LASER-BASED TECHNOLOGY FOR AUTOMATED RUT MEASUREMENT IN ACCELERATED PAVEMENT TESTING

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ABSTRACT

Accelerated Pavement Testing (APT) programs provide a convenient means of simulating the long term performance of in-service pavements. At present, there are approximately fifteen active APT programs in the United States alone. A majority of these programs utilize conventional linear trafficking devices at a fixed-site under full or partial environmental control. With advancing technology, the use of laser based profiling systems has become predominant in the characterization of the test pavement surface, especially with regards to permanent deformation (rutting).

The Florida Department of Transportation (FDOT) currently employs a Heavy Vehicle Simulator (HVS) as the primary tool in its APT efforts. This paper describes the efforts of developing a laser based profiling system for measuring and characterizing test pavement surface deformations, as part of Florida's APT program. A standard methodology of laser data collection, compilation and analysis is also proposed.

INTRODUCTION

The need for faster and more practical methods to assess the long term performance of pavement systems prompted a number of agencies, including Florida Department of Transportation (FDOT), to consider Accelerated Pavement Testing (APT). APT has the potential to provide, within a short time period, reliable information on benefits, cost effectiveness application, and performance of pavement materials/designs while improving pavement technology and understanding of pavement systems behavior. Such information is critical to support informed highway planning, policy and decision-making both at the regional and national levels.

In all APT programs, the magnitude of pavement surface distresses such as rutting, cracking and moisture-induced damage is generally used as a primary indicator of a pavement performance. The need to quantify the pavement surface distress level has resulted in a number of manual or semi-automated measurement techniques and devices. These measuring techniques are, at times, slow, tedious, and labor intensive. With advancing technology, these processes can be automated. Of particular interest is the application of height sensor-based technology. It is particularly well suited for surveying the surface condition of pavement sections.

This paper provides an overview of Florida's experience with its recent implementation and evaluation of a fully automated process of rut measurement as part of its APT program. It uses the height laser-based technology that is providing for versatility, ease and speed of use. A methodology for automated laser data collection, reduction, and analysis is also described.

BACKGROUND

Florida's Accelerated Pavement Testing Program

In Florida's APT program, the accelerated loading is performed using a Heavy Vehicle Simulator (HVS), Mark IV model. The HVS is electrically powered (using external electric power source or electricity from an on-board diesel generator), fully automated, and mobile. It can apply wheel loads between 7 and 45 kips (using dual or super-single tires) along a 10 m (30 ft) test strip within any given test track. A chain-driven carriage system provides for uni- or bi-directional load application with or without wander to the test track. With the wheel wander, the HVS has the capability to apply a load across a centerline width of up to 762 mm (30 in) after a full loading cycle. When wander is considered, the actual loaded footprint width on the test track is the programmed wander plus the loading tire width. For instance, using a 305 mm (12 in) wide super-single tire, specifying (or programming) zero or 762 mm (30 in) wander will respectively result in a 305- or 1066 mm (12- or 42 in) wide footprint on the pavement.

Pavement Profile Measurements

Non-contact pavement profiling technology was initially introduced in the 1960s at the General Motors Research Laboratory *(1)*. Although this technology has been available since then, it still has not fully matured. A considerable amount of research has been conducted to gain further understanding on the factors affecting high-speed profiling from both the analytical and experimental points of view. Still some problems have not fully been resolved, particularly in the interpretation of the measured data and selection of adequate sensing technology *(2)*. Comparative studies have indicated, for instance, that optical and laser-based profilers generally exhibited better performance, in terms of repeatability and accuracy. These studies have also shown that the use of ultrasonic-based profilers may not be appropriate for textured surfaces such as chip seal or open graded pavements, while ambient light could contaminate optical sensors *(3, 4, 5)*. Consequently, in recent years, considerable attention has been particularly focused on the laser-based technology.

For roadway applications, these sensors are usually mounted in the front of a specially designed bumper of the test vehicle. Accelerometers are also provided to isolate the vehicle motions. The sensor signals are then combined through a computerized process to generate a record of the longitudinal (or transverse, if at least three sensors are used) profile along each individual wheel path. Such records are then analyzed to determine the rate of change in the longitudinal (or transverse) pavement surface elevation along the pavement length traversed by the instrumented vehicle. Once a longitudinal profile is measured, any profile-based roughness index, such as International Roughness Index (IRI) or Ride Number (RN), may be calculated. Similarly, relative rut depths may also be determined from the transverse profiles at each desirable location.

Most APT programs are located in a restricted environment, and therefore it is not always possible to use conventional profilers to accurately collect a test section profile. In addition, the presence of the loading system on the pavement test section makes it nearly impossible to operate a profiler to collect data.

IMPLEMENTATION OF NON-CONTACT PROFILING IN APT

Depending on their application, most roadway profilers utilize 32 KHz (or higher) laser sensors. Such higher frequency sensors are generally required under high-speed applications or where a very high resolution is required. Considering the low testing speed in APT, a 16 kHz frequency laser was deemed appropriate. Thereafter, a laser-based system was installed on the underside of the HVS loading assembly/carriage. As shown in Figure 1, this profiling system consists of two 16 kHz lasers mounted 762 mm (30 in) apart on either side of the load carriage. The lasers, model SLS 5000™ manufactured by LMI Silicon, and have a resolution of 0.025 percent of the measurement range. For simplicity, these two laser sensors are described as "left" and "right" laser in this paper. An important factor to consider while selecting the laser configuration is the width of the loaded area. To some extent, this is governed by the maximum transverse wander capability of the APT machine. The maximum spacing between the two laser sensors is dependent on this wander capability, and cannot exceed half of the maximum wander width. Most importantly, the surface profile should be wide enough to accurately map both the wheelpath and part of the unloaded area on either side of the wheelpath.

Profile Data Collection Operational Process

The results of a series of trial tests showed that a 4 kmph (2.5 mph) operating speed of the carriage assembly generated the least number of transient errors during the profile data collection process. In addition, on average, one set of profiles under the current test layout takes approximately 15 minutes to complete. Figure 2 shows a schematic of profile data collection on a representative test section. The wheel carriage starts from the bottom left hand corner and travels longitudinally along the test section to the extreme position on the top left corner. This constitutes the first straight "leg" and provides two longitudinal profiles, one from each laser. Due to their positioning on the carriage, the left laser collects data well outside the loaded wheel path while the right laser collects data from the wheel path. One end of the beam (on which the load carriage is mounted) is then kept fixed, while the other end is laterally shifted 25.4 mm (1 in). The wheel carriage then returns along this "diagonal" leg. Again, two longitudinal profiles are generated along this path. The process of straight and diagonal leg data collection continues as the carriage works its way left to right across the test section. As the carriage approaches the right limits of the profile, the left laser collects data from within the loaded wheel path and the right laser is well outside the wheel path. The lasers have been mounted on the carriage such that at some point in the data collection process, the left laser begins to travel directly over the same legs on the pavement that the right laser has already measured, effectively creating an overlap of longitudinal profiles. The location of this overlap depends on the set up of the testing protocol. All profiles generate a total of 134 longitudinal sets of data from both lasers, including the diagonal legs, and result in a total of seven overlapping longitudinal profiles. The significance of these overlapping longitudinal profiles is discussed further on in this paper.

Laser data is collected on both the straight and diagonal legs at a constant rate of 16 kHz, and is averaged by the data acquisition system in real-time at every 100 mm (4 in) in the longitudinal direction. Thus a total of 58 data points – 100 mm apart - are collected and saved from each leg of the laser path. The resulting data file, therefore, comprises of a data array of 58 rows and 134 columns, covering a total of 5892 mm by 1702 mm (approximately 19 ft by 5.5 ft) of pavement surface. The raw data is then saved in an ASCII format in a database. Because every profile is specific to a given number of HVS passes, the number of HVS passes, along with date and time of testing are also stored in the raw data file. At the start of HVS testing, an "initial" – untested profile is acquired, and this profile is used as a baseline (or reference) measurement for all subsequent profiles acquired on that pavement test section. Subsequently, the resulting profiles are acquired after every 100 passes up to a total of 1000 passes. Thereafter, the data collection interval is successively increased with increasing number of HVS passes. A series of 'Macros' – computer codes – were written in 'MS-Excel – Visual Basic for Applications (VBA), to compile the raw data files and perform the necessary calculations with graphing capabilities. Figure 3 shows typical deformations in a pavement test section with increasing number of HVS passes. One has to note that since height-based lasers were used for data collection, it is important that the height data thus generated be also gathered over the same exact coordinates on the pavement surface. Failure to do so will result in a systematic offset in the resulting profiles. These height measurements may also be used as statistical quality check parameters

All the profile information as collected herein may be used for purposes that include the characterization of test section surface profiles and rut measurements in asphalt pavements, evaluation of curling and warping in concrete pavements, as well as the determination of the deformation and settlement amount of raised pavement markers (RPM) under wheel load.

DATA ANALYSIS

Important Considerations

A first step in creating an automated analysis process/methodology is to ensure that the data collection procedure and format are standardized. Collection of the initial (untested) surface profile is also very important as it constitutes the reference or baseline profile from which all further rut depths are calculated. Because of its significant weight, the HVS has the potential to settle into the asphalt surface layer as testing progresses. Even though the maximum settlement thus far observed is in the range of 3-5 mm, it is sufficient to cause a significant effect in measured rut depth. This potential subsidence or settlement of the testing machine must therefore be taken into consideration. The subsidence is accounted for by using data points that lie well outside the area of load influence in a linear mathematical correction, which is then applied to all subsequent profile data points.

Analysis Functions

As described previously, each set of profile data is acquired as an ASCII file and consists of a 58 x 134 data array. The analysis methodology developed by FDOT acquires the raw data files for a given number of HVS passes, performs the necessary statistical quality checks, and compiles the data in an Excel workbook. The program then performs the necessary calculations to determine the rut depth at any given number of passes. Figure 4 shows a flowchart of the analysis program. For each given test section an Excel workbook is created, which contains the raw data from the initial (untested) profile and all subsequent profiles. The program has been designed to eliminate the need for multiple Excel files representing the same test section.

Two replicate laser data files for a given number of HVS passes are first averaged to generate a single data set representing a surface profile. The program then goes through the following steps to generate the pavement surface profile and calculate the rut depth:

Each data set, for a given number of HVS passes, contains a 58 x 134 data array. Columns 1 through 67 contain data from the left laser whereas columns 68 through 134 contain data from the right laser. These columns have been designated as L1 through L67 and R1 through R67 for the left and right laser respectively. For clarification, one row of data therefore comprises one transverse profile, whereas one column of data comprises one longitudinal profile of the given pavement test section. As described previously, under this configuration, there are seven overlapping legs (sets) of data. That is, columns L61 through L 67 for the left laser and columns R1 through R7 for the right laser should theoretically be identical. However, given the inherent measurement error, these two sets of data are usually slightly different. If a transverse profile were to be plotted (for one row, across all columns), data from the right laser appears to be offset by a value that is equal to the difference in readings from the overlapping columns of data. This can result in a systematic error in the measured rut depth. The program therefore applies this correction to the right laser data, and re-calculates all right laser data points. The correction applied is equal to the average difference in data values of the overlapping sets of data. The correction factor that is applied to the right laser data is calculated by the following equation:

$$K = \frac{(L61 - R1) + (L62 - R2) + (L63 - R3) + (L64 - R4) + (L65 - R5) + (L66 - R6) + (L67 - R7)}{7} \quad ..1$$

Where:
K is the correction factor
L61 through L67 represent height data from the left laser
R1 through R7 represent height data from the right laser

The initial or untested profile is first acquired and serves as a reference or baseline measurement. This reference profile is then subtracted from the final profile (or profile at any desirable number of passes). A straight line drawn across the two highest points on either side of the rut uplifts serves as a virtual straight edge. The rut depth is then calculated as the maximum distance between this line and the deepest point in the rut as illustrated in Figure 5.

For illustration purposes, the various surface profiles generated for a test section are shown in Figure 6. These three-dimensional surface profiles were generated using MATLAB, and clearly illustrate rut development as testing progresses.

Applications of Non-Contact Profiling in APT

Following the successful implementation and evaluation of the non-contact laser based profiling system, FDOT has employed the profiling system in a wide variety of research studies. Some of the applications are:

1. Measurement of rate of rutting in flexible pavement systems.
2. Measurement of slab curling and faulting in rigid pavements
3. Determination of deformation and settlement of raised pavement markers.

For example, as shown in Figure 7, the rut depth calculated from the surface profiles is plotted against the number of loaded HVS passes, to generate a combined rut development graph. Figure 8 is also presented to illustrate the curling of concrete slabs.

Summary

FDOT has installed a two-laser profiler on its HVS testing machine. This system has proved to be an effective tool for profiling accelerated pavement test sections. The profiling system and the analysis program not only accurately map the entire test surface but also result in a great savings of time and effort. To date, FDOT has tested over 50 different test sections with a total of 9-million HVS passes. To date, a total of approximately 3800 pavement test section profiles have been collected and analyzed.

REFERENCES

1. Spangler, E. B and W. J. Kelley, "*GMR Road Profiler – A Method for Measuring Road Profile*", Research Publication GMR-452, General Motors Research Laboratory, Warren, MI, 1964.
2. Gillespie, T. D., S. M. Karamihas, S. D. Kohn, and R. W. Perera, "*Operational Guidelines for Longitudinal Pavement Profile Measurement*", NCHRP Report 434, TRB, National Research Council, Washington, D.C., 1999.
3. Perera, R. W., and S. D. Kohn, "*Road Profiler Data Analysis and Correlation*", Proc., 5th Annual Meeting of Road Profiler User Group, Plymouth, MI, 1994.
4. Perera, R. W., and S. D. Kohn, "*Road Profiler Data Analysis and Correlation"*, Proc., 6th Annual Meeting of Road Profiler User Group, Plymouth, MI, 1995.
5. Sayers, M. W., and S. M. Karamihas, "*Interpretation of Road Roughness Profile Data",* Federal Highway Administration, FHWA/rd-96/101, 1996.

LIST OF FIGURES

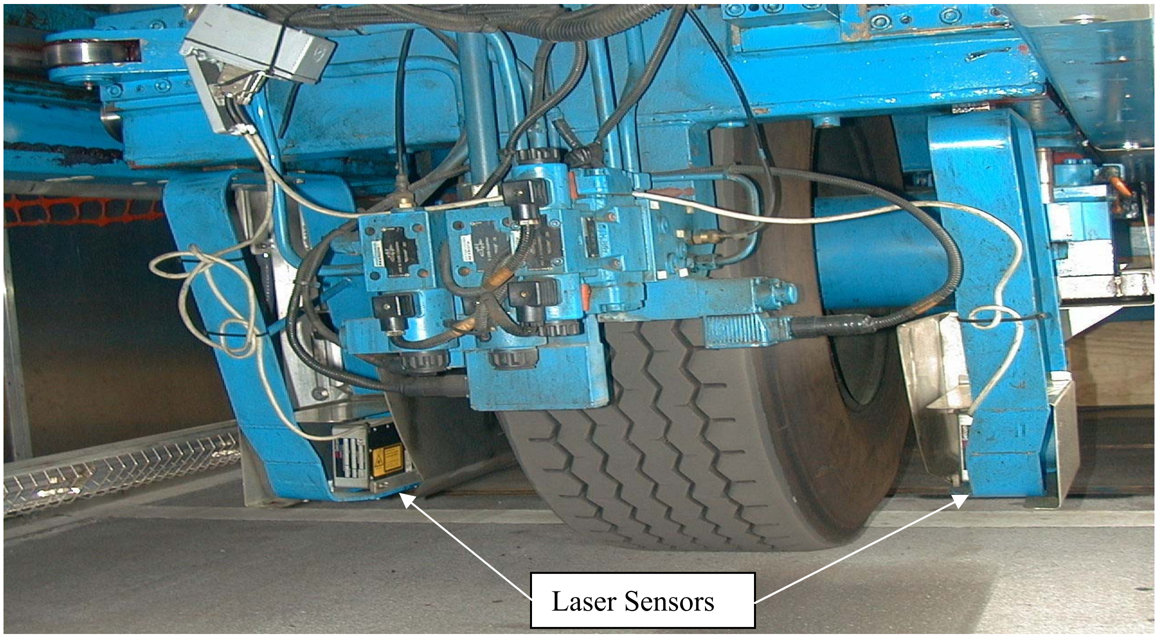
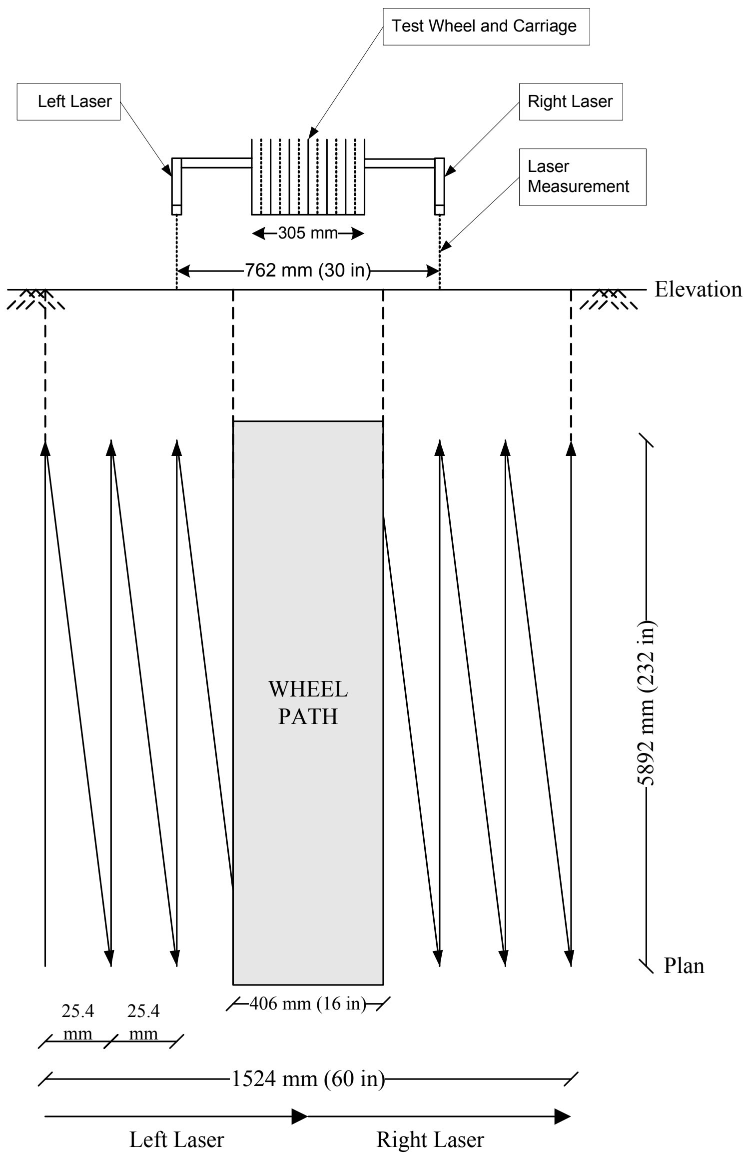


FIGURE 1 Laser based profiling system



Note: Not to scale

FIGURE 2 Schematic of APT test track laser measurement

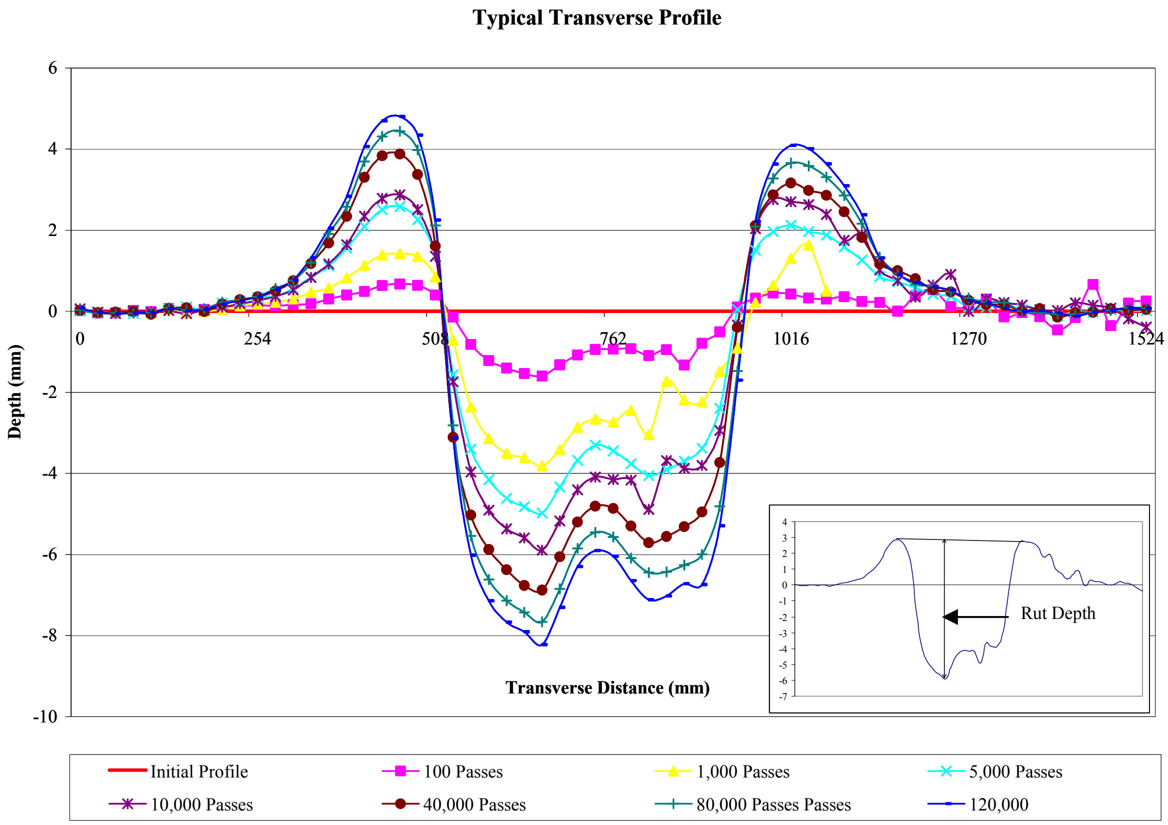


FIGURE 3 Typical transverse profiles for a pavement test section

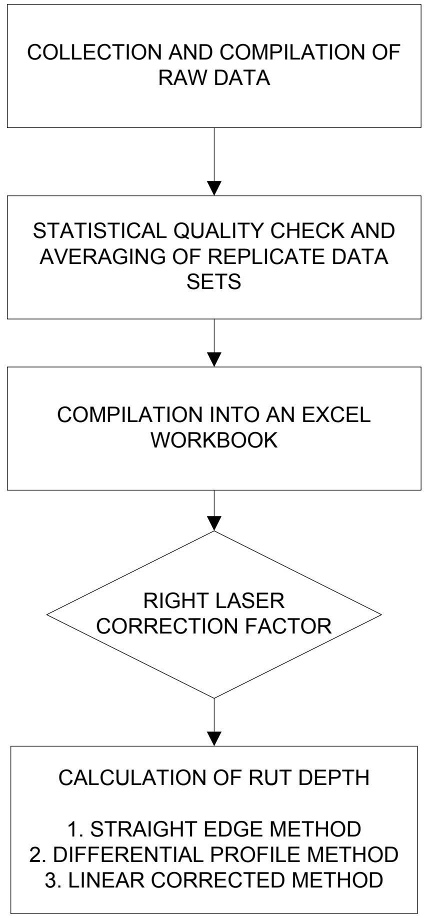


FIGURE 4 Data analysis program flowchart.

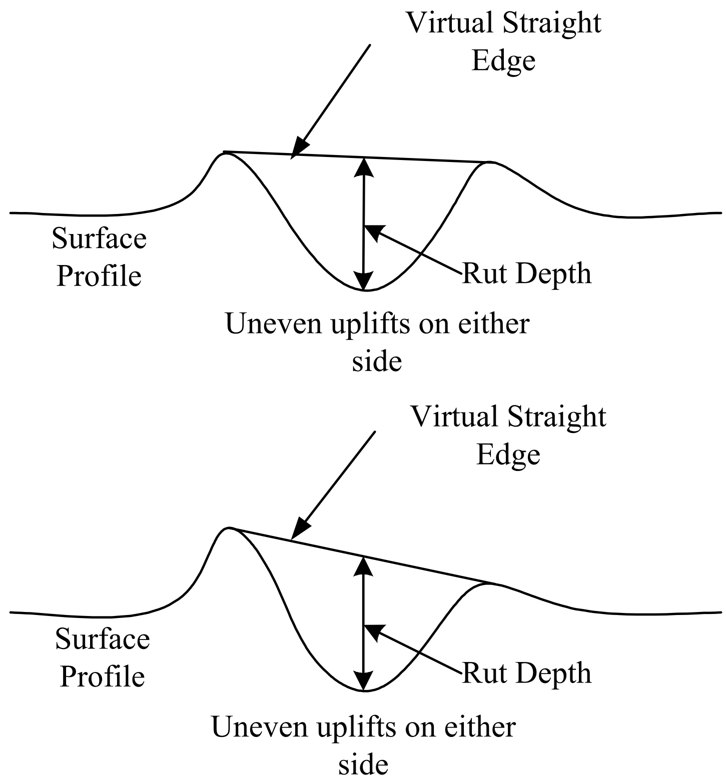


FIGURE 5 Calculation of rut depth from a surface profile.

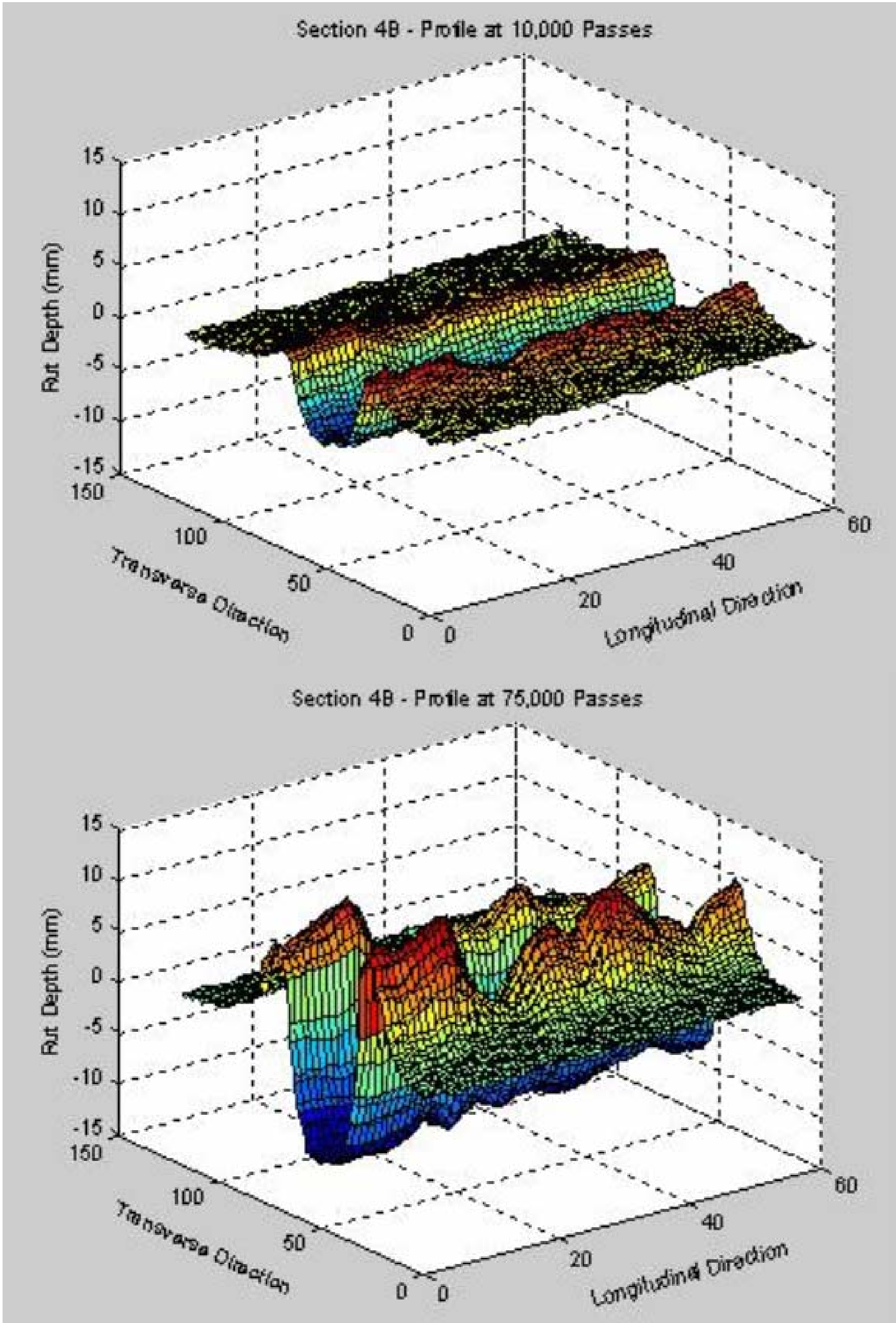


FIGURE 6 Relative profiles of a pavement test section.

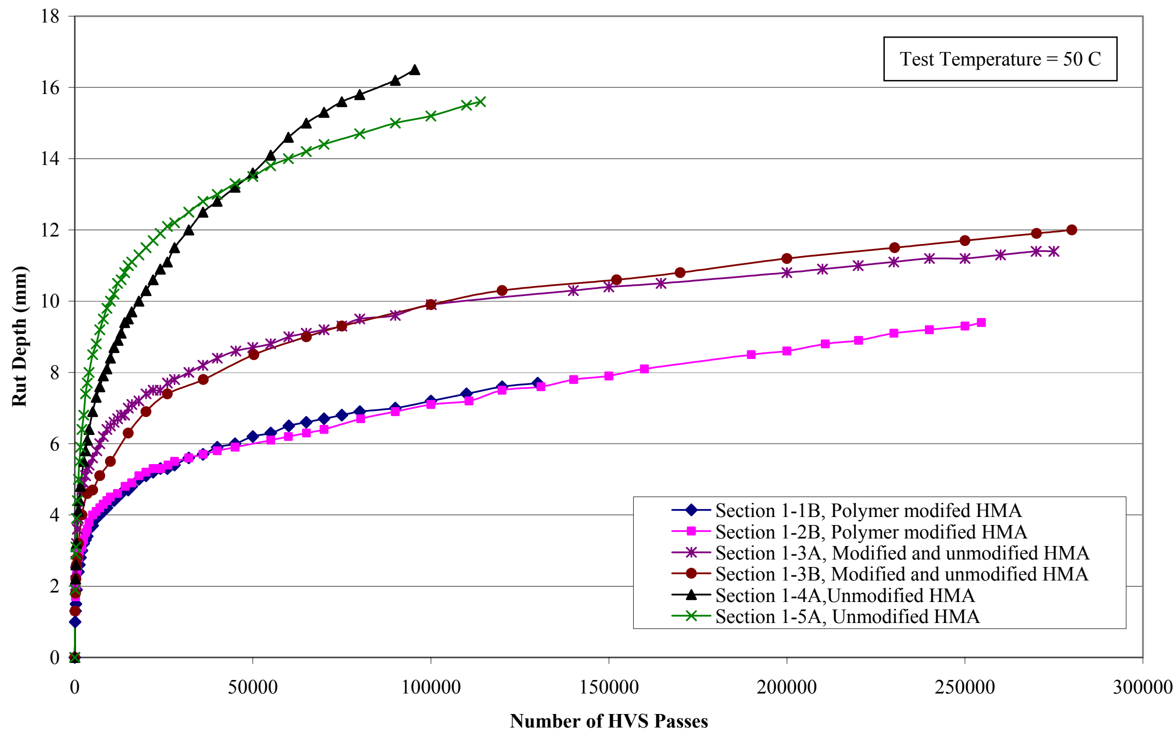


FIGURE 7 Rate of rutting in flexible pavements.

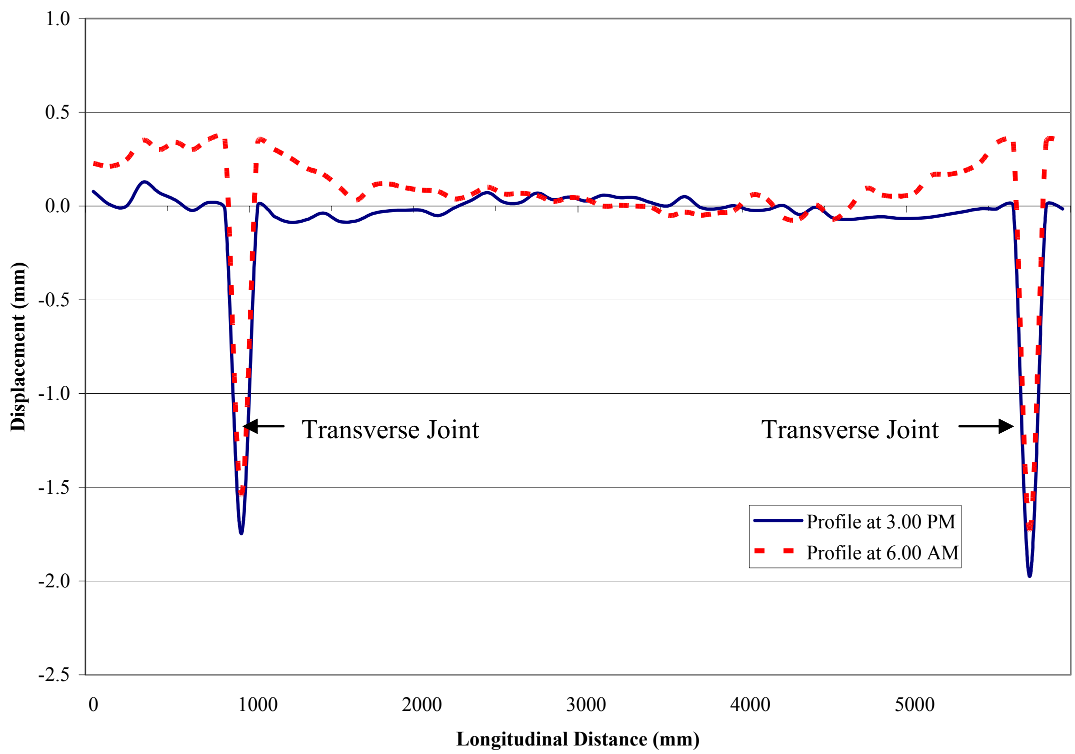


FIGURE 8 Illustration of change in longitudinal profile of concrete slab as a result of temperature change.