m K ( $12.3 \times 10^{-6}$  in/in °F) for steel and aluminum respectively (TET 2011). The thermal deformation is defined as follows:

$$\delta_T = \alpha \times L \times \Delta T \quad (1)$$

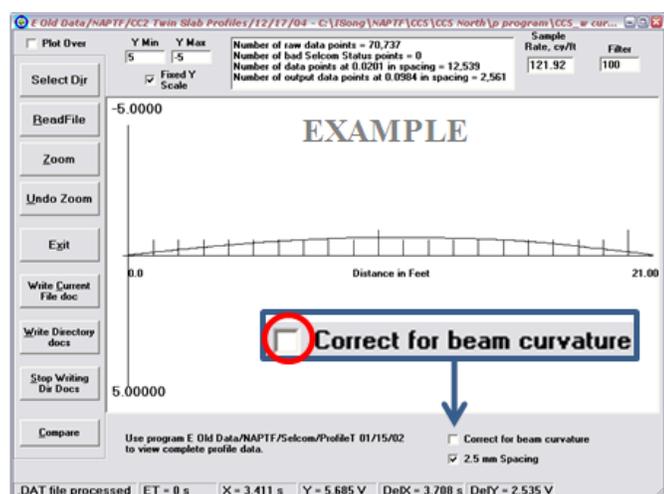
A calibration profile line showing consistent transverse profiles independent of ambient temperature changes is selected inside the NAPTF facility. The calibration line profile measured at the same time of profile measurement on the test pavement becomes a reference point to adjust the amount induced by ambient temperature changes. Equation 2 compensates the vertical discrepancies of the data points along the full length of the profiler. The compensations are performed for every profile data point at each pass number,  $n$ . This equation makes an ide-

ally perfect straight truss profiler and is set as an initial (base) profile line before the start of trafficking to monitor permanent deformation relative to the initial conditions:

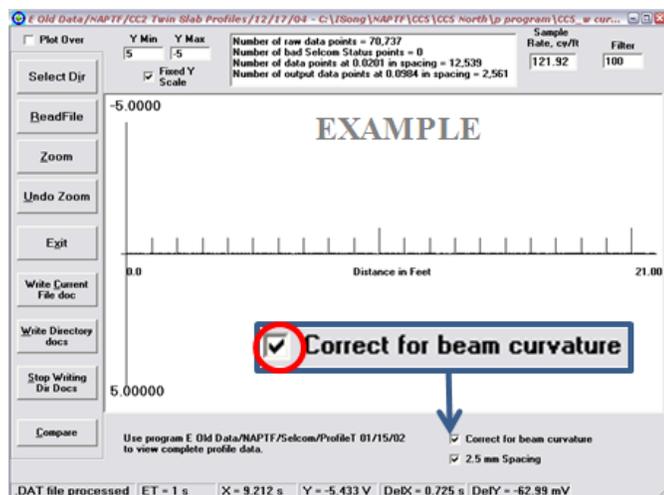
$$P_{i,n} = |r_{i,n} - x_{i,n}| \quad (2)$$

where  $P_{i,n}$  = the processed profile data at pass number  $n$ ;  $r_{i,n}$  = the reference profile data at pass number  $n$ ;  $x_{i,n}$  = the profile data at pass number  $n$ , and  $i$  = the profile data sequences from the 1<sup>st</sup> to the  $i^{\text{th}}$  data set.

Figure 5 shows an example of the beam curvature corrections in the program before test pavement profiling. Notice the change in the reference profile when the beam curvature correction function is activated.



(a)



(b)

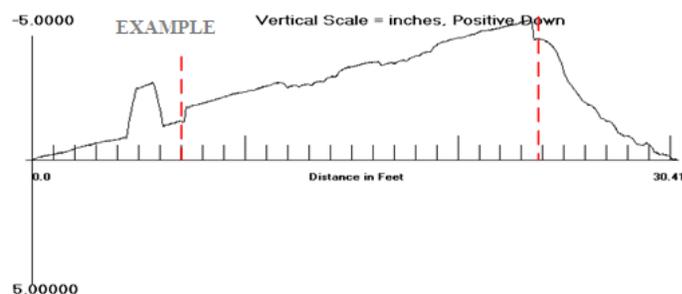
Figure 5. Beam Curvature correction function in the FAA profile data processing software (a) without beam curvature correction; (b) with beam curvature correction.

## 4.2 Sectioning transverse profile

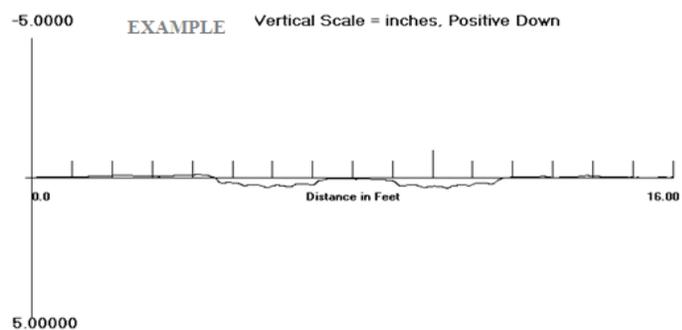
Traffic wandering was considered in the full-scale pavement testing to simulate, in some measure, in-service runway traffic conditions. For the purpose of computing rut depth and upheaval, horizontal traffic zones were divided based on test conditions such as loading and pavement materials or specific analysis purposes. The sectioned profiles were first shifted vertically and rotated to make both start and end elevations equal to zero. A vector rotation can be conducted in terms of a typical linear transform matrix. The vector  $A$  in Equation 3 rotates each vector by an angle  $\theta$  in the counterclockwise direction. The matrix  $A$  representing the transformation will have  $(\cos\theta, \sin\theta)^T$  as its first column and have  $(-\sin\theta, \cos\theta)^T$  as its second column:

$$A = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \quad (3)$$

The procedures are depicted in Figure 6. The portion of the profile to be sectioned is marked by dashed vertical lines. The sectioned profile is shifted vertically and rotated so that the end points have values of zero.



(a)



(b)

Figure 6. Transverse profile processing (a) sectioning; (b) shifting and rotation for rut depth calculations.

## 4.3 Straightedge simulation

Straightedges are widely used to measure pavement depressions because of their simple and easy methods of use. Standards for their use are specified in (ASTM 2011) and in FAA Advisory Circular (AC) 150/5370-10F (FAA 2011). However, the measure-

ment process is time consuming and the accuracy is questionable due to the procedures to identify the measurement location of maximum deviation between straightedge and pavement surface. The profiler with 2.5 mm (0.1 in.) sample spacing was developed to replace the more labor-intensive and time-consuming straightedge measurements, especially for in-service airfield runways.

Song and Hayhoe (2006) have written about straightedge simulation in their paper. As they discussed, a certain length of straightedge moves along the pavement surface profiles and the maximum vertical distance between the straightedge and the pavement surface profiles is calculated for each location along the profile. There are two methods in common use for the measurement of maximum deviation. As illustrated in Figure 7, the first one is to measure the maximum distance to the pavement surface between the straightedge support points and the other is to make the measurement over the full length of the straightedge.

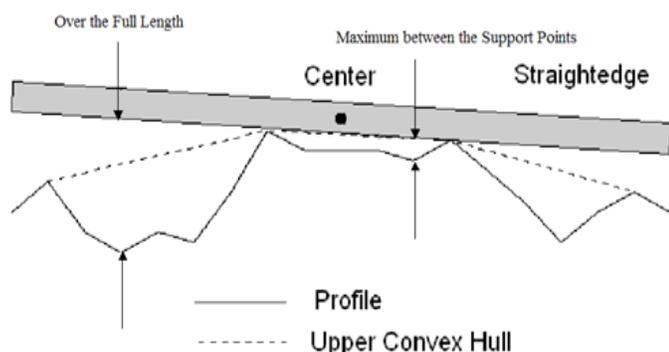


Figure 7. Straightedge calculation methods.

Straightedge simulation methods were utilized to determine the maximum depression, rut depth, and upheavals at pre-determined longitudinal locations as marked in Figure 1. Figure 8 illustrates the change in maximum rut depth with increase in traffic by overlaying transverse profiles in the same figure and by application of the straightedge simulations on the gathered profiles. In the simulation, as seen in Figure 8, the rectangle, representing a 5 m (16 ft) -long physical straightedge, was shifted horizontally to find the locations corresponding to the maximum pavement depression with increased traffic numbers.

#### 4.4 Rut depth measurement

Since permanent deformation in asphalt pavements is one of the most significant distresses affecting performance of the pavement, the procedures to calculate rut depth are critical for HMA pavement evaluation.

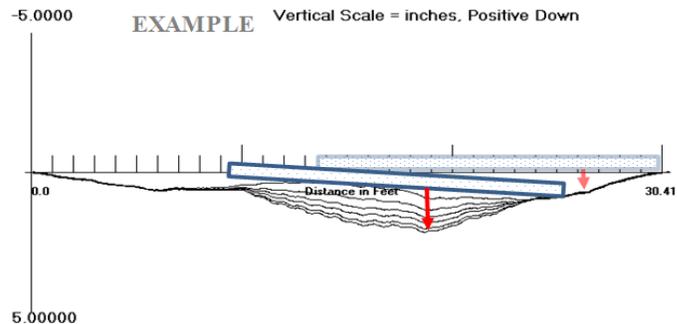


Figure 8. Maximum rut depth determination utilizing the straightedge simulation method.

The rut depth occurring either through consolidation or through plastic flow was monitored with increasing traffic numbers. As described above, the HMA surface depression from the peak elevation to the bottom elevation was measured through straightedge simulation procedures. Rutting is caused by the progressive movement of materials under repeated loads either in the asphalt concrete layer or in the underlying layers. Hence, geometric analyses were also added to monitor the upheaval mostly caused by lateral shear flow of the materials under the surface.

The gathered rut depth data were of downward and upward elevation changes relative to initial (base) profile lines. This step is to determine the relative rut depth and upheaval at given locations as the maximum difference between the two profiles at given intervals during the traffic test.

## 5 RESULTS AND ANALYSIS

The data processing and research results are presented and discussed. Only the results of temperature induced truss beam curvature changes in the data processing steps are presented because the other processing steps have been presented earlier as examples. Rut depth progress from the HMA test sections at the NAPTF with different loading conditions such as load level and tire pressures are also presented.

### 5.1 Profiler movements by temperature changes

The different thermal expansion coefficients for steel and aluminum affect the vertical movements of the truss beam. This movement causes errors in the rut depth calculations. To avoid these errors, measured profiles were adjusted based on the comparisons shown in Figure 9. Ambient temperature changes from approximately 15.0°C (59°F) to 22°C (72°F) were monitored and are shown as the top line in the chart. The relative temperature changes from the reference temperature, 24.3°C (75.8°F), are marked with squares in the figure. Maximum vertical movements of the beam are shown with triangles

and varied up to approximately 2.5 mm (0.1 in.) over the ambient temperature range.

Thermal deformations of the two metals were computed using Equation 1 and are plotted in Figure 9 with asterisk shapes. The thermal expansion coefficient,  $\alpha$ , is the only parameter affecting thermal deformation,  $\delta_T$ , because the total length of metal,  $L$ , and temperature changes,  $\Delta T$ , are the same for the two materials. The computed discrepancy also follows the ambient temperatures, although it is not as good as measured. The coefficient of determination,  $R^2$ , value between measured and computed thermal deformation discrepancy was 0.6229 by linear regression curve fitting as shown in Figure 10. One of the reasons for the relatively low  $R^2$  value could be related to the computations based on the assumptions that each of the materials is continuous and has equal volume. However, the truss profiler has 4 separate bolted truss sections and the steel is placed only on the top of the truss to provide a guide rail to operate the profiling system trolley.

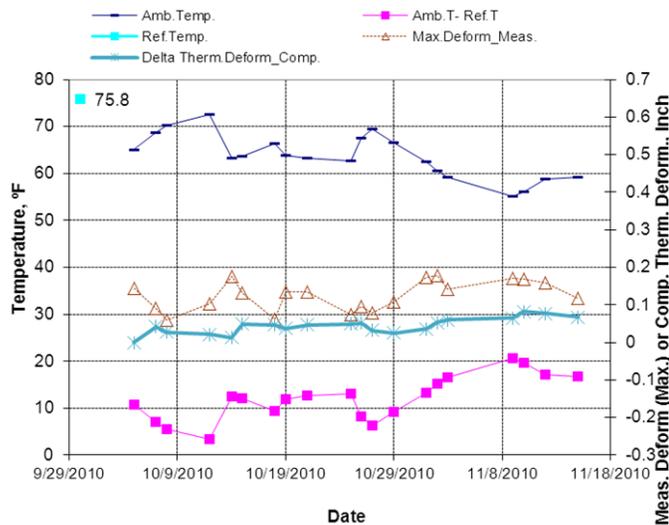


Figure 9. Measured maximum vertical displacement changes in the profiler with ambient temperature changes.

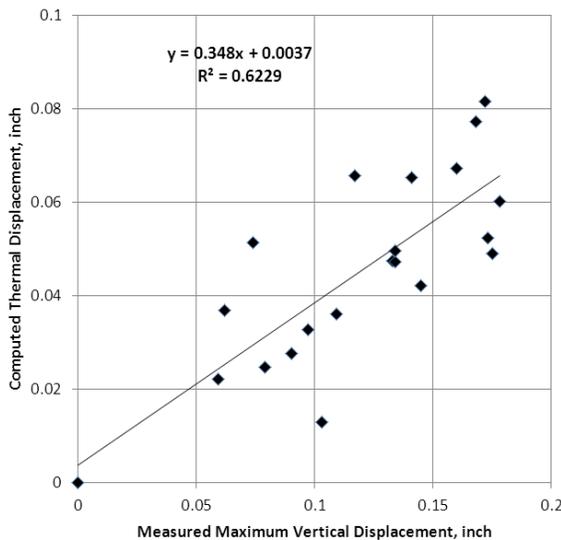


Figure 10. Correlations between measured maximum vertical displacement and computed thermal displacement.

## 5.2 Rut depth

When asphalt concrete is subjected to repeated loading, it hardens with accumulating plastic deformation causing consolidation. If there are no other maintenance activities, or the material heals rapidly, it will reach a point where it is sufficiently stiff for microcracks to initiate and grow. The asphalt concrete starts accumulating more plastic deformation after the initiation of microcracks, which is commonly called “tertiary flow” (Song, 2004). The accumulated stresses from traffic loads after completing the consolidation stages in pavement sub layers, causes these materials to move laterally to the non-trafficked zones depending on their adhesion strengths.

The measured transverse profiles were processed to simulate measurements made with a straightedge. Figure 11 illustrates transverse profile comparisons between 1.50 MPa (218 psi) and 1.75 MPa (254 psi) contact tire pressures at increasing traffic repetitions.

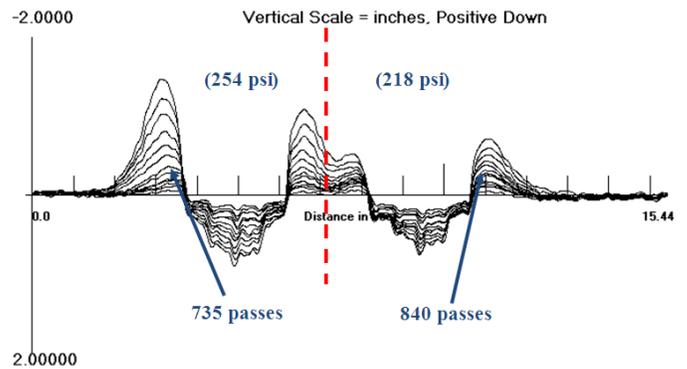


Figure 11. Transverse profiles at increasing traffic repetitions from the 1.50 MPa (218 psi) and 1.75 MPa (254 psi) wheel paths at 27.8 MT (61,300 lbs) wheel load.

The graphical illustrations in Figure 11 show significant increase in upheaval rates from 735 and 840 load repetitions for higher and lower tire pressures respectively.

The increases in computed rut depths for different tire pressures are plotted versus traffic repetitions in Figure 12. Similar results to those shown in Figure 11 were observed from rut depth computations utilizing straightedge simulations. Figure 12 shows rut depth changes with different tire pressures at 27.8 MT (61,300 lbs) wheel load in the PG 64-22 test section also indicates inflection points at 735 and 840 load repetitions for tire pressures of 1.75 MPa (254 psi) and 1.50 MPa (218 psi) respectively. Both inflection points match well with the findings from geometric analyses. The shear stress after consolidation of the pavement materials induced lateral movement of the sublayer materials at the two inflection points. The accumulated plastic flow is expressed as exponential rut depth increases for traffic applications after the two inflection points.

The pavement test sections using PG 76-22 binder have not been completed, and trafficking will continue until they show tertiary flow similar to the PG 64-22 test sections.

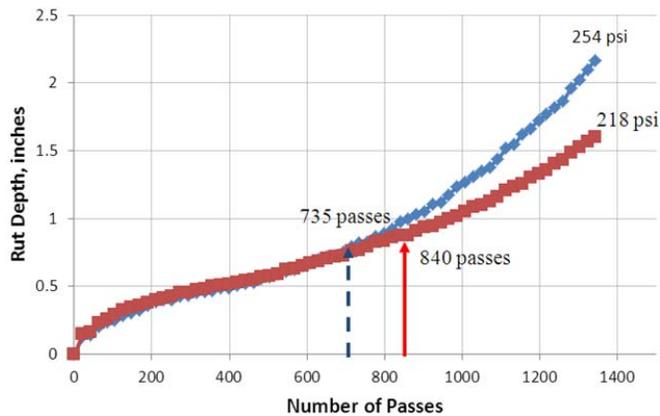


Figure 12. Rut depth changes with different tire pressures at 27.8 MT (61,300 lbs) wheel load in the PG 64-22 test sections.

## 6 CONCLUSIONS

An infrared laser operated truss beam profiler used for monitoring pavement transverse profiles was developed. Using the profiler, data processing protocols for collecting transverse profile data to compute rut depth simulating field straightedge measurement were developed. The procedures include beam curvature corrections caused by different thermal expansion coefficients of the steel and aluminum components in the truss profiler and/or structural irregularity.

The vertical movements of the transverse profiler beam caused by ambient temperature changes were quantified and used for compensating the collected transverse profile data. A reference profile line concept was introduced and utilized to subtract the measured data at each pavement condition.

The transverse profiler was successfully used to measure the performance of flexible pavement test sections with the transverse profile line shape

changes monitored at increasing pass numbers. The traditional hot mix asphalt failure stages of primary, secondary, and tertiary flow based on the rut depth charts and stacked profile lines from the full-scale traffic testing were seen in the results.

## 7 ACKNOWLEDGEMENT AND DISCLAIMER

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