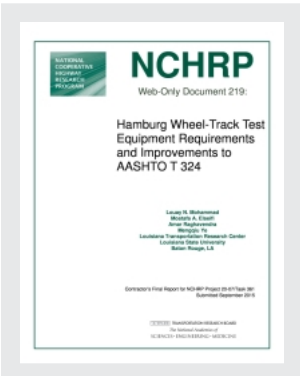

Hamburg Wheel-Track Test Equipment Requirements and Improvements to AASHTO T 324

DETAILS

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Hamburg Wheel-Track Test Equipment Requirements and Improvements to AASHTO T 324

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Contractor's Final Report for NCHRP Project 20-07/Task 361
Submitted September 2015

TRB TRANSPORTATION RESEARCH BOARD
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1. SUMMARY

The objective of this study was to evaluate the capability of the Hamburg Wheel Tracking (HWT) devices available in the US market and to identify potential issues with different aspects of AASHTO T 324 standard procedure in order to ensure proper testing and accurate, reproducible results. Based on the results of this study, researchers were tasked to provide proposed revisions with commentary to AASHTO T 324 to enable the use of a performance type specification for Hamburg test equipment.

A comprehensive experimental program was conducted to evaluate the capability of five commercially available HWT equipment as well as their ability to accurately measure, control, and maintain the desired test conditions as specified in AASHTO T 324. The experimental program concentrated on the following items of the current AASHTO T 324-14:

- Wheel position waveform, frequency, and maximum speed;
- Impression measurement system;
- Temperature measurement and control system;
- Free circulating water on mounting system;
- Wheel dimensions;
- Wheel loads;
- Specimen and track length; and
- Data collection and reporting.

After performing a comprehensive evaluation of the machines conforming to AASHTO T 324, it is concluded that there are differences between commercially available HWT machines in the US market. Furthermore, available HWT machines do not meet all the requirements set forth in AASHTO T 324 including requirements for the waveform, the temperature range, and the reporting parameters. One reason for some of the observed differences is due to the ambiguity of the specification and the lack of detailed requirements for the different aspects of the test method. The following represents a summary of the main findings of the experimental program.

Waveform: Results of the experimental program showed that two of the four machines available in the market were able to produce a sinusoidal wave (Vendors B and D). AASHTO T 324 specifies that the wheel be required to reciprocate over the specimen such that its position varies sinusoidally over time.

Temperature control system: Since the majority of the HWT machines do not have a cooling system, obtaining 25°C (77°F) in the bath is dependent on the incoming water temperature and was not possible when the water temperature was warmer than 25°C. When testing at 50°C, even though the average temperatures at the end of 30 minutes of conditioning were within the specification limit of 50 ± 1°C, some locations in the HMA specimen were not within the specified range. Therefore, a longer pre-conditioning time is recommended. On the other hand, the upper range of 70°C specified by AASHTO T 324 is too high and is not encountered in any regions of the US based on the 50% reliability 7-day

average maximum high pavement temperatures computed using the LTPPBind software. Based on the results of the survey, the highest test temperature used by the states was 56°C.

Deformation measurements: AASHTO T 324 does not currently specify the locations of the deformation readings or the number of deformation readings. Current specification has resulted in major discrepancies among manufacturers, as some machines record deformations at only five locations while others record deformations at 227 locations along the track length. Results also suggest that the deformation readings are sometimes not being recorded at the pre-determined locations along the track.

Data collection and reporting: AASHTO T 324 requires five parameters to be collected and reported to quantify the performance of a mixture to rutting and moisture susceptibility: number of passes at maximum impression, maximum impression, creep slope, strip slope, and Stripping Inflection Point (SIP). Upon review of the current requirements detailed in AASHTO T 324, one may note that not enough specifics are provided to allow for consistent analysis and reporting of the five aforementioned performance indicators.

At least seven methods, developed by four manufacturers and two state DOTs, were identified for analyzing HWT test data and reporting the performance parameters. Two mixtures (Mix 1 and Mix 2), which were tested using the HWT manufactured by Vendor A, were selected for analysis by the various methods. Mix 1 was a poor performing mixture that stripped during testing and Mix 2 was a good performing mixture that did not strip during testing. For Mix 1, substantial differences were observed amongst the different analysis methods especially in the reporting of the SIP. Furthermore, some of the available methods do not report the five performance parameters specified by AASHTO T 324. For Mix 2, only two of the seven methods successfully identified this mix as a non-stripping mix. In addition to these discrepancies, the approach adopted by Iowa DOT can only analyze HWT results obtained from the machine manufactured by Vendor A.

Based on the results of the experimental program, revisions to AASHTO T 324 and to the configurations of the available HWT machines are recommended. Modifications are proposed to address equipment capabilities, components, or design features in order to ensure proper testing and accurate, reproducible results. Proposed modifications are discussed in this report to ensure repeatable measurements and that the results from different manufacturers are comparable. These modifications include change to temperature measurement and range, impression measurement system, data collection, and data analysis and reporting. In addition to the proposed modifications to the AASHTO T 324 specifications, the vendors may need to modify their equipment to meet the new specification requirements.

After addressing the proposed modifications to the equipment configurations and to the specifications, a laboratory experimental program shall be conducted in order to compare the results obtained with HWT devices from various manufacturers when testing the same asphalt mixture. The experimental program recommends testing contrasting asphalt mixtures using the four main types of Hamburg test equipment available in the US market and comparing the results statistically in accordance with ASTM E 1169 Standard Practice for Conducting Ruggedness Tests.

2. INTRODUCTION AND RESEARCH APPROACH

This report presents the results of NCHRP Project 20-07/Task 361, Hamburg Wheel-Track Test Equipment Requirements and Improvements to AASHTO T324. This chapter describes the problem statement, objective, and research approach.

2.1. Problem Statement

The Loaded Wheel Test (LWT) is a laboratory-controlled rut depth test that uses loaded wheel(s) to apply a moving load on hot-mix and warm-mix asphalt (HMA, WMA) specimens to simulate traffic load applied on asphalt pavements. In the 1970s, Helmut-Wind Incorporated of Hamburg proposed a test method and developed specification requirements to measure the combined effects of rutting and stripping susceptibility. The equipment developed was named the Hamburg Wheel Tracking Device (HWTD) and has been used for over four decades worldwide. The HWTD measures the combined effects of rutting and moisture damage (stripping) by rolling a steel wheel across the surface of an asphalt concrete slab that is immersed in a temperature-controlled water bath. The interest and use of LWT in performance specifications, alternatively referred to as rut testers or torture testers, has seen an increase in recent years. This interest can be attributed to several factors, including the use of such devices by FHWA and many state Departments of Transportation (DOTs). Other important factors in this increased popularity are the ease of use and good correlation to field performance, which led many DOTs to incorporate LWT tests in their specifications as a pass or fail acceptance criteria.

As the popularity of this test equipment increased, several manufacturers started producing their own variation of the LWT, while others adapted their existing designs from a load over a rubber hose to deadweight loading from a steel wheel. Those machines were built using various solutions for controlling the wheel speed, measuring the rut depth, water bath temperature control, and reciprocating mechanisms, to name a few. These different machines are all currently being used by highway agencies and research centers. Despite the aforementioned discrepancies among the different LWT machines, no comprehensive study has been conducted to compare the results from different manufacturers.

In 2010, Shiwakoti et al. carried out a research study focused on wheel tracking devices to develop a rapid test method to evaluate moisture sensitivity *(1)*. The Asphalt Pavement Analyzer (APA) and the Hamburg Wheel Tracking Device (HWTD) were used for this research. Compacted cylindrical samples were fabricated using the Superpave Gyratory Compactor. However, the APA tests were carried out using the rubber hose instead of the metal wheel. Results showed major differences on the stripping behavior. APA results did not indicate any stripping inflection points, contrary to the HWTD results that showed significant stripping susceptibility. A recent study carried out by the Iowa DOT *(2)* statistically evaluated the results from 150 test runs on gyratory specimens using a two-wheel HWTD manufactured by Precision Machine and Welding (PMW). Linear variable differential transducers (LVDTs) were used to measure rut depths at eleven locations across the wheel track per pass. Measurements were recorded to the nearest 0.01 mm every 20th pass for the first 1,000 passes. The frequency was reduced to every 50th pass thereafter. Results indicated that the impression measurement location was found to be a source of significant variation in the HWTD. The study suggests that the differences are likely due to the non-uniform wheel speed across the specimen, geometry of the specimen, and air void profile.

2.2. Research Objective

The objectives of this research as stated in the project description are to [1] document the capabilities of available commercial Hamburg test equipment, [2] determine Hamburg test equipment capabilities, components, or design features that ensure proper testing and accurate, reproducible results, and [3] provide proposed revisions with commentary to AASHTO T 324 to enable the use of a performance type specification for Hamburg test equipment. In this study, reference to AASHTO T 324 implies reference to the latest standard published in 2014, AASHTO T 324-14.

2.3. Research Approach

The approach to be followed in this research project was consistent with the guidelines outlined in the project description. The proposed research activities were divided into five tasks. Task 1 consisted of collecting and critically reviewing all available Hamburg test equipment capabilities, and specifications. In Task 2, laboratory experiments were conducted to determine the capabilities of available Hamburg equipment and the adequacy of AASHTO T 324. In Task 3, and based on the results of Task 2, revisions were proposed to AASHTO T 324 to ensure repeatability and accuracy of measurements. In Task 4, a statistically based experimental plan was developed to validate proposed requirements for Hamburg equipment and for specimen preparations and their impacts on test results and acceptance test criteria. Finally, Task 5 consisted of preparing a final report that summarizes the project findings and conclusions, document the study results, and presents recommended revisions to AASHTO T 324. Detailed descriptions of the proposed research effort are presented in the following sections.

2.3.1 Task 1 – Available Hamburg Test Equipment Specifications

The objective of this task is to conduct a critical review of the test capabilities, specifications, and similarities and differences of available Hamburg test equipment in the US. AASHTO T 324 "*Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)*" establishes the testing protocol as well as the data-reporting format. However, the standard in its most current version vaguely describes some critical aspects of the testing procedure and data analysis, leaving room for ambiguous interpretation. Further, some commercially available machines do not fully comply with its equipment requirements resulting in discrepancies in the reported results. A comparative review of some of the critical technical aspects of the representative equipment in the US was carried out and presented to what is required by AASTHO T 324. It is worth noting that results of this task, which are presented subsequently in this report, identified four major manufacturers of HWT in the US. These vendors are referred to as vendors A, B, C, and D to protect the anonymity of the vendors.

2.3.2 Task 2 – Engineering Desk Analysis of Existing Hamburg Test Systems

In this task, engineering desk analysis was conducted to identify potential issues on different aspects of the AASHTO T 324 procedure, mainly on its specifications of what needs to be measured, and the needed accuracy and resolution of the measurements. As these critical points are identified, the work progressed to evaluate the capability of the existing equipment to accurately measure, control, and maintain the desired test conditions. Finally, the minimum equipment capabilities, components, and design features to ensure the consistency and accuracy of the test were presented. This task concentrated on the following items of the current AASHTO T 324:

- Loading mechanisms;
- Temperature measurement and control system;
- Impression measurement system;
- Specimen dimensions; and
- Data collection and reporting.

Other factors within the current standard were also analyzed to accommodate any changes and new recommendations as needed. The current issues on each of these sections, as well as potential improvements were evaluated and presented.

2.3.3 Task 3 – Propose Revisions to AASHTO T 324

Based on the results of Task 2, revisions to AASHTO T 324 were proposed to incorporate the equipment capabilities, components, or design features that ensure proper testing and accurate, reproducible results. Modifications were based on the aforementioned components and whether existing HWT equipment possess the needed technologies to meet the required specifications.

2.3.4 Task 4 – A Framework for Future Laboratory Evaluation

Upon completion of Tasks 3, Hamburg test equipment capabilities, components, and specifications would have been reviewed and modified to ensure proper testing, accurate, and reproducible results such that it may be used in performance-based specifications. In Task 4, a detailed experimental plan was developed to validate the proposed equipment configurations and specifications developed in Tasks 2 and 3 and to meet the recommended modifications to AASHTO T 324.

2.3.5 Task 5 – Prepare and Submit Final Report

The objective of Task 5 was to complete a final report documenting the entire research effort. Task 5 was divided into two subtasks that include preparation of a draft and a final report. The report summarized the findings and conclusions and presented the recommended modifications to AASHTO T 324 along with the developed research framework. Task 5 also included a detailed review of the capabilities, specifications, similarities, and differences among the available Hamburg test equipment in the US.

3. METHODOLOGY AND EXPERIMENTAL PROGRAM

3.1. Review of Test Equipment Specifications

In preparation for the upcoming tasks, a critical review was conducted of the test capabilities, specifications, and similarities and differences of available Hamburg test equipment in the US. A comparative review of some of the critical technical aspects of the representative equipment in the US was carried out and presented to what is required by AASTHO T 324. It is worth noting that results of this task, which are presented subsequently in this report, identified four major manufacturers of HWT in the US. These vendors are referred to as vendors A, B, C, and D to protect their anonymity.

3.2. Nationwide Survey

A nationwide survey was conducted to collect information from state agencies on the use of HWTs. The survey was posted online and was distributed through various LISTSERVs; it was also announced at related TRB committees. The research team complemented states' responses with a review of state specifications available online as well as through email communications, which allowed a 100% response rate. A copy of the survey is provided as well as the contact information of survey respondents are presented in Appendix A. The prepared survey consisted of 13 questions, which are listed below:

1. What type of LWT do you use? (Please choose one or more manufacturers)
2. Does your machine have a single wheel or two wheels?
3. Which specification do you use? (Please choose one)
4. How often do you calibrate your LWT (months)?
5. What does the calibration include?
6. Is your laboratory AMRL certified for AASHTO T-324?
7. What test temperature(s) do you use? (°C)
8. What is the acceptance criteria used in your state? Please attach a copy of your specifications.
9. What type of specimens do you use?
10. Does you agency specify requirements for the Hamburg test specimen fabrication?
11. Do you have test data that you can share? (Please choose one)
12. How is the result of the Hamburg test reported?
13. How do you use the data you obtain from the machine?

3.3. Experimental Program

The objective of the experimental program was to identify potential issues with different aspects of AASHTO T 324 standard procedure, mainly on its specifications of what needs to be measured, and the needed accuracy and resolution of the measurements. As these critical points are identified, the research team evaluated the capability of the existing equipment to accurately measure, control, and maintain the desired test conditions. Finally, the minimum equipment capabilities, components, and design features to ensure the consistency and accuracy of the test were presented. The experimental program concentrated on the following items of the current AASHTO T 324:

- Wheel position waveform, frequency, and maximum speed;

- Impression measurement system;
- Temperature measurement and control system;
- Wheel dimensions;
- Wheel loads;
- Specimen and track length; and
- Data collection and reporting.

Other factors within the current standard were also analyzed to accommodate any changes and new recommendations as needed. The following sections present the experimental program conducted to evaluate the aforementioned factors for the different Hamburg equipment available in the US market.

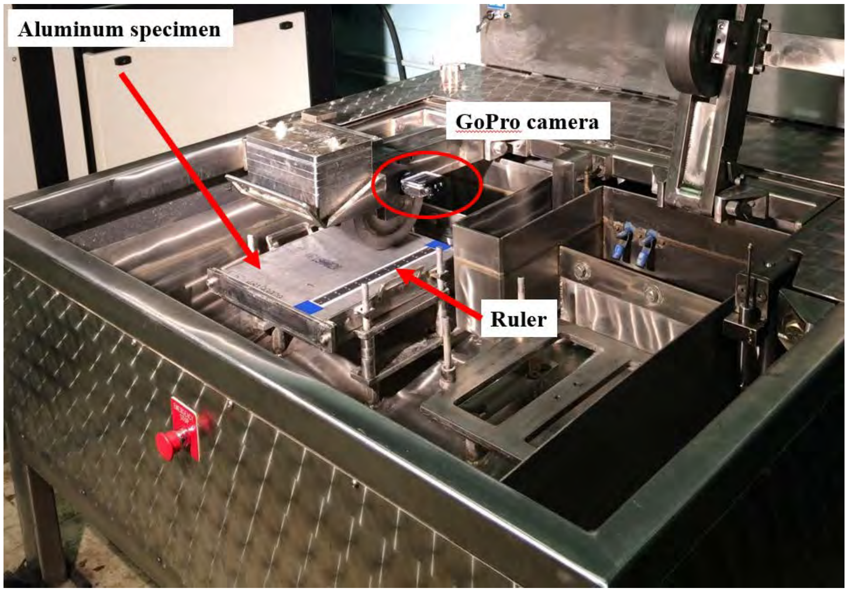
3.3.1 Wheel Position Waveform, Frequency, and Maximum Speed

Section 5.1 of AASHTO T 324 specifies the movement of the wheel over the specimen. The wheel is required to reciprocate over the specimen such that its position varies sinusoidally over time. The frequency of this movement is specified to be 52 ± 2 passes per minute. Additionally, the maximum speed is specified to be 0.305 m/s (1 ft/s) and is expected to be reached at the midpoint of the specimen. An extensive evaluation of the HWTs identified in the project was undertaken to assess compliance with the specifications of section 5.1. HWTs from Vendors A, B, C, and D were evaluated in this study.

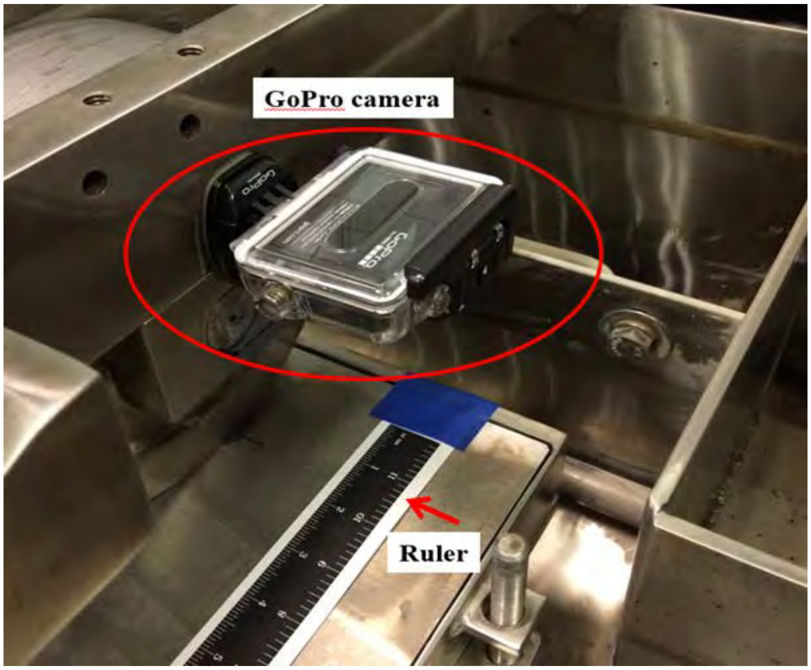
Two approaches were considered to record the position of the HWT wheel as a function of time. The first approach studied the feasibility of using an accelerometer to measure acceleration of the sliding mechanism. The acceleration could subsequently be integrated with respect to time to obtain velocity and integrated once more to yield distance or position. However, this approach required acquisition of correctly sized accelerometers and signal conditioning equipment. The second approach studied the possibility of using a video camera to capture images at a high rate and performing image analysis to obtain the position of the wheel as a function of time. The second approach was selected as the equipment and accessories needed to perform the experiment were available in-house.

A GoPro camera was used to capture the video of the HWT wheel during its travel. This camera was attached to the moving loading arm using an adhesive mount. Figure 1 shows the camera set up with an adhesive mount. Aluminum slab specimens were fabricated and used to minimize vibrations during video recording. A ruler was affixed to the top of the slab and the camera was focused on the ruler. As the loading arm moves along its track, the attached camera focuses on different parts of the ruler along the slab specimen. The ruler reading coinciding with the center of each frame of video was recorded during post-processing. This information was combined with time data (obtained from a video recording rate of 240 frames/second) to obtain a distance versus time graph.

Two types of rulers were evaluated by the research team and are presented in Appendix B. Various camera mounting systems (gooseneck/clamp and adhesive mount), camera-to-specimen distances, and lighting sources were evaluated to obtain an accurate video. The best video quality was obtained with a non-reflective paper ruler (1/16 in. subdivision), an adhesive mount, a focus distance of 5 in., and a professional lighting source (Lowel DP).



(a) Overall setup



(b) Camera and ruler

Figure 1
Experimental setup for wheel position analysis

The HWT was allowed to reciprocate for a few cycles before triggering the GoPro camera to capture video at 240 frames/second. The GoPro camera setup and control were achieved using the GoPro app on the iPhone. The video data file was further processed as follows:

1. The video file was split into individual image frames. Each picture frame obtained was 1280 pixels wide and 720 pixels high.
2. MATLAB software was used to add a vertical red line in the middle of each frame (i.e., to change the color of column number 640 to red).
3. The images were re-assembled back to a video file.
4. The video was analyzed frame-by-frame and the position on the ruler coinciding with the red line was noted. The corresponding frame number was also recorded. It should be noted that the time increment from one frame to the next is 1/240 second.

Figure 2 presents the image of a frame after the red line addition in MATLAB software. In this frame, the red line coincides with the 2.75 in. mark on the upper scale of the ruler.

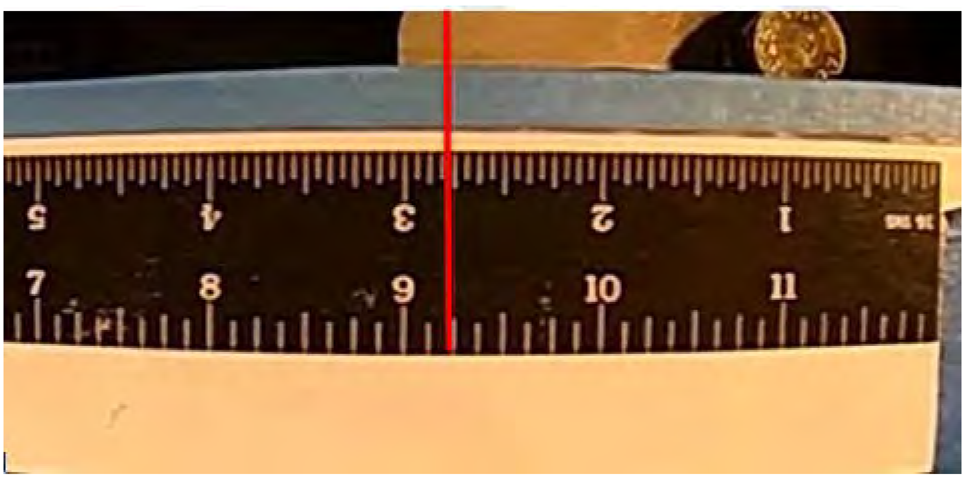


Figure 2
Image frame after MATLAB processing

Figure 3 shows a typical plot of the recorded ruler readings or the wheel position as a function of time, obtained with the aforementioned post-processing procedure.

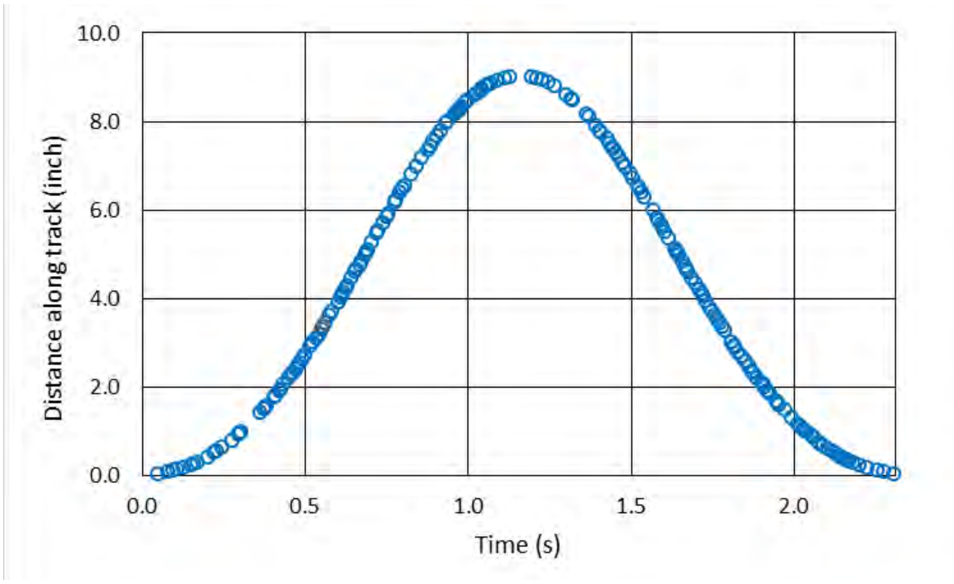


Figure 3
Wheel position as a function of time

3.3.2 Impression Measurement System

Section 5.3 of the AASHTO T 324 specification requires that an LVDT be used to measure the impression of the wheel as it tracks over the specimen. It further specifies that the LVDT have a minimum range of 20 mm (0.8 in.) with an accuracy of 0.15 mm (0.006 in.). Additionally, this system should be capable of measuring the impression at least every 400 passes, recording the number of passes applied, and be able to collect the measurements without stopping the test.

The current equipment verification procedure detailed in the Appendix of AASHTO T 324 requires that the LVDT be checked in accordance with the applicable ASTM D 6027 procedure or per manufacturer's recommendations. However, it does not require verification that the measurements be recorded at specific locations along the track. These locations, currently set by the vendors, should be standardized to enable test result comparisons between different vendors.

As a first step, the calibration of the LVDTs was verified for all the HWTs evaluated. Additionally, an aluminum specimen with a curvature mimicking a rutted specimen was designed and fabricated to enable verification that the impression readings were being recorded at the locations specified by the vendors. Figure 4 presents the picture of the fabricated specimen and the engineering drawing of the specimen is presented in Appendix C. Since the curvature or "rut" of this specimen is machined per the drawing in the appendix, the depression at any location along the track is precisely known. The maximum depression of the manufactured specimen is 19.05 mm (0.75 in.) and is located at the midpoint of the track. The aluminum specimen allows for verification of LVDT readings and confirms if the readings are being recorded at the locations specified by the vendors.

Figure 4
Metal specimen for verifying locations of deformation readings

During the course of the study, the research team fabricated a new metal specimen with a longer curved track length to avoid the problem of the wheel "climbing out" of the track. The machine drawing of this metal specimen and the analytical solution of the wheel and metal-specimen interaction is presented in Appendix C.

Figure 5
Modified metal specimen for verifying locations of deformation readings

The calibration of the impression measurement systems from the vendors were verified as described in the instruction manuals provided with the machines. Next, the aluminum specimen was installed in each of the machines to verify that the readings were being recorded at exactly the locations specified by the vendors. The steps of this procedure are described as follows:

1. The aluminum specimen was flipped upside down to enable the machine to obtain the "zero" readings. Figure 6(a) presents the picture of the flipped specimen, showing the flat surface for the "zero" readings.
2. The HWT was allowed to reciprocate for 80 cycles to enable the machine to record "zero" readings.
3. The aluminum specimen was flipped again to allow the wheel to track over the curved machine surface. This is shown in Figure 6(b). The aluminum specimen was also centered along the track of the wheel.
4. The HWT was allowed to reciprocate for 80 additional cycles to ensure that readings of the curved surface of the aluminum specimen were recorded.

(a) Flat surface for obtaining zero readings

(b) Recording deformation readings along the curvature (ruler shown for scale)

Figure 6
Procedure for verifying locations of deformation readings

It is also noted that the impression of the curvature of the metal specimen was recorded by connecting the electrical output of the machine LVDT to a data acquisition system. As shown in Figure 7, data were collected at a frequency of 100 Hz. Impression measurement system readings obtained from all the machines were compared to this reference profile.

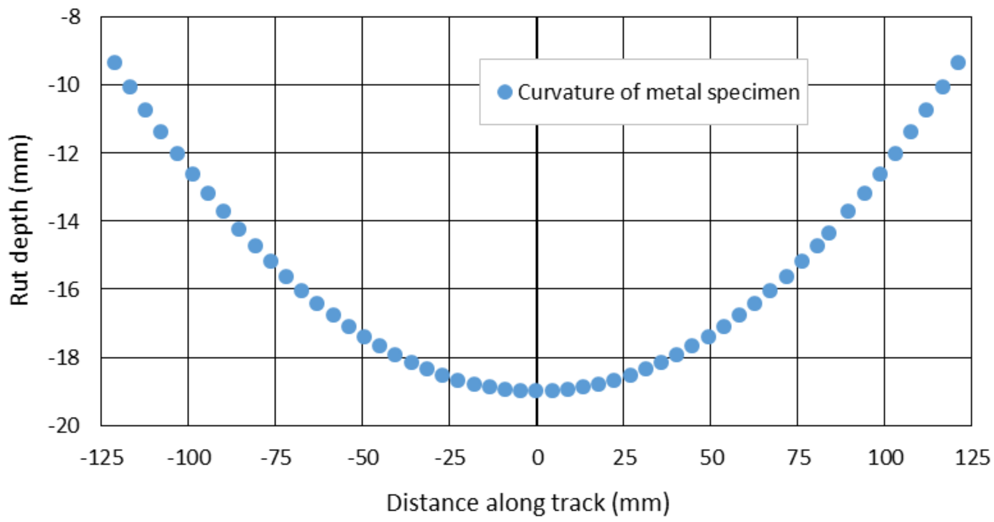


Figure 7
Curvature of the metal specimen recorded by machine LVDT connected to data acquisition system

3.3.3 Temperature Control System

The temperature control system comprises a water tank, heater(s), temperature sensor(s), circulating pump, and controller. AASHTO T 324 specifies that the temperature control system in the HWT be capable of maintaining the set temperature in the water tank to within ±1.0°C over a range of 25 to 70°C (77 to 158°F). Additionally, it specifies that the water be mechanically circulated in the tank to reduce the temperature gradient. The following section describes the experimental setup used for this purpose.

The current AASHTO T-324 specification requires verification of the temperature in the bath at four locations. The procedure also specifies the preconditioning time for temperature stabilization to be 30 minutes. In order to quantify the temperature gradient across the specimen and to verify that the preconditioning duration is adequate, instrumented hot mix asphalt (HMA) specimens were used. Four Resistance Temperature Detectors (RTDs) were used with each SGC specimen, with two RTDs on top and two on the bottom of the slab specimen. Figure 8 shows the locations of the RTDs in the SGC specimen. Details of the specimen preparation and instrumentation are presented in Appendix D. The RTDs were connected to a DATAQ DI-718Bx data acquisition system for monitoring. The data was collected at a sampling rate of 1/8 (or 0.125) Hz.

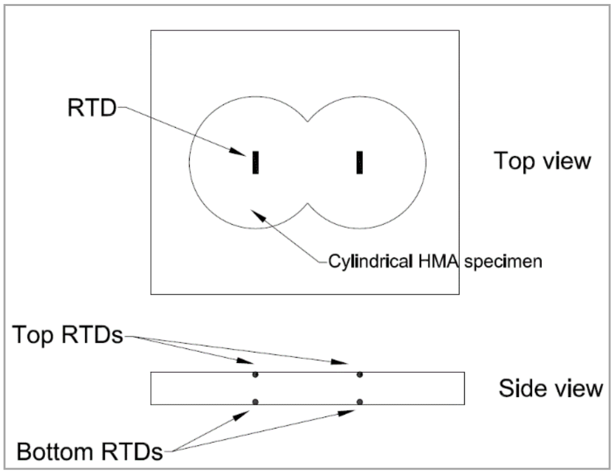


Figure 8
Temperature sensor locations

3.3.4 Wheel Dimensions

The thickness and diameter of the wheels from the different manufacturers were measured. A digital caliper was used for this task. The measurements were taken diametrically and along the thickness of the wheels at four different locations as indicated in Figure 9.

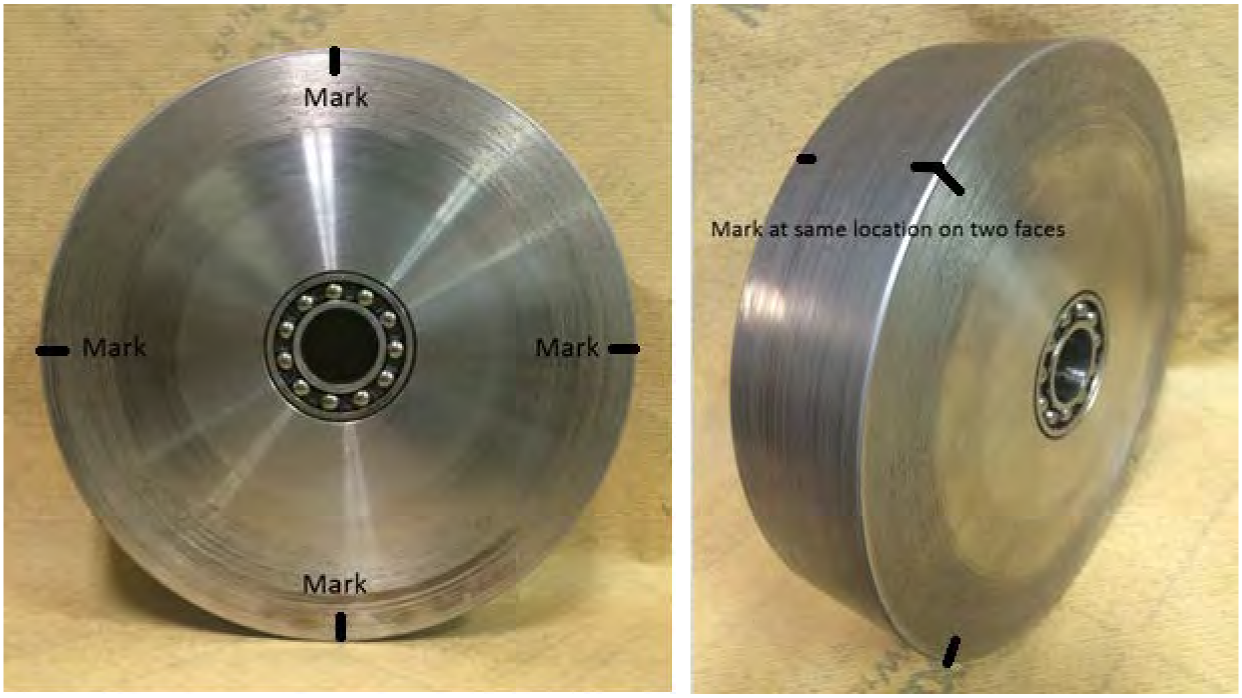


Figure 9
Measuring details: The geometry of the steel wheel (Vendor A)

3.3.5 Wheel Loads

Section 5.1 of AASHTO T-324 specifies the load on the wheel is 703 ± 4.5 N (158 ± 1.0 lbs.). The load on the wheel is measured by a calibrated load cell. For vendor A, a spacer is placed to ensure the wheel is horizontally levelled; see Figure 10.

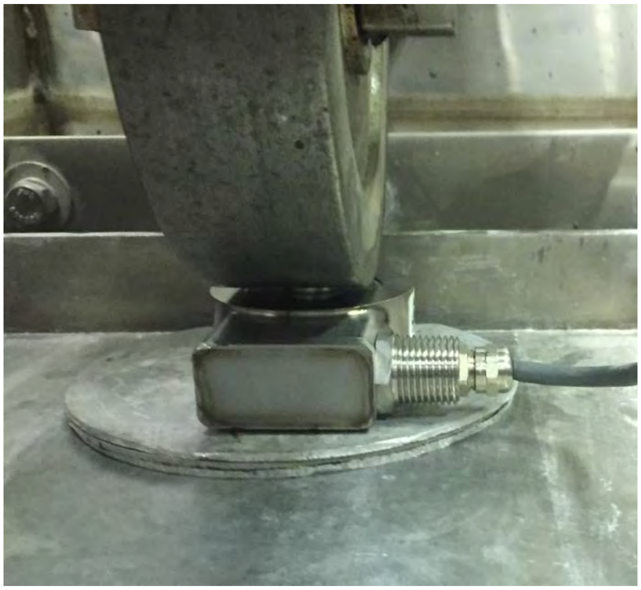


Figure 10
Measuring details: The process of using load cell (Vendor A)

3.3.6 Specimen and Track Length

AASHTO T 324 specifies that two High Density Polyethylene (HDPE) molds be used to secure the specimen in the testing tray of the machine. The schematic from the specification is shown in Figure 11. As can be seen, the specification allows some of the dimensions to be decided by the manufacturer. The wheel track lengths of the evaluated machines were obtained by analysis of the GoPro data. The ruler reading from the video frames corresponding to the ends of the track were noted to compute the track length.

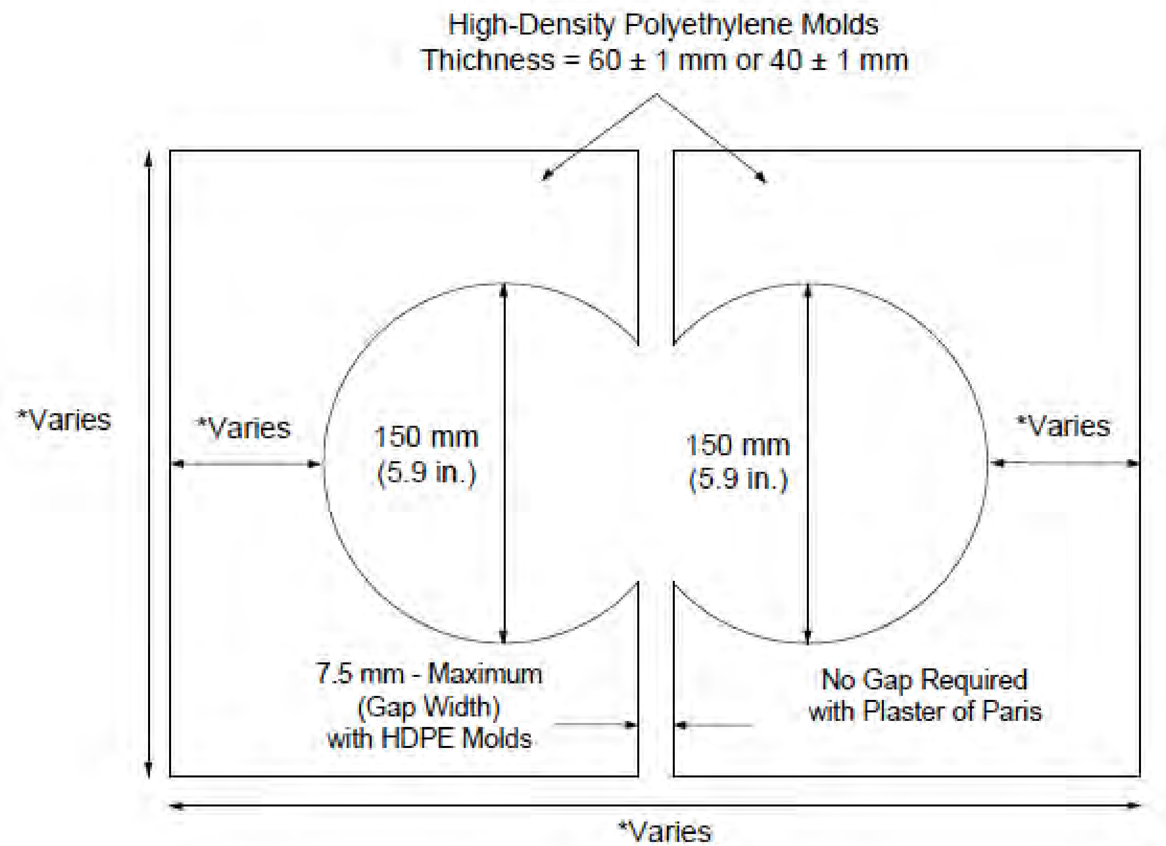
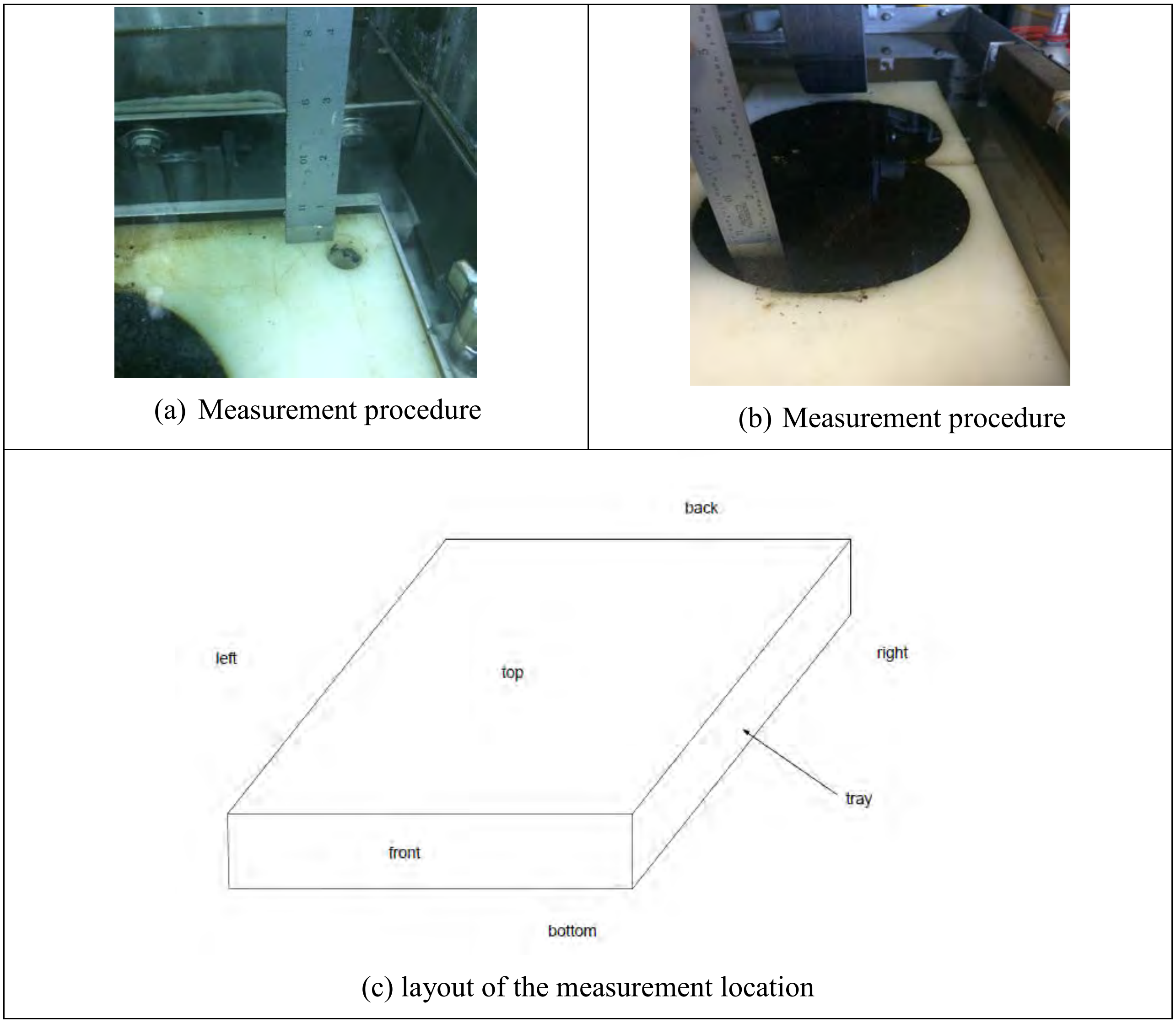


Figure 11
Specimen mold (reproduced from AASHTO T 324)

3.3.7 Free Circulating Water on Mounting System

Sections 5.5 and 5.6 of AASHTO T-324 requires that the specimen mounting system (slab or cylinder) must suspend the specimen and provide a minimum of 20 mm (0.8 in.) of free circulating water on all sides. After filling the water tank and inserting the specimens, the water depths on all sides were measured using a ruler (Figure 12(a) and (b)). For each tray, six sides of free water circulating were measured (Figure 12(c)). For each side, three measurements were conducted and the average results were reported.



(a) Measurement procedure

(b) Measurement procedure

(c) layout of the measurement location

Figure 12
Free water circulating on the mounting system

3.3.8 Data Collection and Reporting

AASHTO T 324 requires five parameters to be collected and reported to quantify the performance of a mixture to rutting and moisture susceptibility: number of passes at maximum impression, maximum impression, creep slope, strip slope, and Stripping Inflection Point (SIP). In this analysis, the data collection schemes adopted by the vendors were reviewed and evaluated. Specifically, the number of data points collected and the spacing between the data points were identified and summarized. In addition, the calculation schemes for the five performance indicators were reviewed and analyzed. It should be noted that the current AASHTO T 324 specification only requires data collection at the center (± 1/2 in.) of the track. However, state agencies utilize different collection schemes in the calculation of the rut depth.

4. RESULTS AND ANALYSIS

This chapter presents the main findings of NCHRP Project 20-07/Task 361. It includes the main findings of the review of the available Hamburg test equipment specifications, the results of the nationwide survey, and the results of the experimental program.

4.1. Review of Test Equipment Specifications

This section documents the technical specifications of the available Hamburg testers in the US market. Equipment manufacturers are referred to as vendors A, B, C, and D to protect the anonymity of the surveyed vendors. The key elements of AASHTO T 324 specifications to conduct the Hamburg Wheel Track (HWT) test were identified to be the loading mechanism, temperature measurement and control system, impression measurement system, test specimen size, and data collection and reporting sections. Tables 1 to 5 summarize the equipment specifications in terms of load, temperature, deformation, specimen size, and data collection mechanisms. The relevant sub-sections of AASHTO T 324 are included in each table below.

Table 1. Temperature measurement and control system (AASHTO T 324, section 5.2)

Vendor		A		B	C	D
		Standard model	Economy model			
Sensor	Type	Type T	Type T	Type J	RTD	RTD
	Range (°C)	-200 to 350	-200 to 350	0 to 760	Room temp to 70	-25 to 199
	Number	2	1	1	2	3
	Location	Next to each specimen	Right side	Bottom tank	Next to each specimen	One between specimens, two to be positioned by user
Tank volume (gal)		40	18	15 (2 tanks)	34 (3 tanks)	22.9
Heater (kW)		2 x 4.5 Immersion Heaters	4.5	4.5	4.0	2 x 1.5
Circulating pump (gpm)		34	9	11	10	17
Temperature control tolerance (± °C)		0.3	0.3	1	1	0.5

Table 2. Loading mechanism (AASHTO T 324, section 5.1)

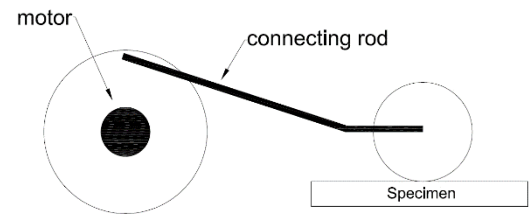
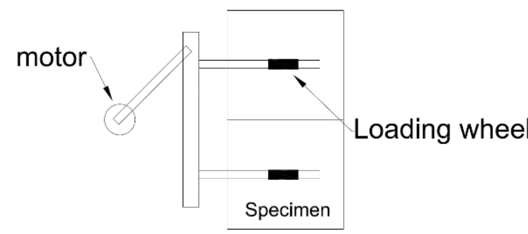
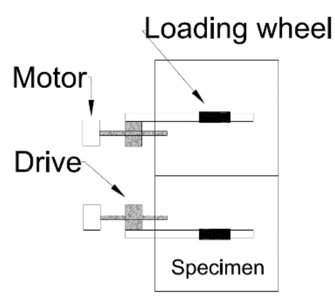
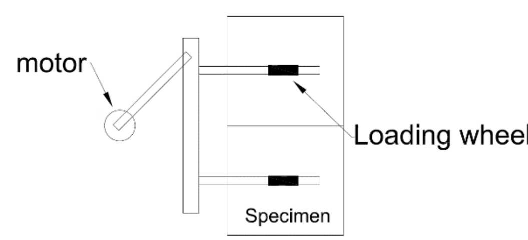
Vendor	Load	Sinusoidal Wheel Speed	Drive	Schematic
A	Deadweight	No	Slider-crank	
B	Pneumatic cylinder	Yes	Scotch-yoke	
C	Deadweight	Yes	Two independent motors and drives	
D	Deadweight	Yes	Scotch-yoke	

Table 3. Impression measurement system (AASHTO T 324, section 5.3)

Vendor	A		B	C	D
	Standard model	Economy model			
Sensor type	LVDT	LVDT	Magnetostrictive	LVDT	Potentiometric position sensor
Range (mm.)	50.8	50.8	101.6	50.8	50.0
Tolerance (± mm)	0.15	0.15	0.0762	0.1	0.045
Location	Mounted on the side of the specimen	Mounted on the side of the specimen	Top of cylinder	Attached to the back of loading arm	Mounted on side of frame in line with wheel

Table 4. Specimen and track length (AASHTO T 324, section 6.4.2)

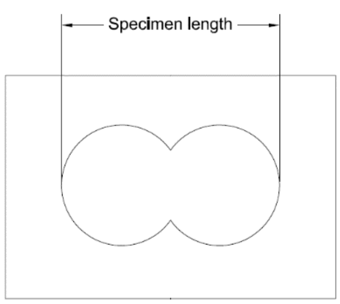
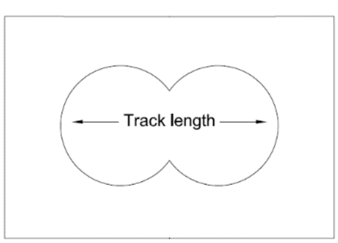
Vendor	A		B	C	D
	Standard model	Economy model			
	10.671 inch	10.671 inch	10.100 inch	10.700 inch	10.700 inch
	9.000 inch	9.000 inch	9.000 inch	9.000 inch	9.060 inch

Table 5. Data collection and reporting

Vendor	A		B	C	D
	Standard model	Economy model			
Number of data points collected across specimen	11	11	5	Selectable up to 21	227
Range (± from midpoint), inch	4.5	4.5	4.5	4.5	4.45
A/D resolution (bit)	16	16	12	17	16

4.1.1 Loading Mechanism

The four HWTs identified apply the load to the specimen using either a dead weight or by using a pneumatic cylinder. The effect of using these two methods of load application was investigated as part of the experimental program.

4.1.2 Wheel Speed

The existing HWT devices can be broadly classified into sinusoidal (Vendors B, C, and D) and non-sinusoidal loading testers (Vendor A). Due to the geometry of the loading mechanism, the speed of the travelling wheel varies sinusoidally (in the case of Vendors B, C, and D) or in a non-sinusoidal fashion (Vendor A). The geometry of the non-sinusoidal test machine is shown in Figure 13. This mechanism is identical to the crankshaft-connecting rod-piston mechanism used in automobiles and the wheel (crank circle) speed equation can be obtained from automotive engineering texts.

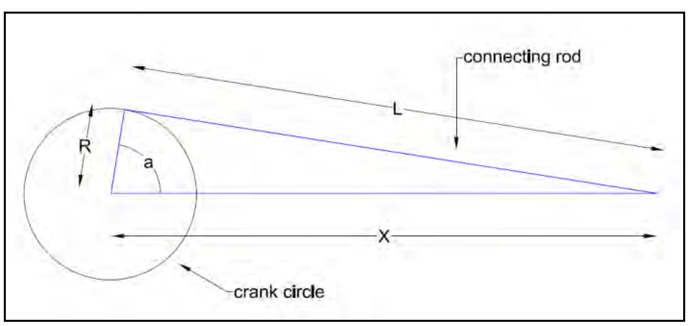


Figure 13
Crank-slider mechanism

There are three consequences of a non-sinusoidal wheel speed: [1] the total time of loading of the front half of the specimen is less than that of the rear half of the specimen; [2] the average speed on the front half of the specimen is more than the average speed on the rear half of the specimen; and [3] the maximum speed is not achieved at the mid-point of the stroke, but rather at some point on the front specimen.

4.1.3 Temperature Measurement and Control System

AASHTO T 324 test specification currently requires the water bath to be able to control the temperature from 25 to 70°C (±1.0°C) using a mechanical circulating system. Vendors A and B use thermocouples while vendors C and D use Resistance Temperature Detectors (RTDs) as sensors to measure and control bath temperature. Both sensor technologies (thermocouples and RTDs in conjunction with signal conditioning electronics and analog-to-digital converters) meet the accuracy requirement of the test method and the text in AASHTO T 324 section 5.2 should continue to remain technology neutral. The HWTs employ an immersion type heater(s) to heat and maintain the temperature in the water bath. A pump circulates the water continuously to minimize the temperature gradient.

4.1.4 Impression Measurement System

In the current version of the AASHTO T 324 test method; there is a requirement of a specific type of sensor (an LVDT, or Linear Variable Differential Transformer) to measure the rut depth. The minimum range of this sensor is specified as 20 mm, with an accuracy requirement of 0.15 mm. Table 3 lists the details of the impression measurement systems as implemented by the evaluated vendors. The sensing technologies used include LVDT, magnetostrictive, and potentiometric methods. The ranges of these sensors vary between 50 and 100 mm. Table 3 also shows the locations of these sensors in the various vendors' designs. Some of the designs incorporate side-mounts or mounting on the back of the loading arm, while others mount them on top of the loading arms or the pneumatic loading cylinders. The readings from the various designs should provide similar results, provided there are no compliance issues.

4.1.5 Specimen Length and Track Length

The cylindrical specimen mounting system in AASHTO T 324 allows some dimensions to be set by the test system vendor (Figure 2 of T 324). Table 4 shows the total specimen length, without any gap, for each of the four vendors. The molds provided by vendors A, C, and D allow a total specimen length of 10.7 in. while the corresponding dimension for vendor B is 10.1 in. Currently, the track length in most of the test machines is close to 9.0 in. These dimensions were verified as part of the experimental program.

4.1.6 Data Collection and Reporting

Table 5 summarizes the data points collected per cycle and the range of travel covered by the surveyed vendors. The number of data points collected varies from five (Vendor B) to 227 (Vendor D). These data points can be collected over the entire range of travel of the wheel. For example, the range of ± 4.5 in. from the center of the specimen equates to a total 9.0 in. track length that can be covered. The impression measurement requirement in the current version of AASHTO T 324 specifies that the system be capable of measuring the rut depth "at the center (± 1/2 in.) along the length of the wheel's path." However, the report section (10.1) of AASHTO T 324 stipulates that the "maximum impression" be reported.

4.2. Findings of the Nationwide Survey

A nationwide survey was conducted to collect information from state agencies on the use of HWTs. The survey was posted online and distributed through various list serves; it was also announced at related TRB committees. The research team complemented states' responses with a review of state specifications available online as well as through email communications, which allowed a 100% response rate. References are provided for the following state specifications: Iowa *(2),* Montana *(3),* Colorado *(4),* Utah *(5),* Texas *(6)*, Oklahoma *(7)*, Wisconsin *(8)*, Louisiana *(9)*, California *(10)*, Illinois (*11*) and Washington *(12).* A copy of the survey and the contact information of survey respondents are also provided in Appendix A.

Figure 14 presents the current use of HWTs by the different states. While 21 out of 50 states indicated that they use HWT (Figure 14), further evaluation of state specifications showed that only 12 states use it for acceptance of asphalt mixes. Nine states are currently using HWT for research purposes or are in the process of implementing HWTs in their specifications (e.g., New Mexico). Of the remaining states, 17 states reported that they use the Asphalt Pavement Analyzer (APA), which is another type of laboratory wheel-tracking device standardized by AASHTO T 340 but is not within the scope of this research project.

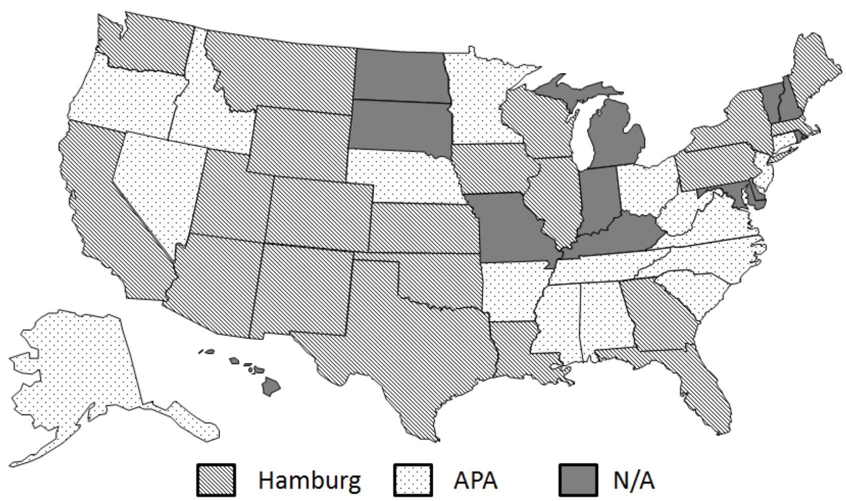


Figure 14
States Using HWT and APA

The states that currently use HWTs in acceptance of asphalt mixes are California, Colorado, Illinois, Iowa, Louisiana, Massachusetts, Montana, Oklahoma, Texas, Utah, Washington, and Wisconsin. It is noted that Wisconsin DOT contracts out HWTs testing but the test is included in their specifications. It appears from the responses that many states are in the process of adopting this test in their specifications and one would expect the number of states using the HWT to increase significantly in the next five years. For instance, Vermont, Georgia, New York, and South Carolina indicated in their responses the possibility of adopting this test in the near future.

4.2.1 Type of HWTs Used

The second question in the survey related to the HWT brands used by the states. Available vendors are Troxler Electronic Laboratories, Inc.; Pavement Technology, Inc. (PTI); James Cox & Sons, Inc.; and InstroTek, Inc. Among those 12 states that specify HWT, a Troxler is used; however, it is noted that the other products are relatively newer and the states may acquire HWTs from the other vendors in the future. Since HWTs can be conducted on one-wheel or two-wheel devices, states were asked how many wheels they use. While Massachusetts uses one-wheel, all other states indicated that they are using two wheels devices.

4.2.2 Test Methods Used

States were polled on the test method used to conduct Hamburg wheel testing in their specifications. Since AASHTO T 324 does not specify a test temperature, all states need to modify the test method to reflect local environmental conditions. While Texas, Colorado, and Montana DOT are using their own state specifications (Tex-242F, CP-L 5112, MT-334, respectively), all other states use AASHTO T 324 or modified AASHTO T 324 as their specifications. Kansas and Florida mentioned they use Tex-242F state specifications as designation if needed.

The survey also polled the respondents on how often their states calibrate their HWT devices. Based on the responses, seven states indicated that they calibrate the devices every 12 months. Colorado, Illinois, and Oklahoma indicated that they calibrate the water bath temperature every six months and all other components every 12 months. Texas and Washington calibrate all HWT components every six months (Figure 15). It is noted that results presented in Figure 15 are only for the states that use HWTs for acceptance of asphalt mixes and not for research purposes. According to AASHTO T 324, water bath temperature needs to be calibrated every six months. Wheel-load and LVDTs should be calibrated based on manufacturer's recommendations. AASHTO T 324 also requires "verifying that the wheel is reciprocating on the test sample at 52 ± 2 passes per minute" but does not mention how often it should be calibrated. Based on the survey responses, all states calibrate load, LVDTs, and temperature. Oklahoma is the only state that documents a detailed procedure on how to calibrate HWT for temperature, load, LVDTs, and wheel frequency. From these responses, it appears that HWT calibration needs to be more detailed in AASHTO T-324 to allow for comparable precision between the states.

The states were also asked whether their laboratory is AMRL certified for AASHTO T 324 or not. Among those 12 states that specify HWT, Colorado, Wisconsin, and Massachusetts are not AMRL certified for AASHTO T-324. Results were verified from the AMRL website: http://www.amrl.net/amrlsitefinity/default/aap/r18labs.aspx

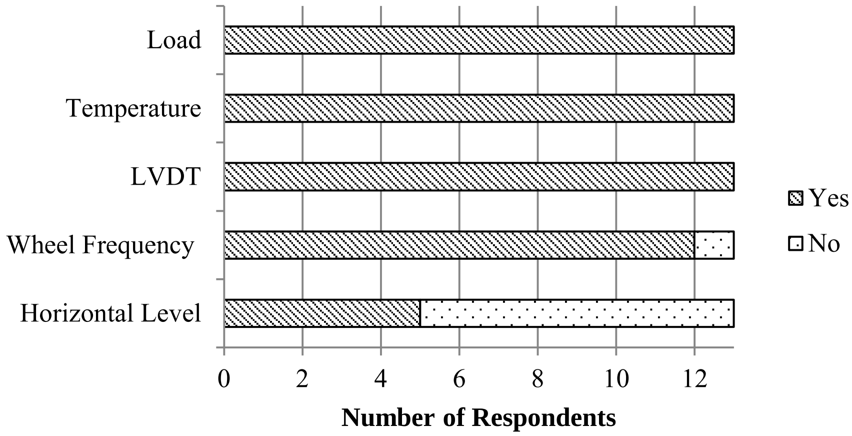


Figure 15
Calibration of HWT

4.2.3 Test Temperature

Respondents were polled on the water bath temperature. Based on the survey responses and state specifications, California, Montana, Utah and Colorado use at least two different test temperatures based on PG, which correspond to 44°C and 56°C. Massachusetts DOT use 45°C (113°F). The remaining states use 50°C (122°F) only (Figure 16).

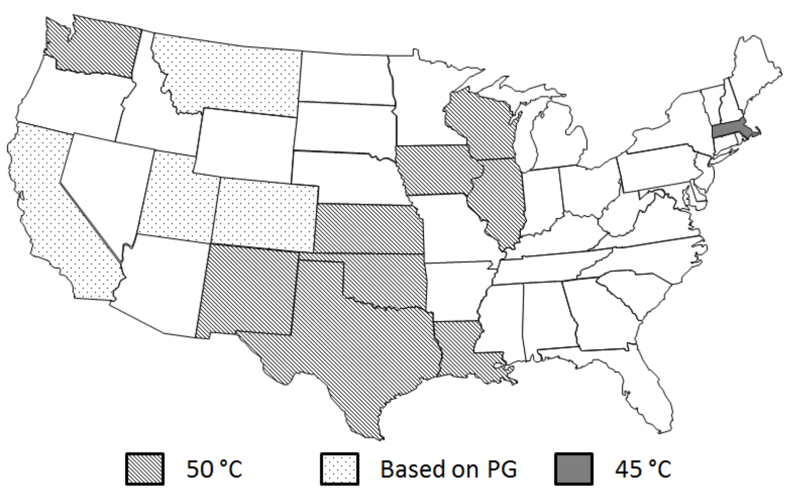


Figure 16
Test Temperature(s)

4.2.4 *Mix Acceptance Criteria*

Mix acceptance criteria based on HWT varies among the states. The main results from the HWT are the maximum rut depth and the stripping inflection point (SIP). Based on the state specifications, only California, Wisconsin, and Iowa use both maximum rut depth and stripping inflection point as acceptance criteria (Figure 17). The remaining states use only the maximum rut depth as acceptance criterion. California specifies the minimum number of passes at SIP for different PG. Iowa and Wisconsin specify that the ratio of stripping slope to creep slope should be equal or larger than 2.0. Illinois states that "It may be useful to run every test for 20,000 wheel passes to collect additional data on moisture sensitivity" (*11*) and Oklahoma states that SIP may optionally be computed and reported for information. The maximum allowable rut depth varies among states. Colorado specifies that a maximum rut depth greater than 4 mm (1.57 in) before 10,000 passes be considered a failure. Illinois restricts the minimum number of wheel passes when maximum rut depth reaches 12.5 mm, which shall be selected based upon the PG Grades. Among state specifications, California, Colorado, Texas, Louisiana, Iowa, Montana, Wisconsin, and Illinois clearly list the requirement for the minimum number of passes at a specific rut depth or the max rut depth at a specific number of passes. Other state specifications just mention that the criteria shall be selected based upon PG grade or based on specifications but do not list a specific rut depth. The details of the state specifications are provided in Appendix A.

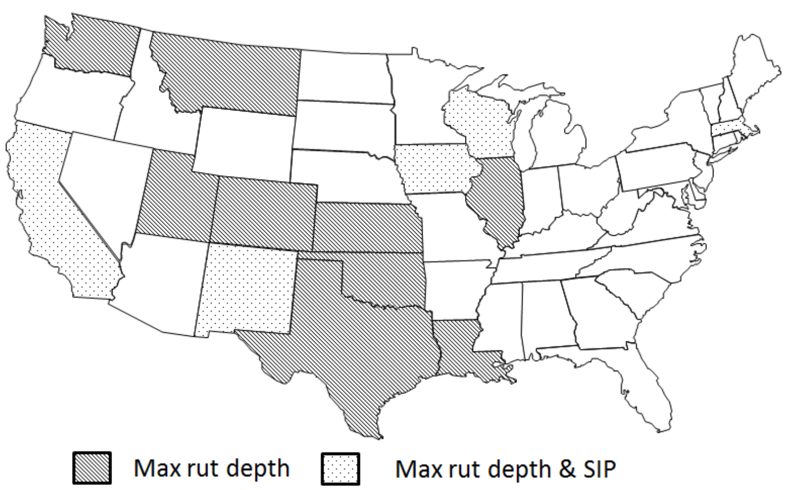


Figure 17
Acceptance Criteria Used by the States

States were also polled on the type of specimens. Montana, Utah, and Colorado allow using either slab or cylinder; other states use cylindrical specimens only given their convenience. Agencies were also queried whether they specify certain requirements for the test specimen fabrication. Among the 12 states, only Washington, California, and Louisiana do not specify requirements for specimen fabrication.

4.2.5 Reporting of Test Results

The method adopted to calculate the maximum rut depth varies among state agencies. Since AASHTO T-324 requires reporting the maximum depression only, seven states report the maximum rut depth only (California, Colorado, Massachusetts, Utah, Washington, and Wisconsin). For the other states, the rut depth is calculated by taking the average of several readings. Texas and Oklahoma use the average of the three centered sensor readings. Illinois also uses the average of three sensor readings, which include the sensor at which the maximum rut depth is measured and the two sensor readings around it. Louisiana takes the average of the five center points. Montana reports the average of the seven center sensor readings. For Iowa, if the average rut depth at the final pass is larger than 12 mm, they use the average of the five sensor readings. On the other hand, if the average rut depth is smaller than 12mm, they use the average of 10 sensor readings.

4.3. Wheel Position Waveform, Frequency, and Maximum Speed

Section 5.1 of AASHTO T 324 specifies the movement of the wheel over the specimen. The wheel is required to reciprocate over the specimen such that its position varies sinusoidally over time. The frequency of this movement is specified to be 52 ± 2 passes per minute. Additionally, the maximum speed is specified to be 0.305 m/s (1 ft./s) and is expected to be reached at the midpoint of the specimen. An extensive evaluation of the HWTs identified in the project proposal was undertaken to assess compliance with the specifications of section 5.1. Details of the experimental program were presented in section 3.

4.3.1 Test Results

4.3.1.1 Wheel Position Analysis

Figure 18(a) presents a plot of the recorded ruler readings or the wheel position as a function of time for the machine from Vendor A. The fitted curve was plotted using the equation for a sinusoidal wave. The resulting plot shows differences between the expected and the measured position readings. This was expected as the HWT from Vendor A is designed to follow the equation for the slider-crank mechanism and not a sinusoidal wave.

This procedure of recording and processing video data was repeated for the scotch-yoke mechanism incorporated by Vendor B and the results are presented in Figure 18(b). Results are compared to the sinusoidal wave. Table 6 presents the equations for the pure sinusoidal and non-sinusoidal waveforms.

The difference between a pure-sinusoidal machine and a non-sinusoidal machine can be observed in Figure 18. In the case of a pure-sinusoidal machine, the wheel spends equal amounts of time on the front and back halves of the track. However, in the case of the non-sinusoidal machine, the wheel spends more time on the back half of the track (55%) as compared to the front half (45%).

Figure 18(c) shows the results obtained for the HWT from Vendor C. The wave shape is characterized by a linear region in the middle (shown as region ‘A’), followed by a slow-down, and finally by a small stationary duration (shown as region ‘B’) at the track ends. It should be noted that the wheel travels at a constant rate of speed in the region shown by ‘A’ on the graph.

The waveform obtained for the machine from Vendor D is shown in Figure 18(d). This machine also uses the scotch-yoke mechanism and produces a pure-sine position waveform. Because of this configuration, the wheel in this machine spends equal amounts of time on the front and back halves of the track.

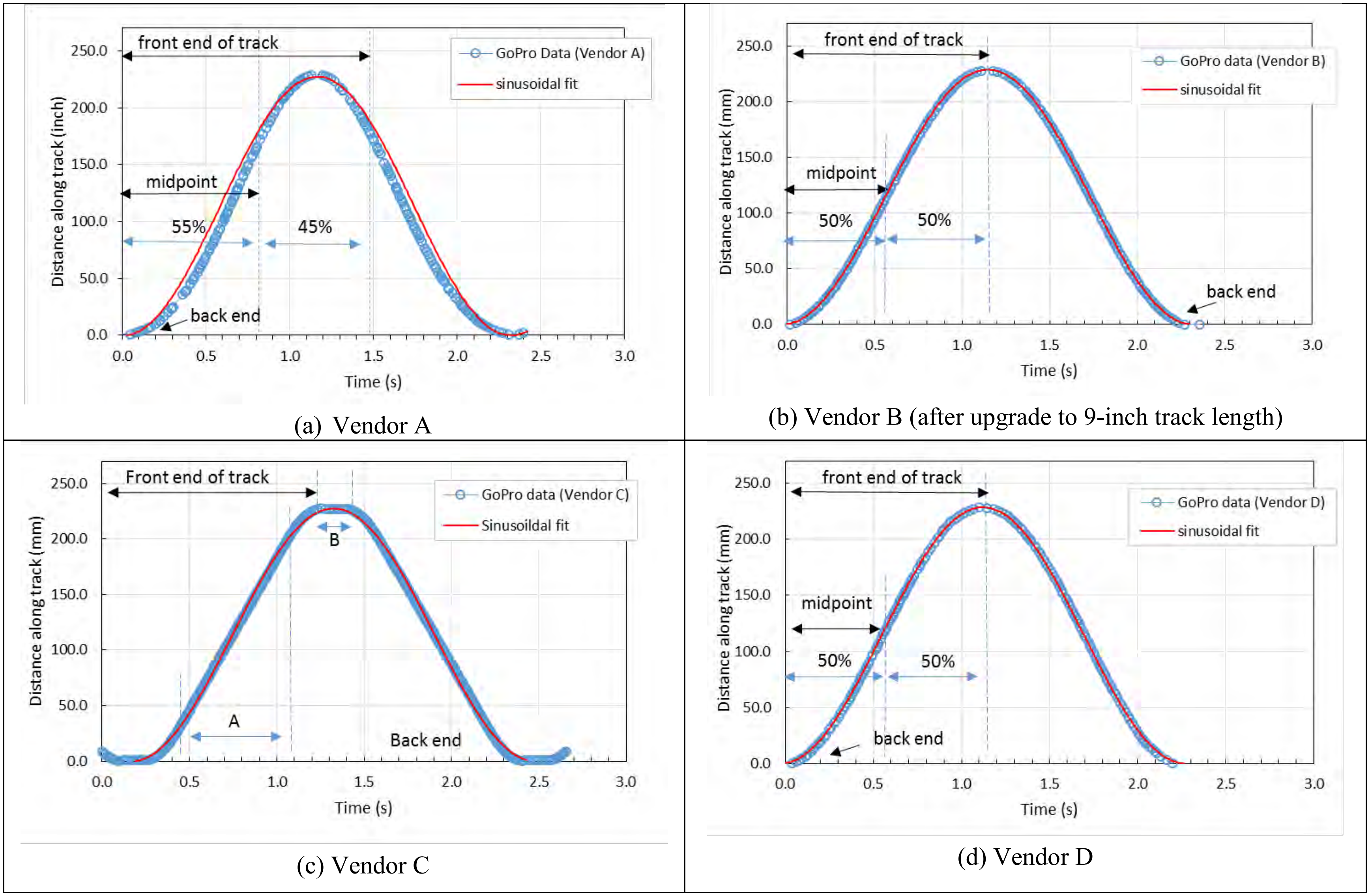


Figure 18
Wheel position analysis

Table 6. Equations for the position of the wheel

Vendor	Mechanism	
	Slider-crank (non-sinusoidal)	Scotch-yoke (sinusoidal)
A	$x = rcos\left(\frac{2\pi t}{T}\right) + \sqrt{l^2 - r^2 sin^2(\frac{2\pi t}{T})}$	
B, C, and D		$x = \sin(t)$

where,

x = horizontal position of the wheel (in),

t = time (min),

T = cycle time (=1/26 cycles per minute),

l = length of the connecting rod (in), and

r = radius of the crank circle.

Since LTRC is in possession of two identical machines from Vendor A (referred to A-1, A-2), the position analysis experiment was performed on both machines to examine the repeatability of results. Both machines are of the same model type with two-wheel configuration. Figure 19 presents the results obtained. It can be observed that the curves were very close to each other, indicating that the results were repeatable.

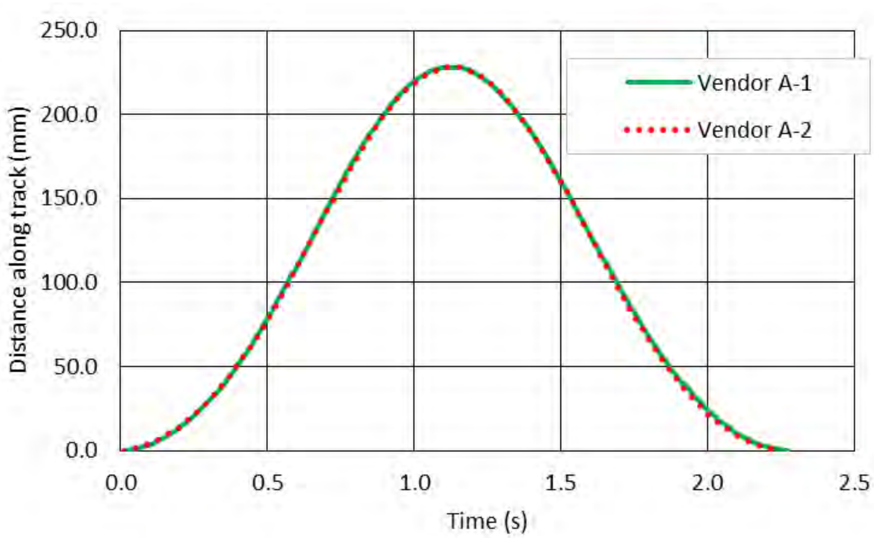


Figure 19
Wheel position analysis on machines from Vendor A

In an effort to quantify the deviations from a pure-sinusoidal waveform, a goodness-of-fit measure, RMSE (root mean square error), was computed for all the waveforms. The equation used for computing RMSE is shown in Equation (1) and an example of the computed error is shown in Figure 20. The results of the computation are shown in Table 7. The pure-sinusoidal machines from Vendors B and D had the lowest RMSE, followed by the machine from Vendor C, while the non-sinusoidal machine from vendor A exhibited the highest RMSE values.

$$RMSE = \sqrt{\frac{\sum e_i^2}{n}} \qquad (1)$$

where,

e_i = deviation from a pure sinusoidal curve, and

n = number of data points.

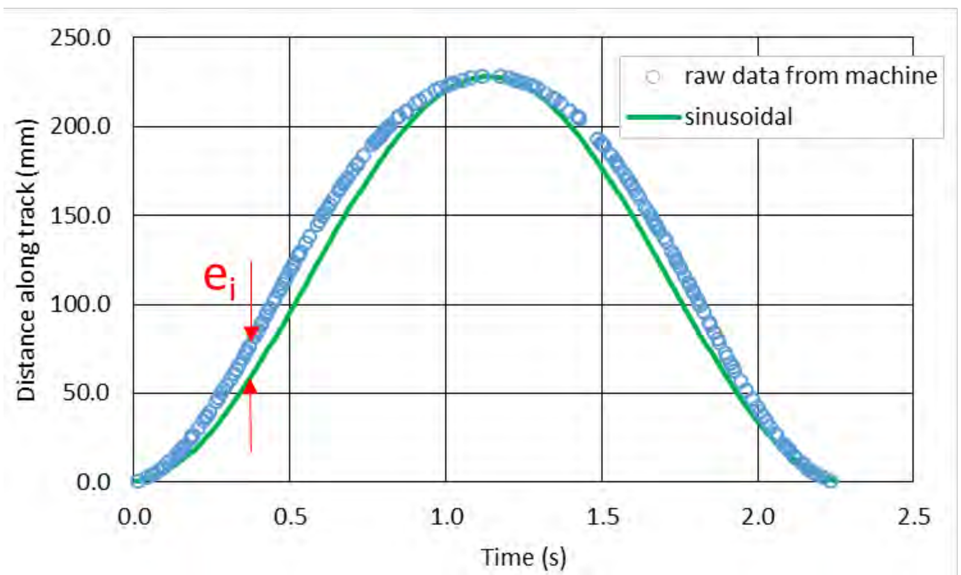


Figure 20
Illustration of Root Mean Square Error computation

The absolute mean deviation (AMD) was calculated according to the following equation:

$$AMD = \frac{1}{n}\sum_{i=1}^{n}|x_{mi} - x_{si}| \qquad (2)$$

where,

x_{mi} = measured distance along track, and

x_{mi} = theoretical distance along track for a sinusoidal wave.

Table 7. AASHTO T 324, section 5.1 parameters

		Vendor A-1	Vendor A-2	Vendor A-3	Vendor B	Vendor C	Vendor D
Waveform RMSE (mm)		13.21	14.48	13.21	1.02	3.05	1.02
Waveform AMD (mm)		11.43	14.48	13.20	0.88	3.05	1.01
Frequency (passes per minute)		51.8	52	52	51.2	52.1	52.2
Speed	Midpoint (m/s)	0.33	0.33	0.30	0.27	0.31	0.31
	Maximum (m/s)	0.33	0.33	0.30	0.27	0.31	0.31
	Distance of maximum speed location from midpoint (mm)	17.02	8.89	14.22	0.00	0.00	0.51

4.3.1.2 Frequency

The number of passes of the wheel over the specimen is specified to be 52 ± 2 passes per minute. The video of the wheel reciprocating over the specimen was recorded for one minute and the data were analyzed to compute the frequency of traversal as follows:

$$f = \frac{52 * 60}{t} \quad (3)$$

where,

f = frequency (passes per minute); and

t = time for completion of 52 passes (seconds).

Table 7 presents the results obtained for the machines evaluated. It should be noted that all the machines performed within the current tolerance of 52 ± 2 passes per minute.

4.3.1.3 Maximum speed and location of maximum speed

The speed of the wheel travel was obtained by computing a moving linear fit of the data. Figure 21 presents an example of speed computation at the midpoint of the traversal. In this case, the slope was computed using five data points around the midpoint of the track. Table 7 presents the results for all the machines evaluated. It can be observed that the maximum speed for the machines evaluated was 0.305 m/s (1 ft/s). The current specification in AASHTO T 324 states that the maximum speed be "approximately 1 ft/s" and that it be reached at the midpoint of the specimen. The locations of the maximum speeds were close to the midpoint of the specimen for the machines from Vendor B, Vendor C, and Vendor D while for the machine from Vendor A, it was obtained at a distance of 13.5 mm (0.53 in) on average from the midpoint of the track. These results are in conformance with the theoretical computations for the sinusoidal (maximum occurs at midpoint) and non-sinusoidal configurations. The theoretical location for the maximum velocity for the non-sinusoidal geometry used by Vendor A is 15.5 mm (0.61 in) from the midpoint of the track. This is due to the property of the slider-crank mechanism used by Vendor A, where the maximum velocity occurs when the coupling link is tangential to the crank circle. The numerical analysis involved solving for the derivative of the velocity equation and equating it to zero as presented in Appendix C.

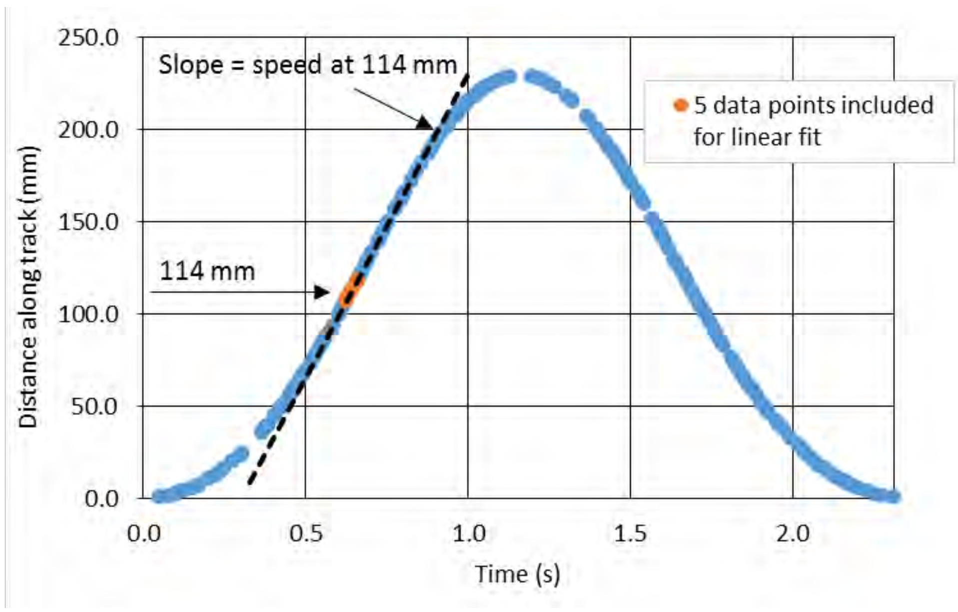


Figure 21
Speed computation at center of track

4.4. Experiment I – Wheel Dimensions

Results of the measurements for vendors are shown in Table 8. It is noted that the research team had access to three machines of Vendor A (referred to A-1, A-2, and A-3), which the first two are standard model machines and the last one is the economy model machine. Therefore, the same testing protocol was applied to the three machines to assess whether consistent measurements are obtained for different equipment from the same vendor. As shown in this table, some of the wheels' diameters were slightly below the specified diameter (203.2 mm) in AASHTO T 324 because of normal wear. The width (47.0 mm) was also slightly greater than the specified width in AASHTO T 324 due to normal wear, as the wheel tends to bulge with time.

Table 8. Wheel dimensions measured from different manufacturers

	Vendor A-1		Vendor A-2		Vendor A-3		Vendor B		Vendor C		Vendor D	
	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel
Diameter (mm)	203.2	203.1	203.1	203.1	203.1	203.2	203.3	203.3	202.9	202.9	203.6	203.0
	203.2	203.2	203.2	203.2	203.2	203.2	203.4	203.3	203.0	203.0	203.6	203.0
	203.1	203.2	203.2	203.1	203.1	203.2	203.3	203.2	203.0	203.0	203.0	203.9
	203.1	203.1	203.1	203.1	203.2	203.2	203.2	203.2	202.9	203.0	203.0	203.9
Width (mm)	47.4	47.5	47.5	47.6	47.1	47.5	47.7	47.7	47.0	47.0	46.4	46.9
	47.6	47.6	47.6	47.5	47.2	47.3	47.8	47.8	47.0	47.0	46.8	46.9
	47.5	47.5	47.5	47.6	47.1	47.2	47.7	47.7	47.0	47.0	46.9	46.9
	47.6	47.6	47.4	47.5	47.1	47.1	47.7	47.7	47.0	47.0	46.3	46.6
Diameter Avg. (mm)	203.1	203.1	203.1	203.1	203.1	203.2	203.3	203.3	203.0	203.0	203.3	203.5
Width Avg. (mm)	47.5	47.5	47.5	47.6	47.2	47.3	47.7	47.7	47.0	47.0	46.6	46.8

It is noted that AASHTO T 324 does not currently set a tolerance for the wheel dimensions and only specifies the averages. This may need to be revised, as the user has currently no indication on how much the wheel dimensions can deviate from the specified values. Figure 22 and Figure 23 present the average measurements (diameter and width) as well as their deviations from the specified values in AASHTO T 324.

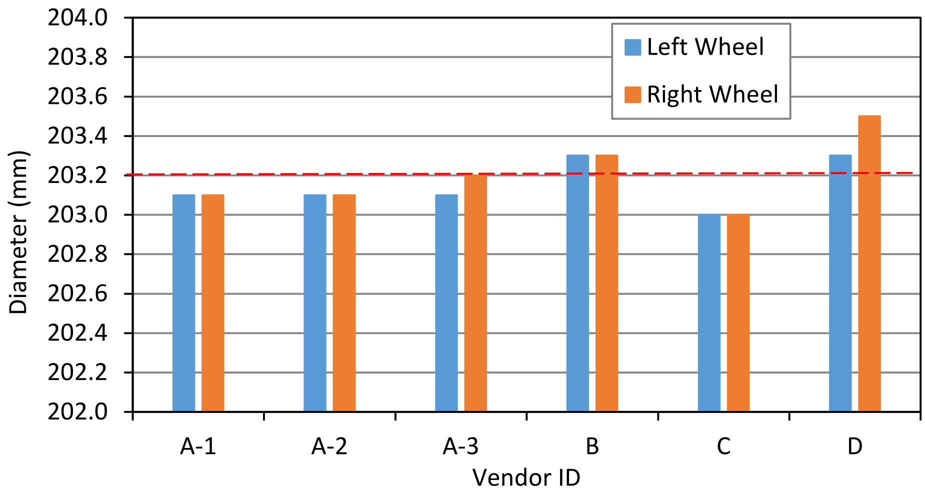


Figure 22
Wheel diameters for the different manufacturers

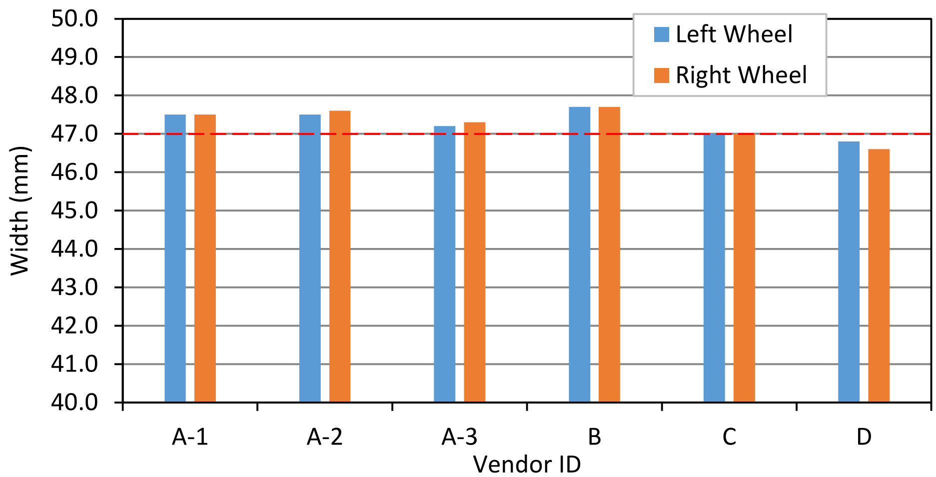


Figure 23
Wheel width for the different manufacturers

4.5. Experiment II – Wheel Loads

The results of the measurement of load wheel are shown in the Figure 24. Both left and right wheel load were measured. As shown in Figure 24, except for the Vendor B right wheel, all the test wheel loads were within the 703 ± 4.5 N (158 ± 1 lbs.) as required by AASHTO T 324. It is noted that all vendors use pound as the unit when calibrating the wheel loads. In this case, Vendor B right wheel load was 157 lbs., which is within the load requirement.

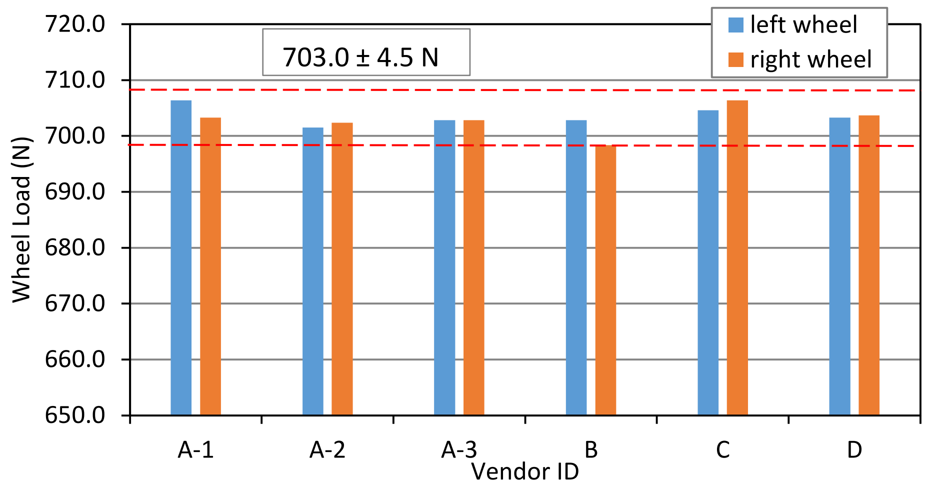


Figure 24
Wheel loads for the different manufacturers

4.6. Experiment III – Free Circulating Water on Mounting System

AASHTO T-324 specifies that the mounting system needs to provide at least 20 mm (0.8 in.) of free circulating water on all sides. The measurements of each vendor's free water length are presented in Table 9. As shown in this table, a number of machines did not meet the requirements set forth by AASHTO T-324 and requires modifications. It is also noted that Machine A-3 was a different model than Machines A-1 and A-2.

Table 9. Free circulating water depth

	Vendor A-1	Vendor A-2	Vendor A-3	Vendor B	Vendor C	Vendor D
Top (mm)	38.1	22.3	34.9	17.5	27.3	20.6
Bottom(mm)	108.0	108.0	98.4	22.2	88.6	90.5
Left(mm)	44.5	47.6	6.4	73.0	71.2	71,4
Right(mm)	227.0	227.0	0.0	0.0	108.0	69.9
Front (mm)	257.2	266.7	217.2	98.4	70.62	196.9
Back(mm)	231.8	231.8	101.6	152.4	179.8	82.6

4.7. Experiment IV – Temperature Measurement and Control System

The goals of this experiment were twofold: (1) to determine if the currently specified preconditioning duration was sufficient and (2) to determine the temperature uniformity in the bath. To accomplish this, instrumented hot-mix-asphalt cylindrical specimens were used, with embedded Resistance Temperature Detector (RTD) sensors. The locations of the sensors and the labelling convention are presented in Appendix D. Eight RTDs were used, two in each cylindrical specimen. Details of the specimen preparation and instrumentation are also presented in Appendix D.

The temperature evaluations were initially conducted at 50°C (122 °F), the temperature used by the majority of users of this equipment. Later, at the request of the panel, 25°C (77 °F) and 70°C (158 °F) (the extremes in the current specification) were added to the evaluation.

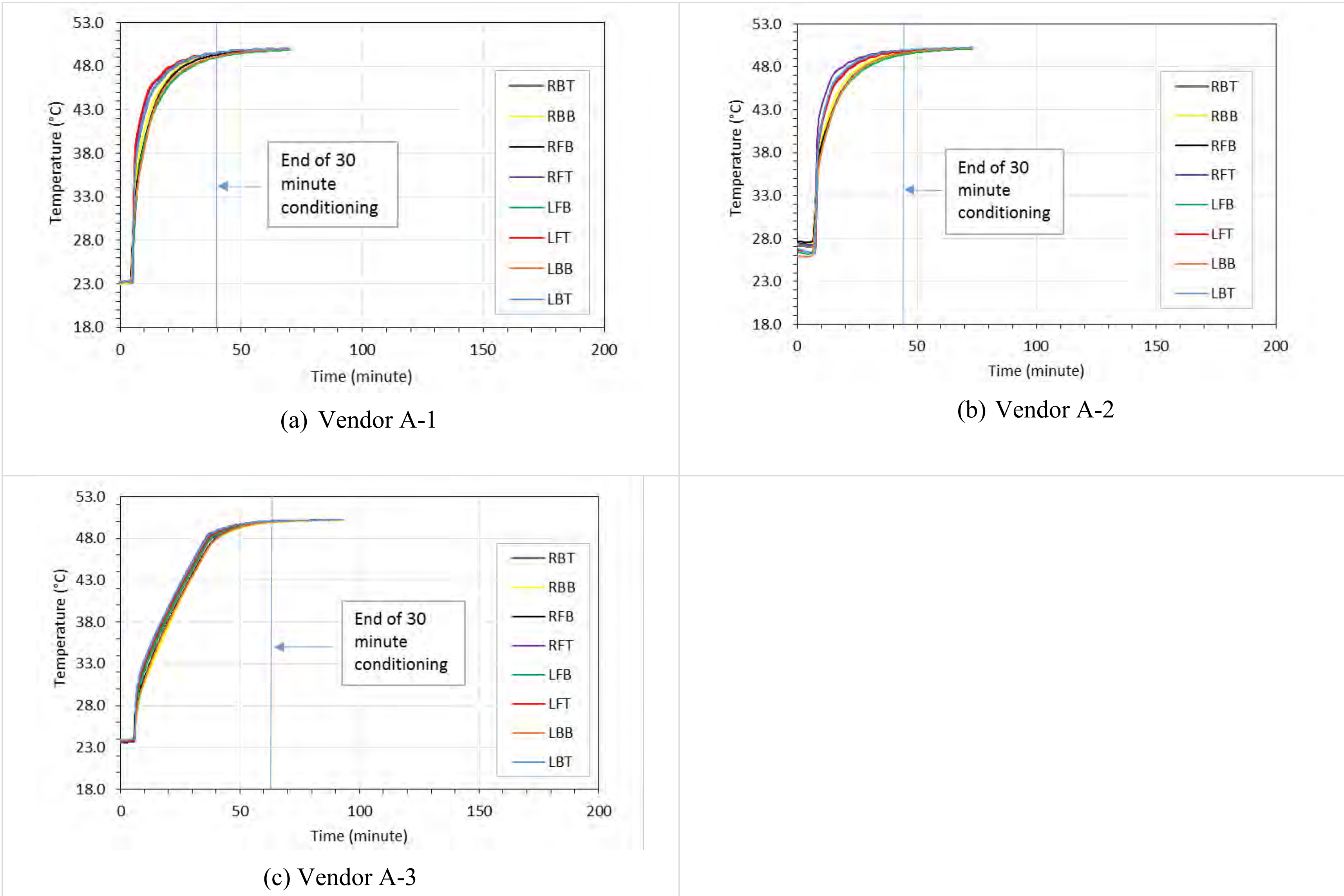
4.7.1 Evaluation at 50 ℃

Figure 25 and Figure 26 present the data collected from the embedded temperature sensors for the machines evaluated. Results are shown for two standard model and the economy model machine from Vendor A. Table 10 presents the details of the temperature experiment at 50°C. In this experiment, the data collection system was turned on prior to immersing the specimen in the water bath (time = 0). The conditioning period time started once the water in the temperature bath has attained the target test temperature, which is 50°C in this case (Time for the water bath to reach 50°C shown in Table 10). If the temperature of the incoming water is cooler than the setpoint, the machine heater(s) heat the water up to target temperature, during which time the specimens are also heating up, albeit with a slight delay.

The temperatures at the end of 30 and 60 minutes of conditioning are shown in Figure 27 and Figure 28. The average temperature after 30 min of conditioning is presented in Table 10. As shown in Table 10, the average temperatures at the end of 30 minutes of conditioning were within the specification limit of 50 ± 1°C, even though some of the readings (one sensor for vendor A and four for vendor D’s machine) were slightly below the 49°C limit. At the end of 60 minutes of conditioning, all sensors were within the tolerance limits.

Table 10. Details of the temperature experiment at 50°C

Vendor	**Start time of experiment (min)**	**Time for the water bath to reach 50°C (min)**	**Time at the end of the 30 min conditioning (min)**	**Average temperature after 30 min of conditioning (°C)**
A-1	5	10	40	49.3
A-2	7	13	43	49.7
A-3	5	33	63	50.0
B	10	70	100	49.3
C	0	119	149	49.8
D	1	7	37	49.1



(a) Vendor A-1

(b) Vendor A-2

(c) Vendor A-3

Figure 25
Temperature versus time graphs at 50°C (machines from Vendor A)

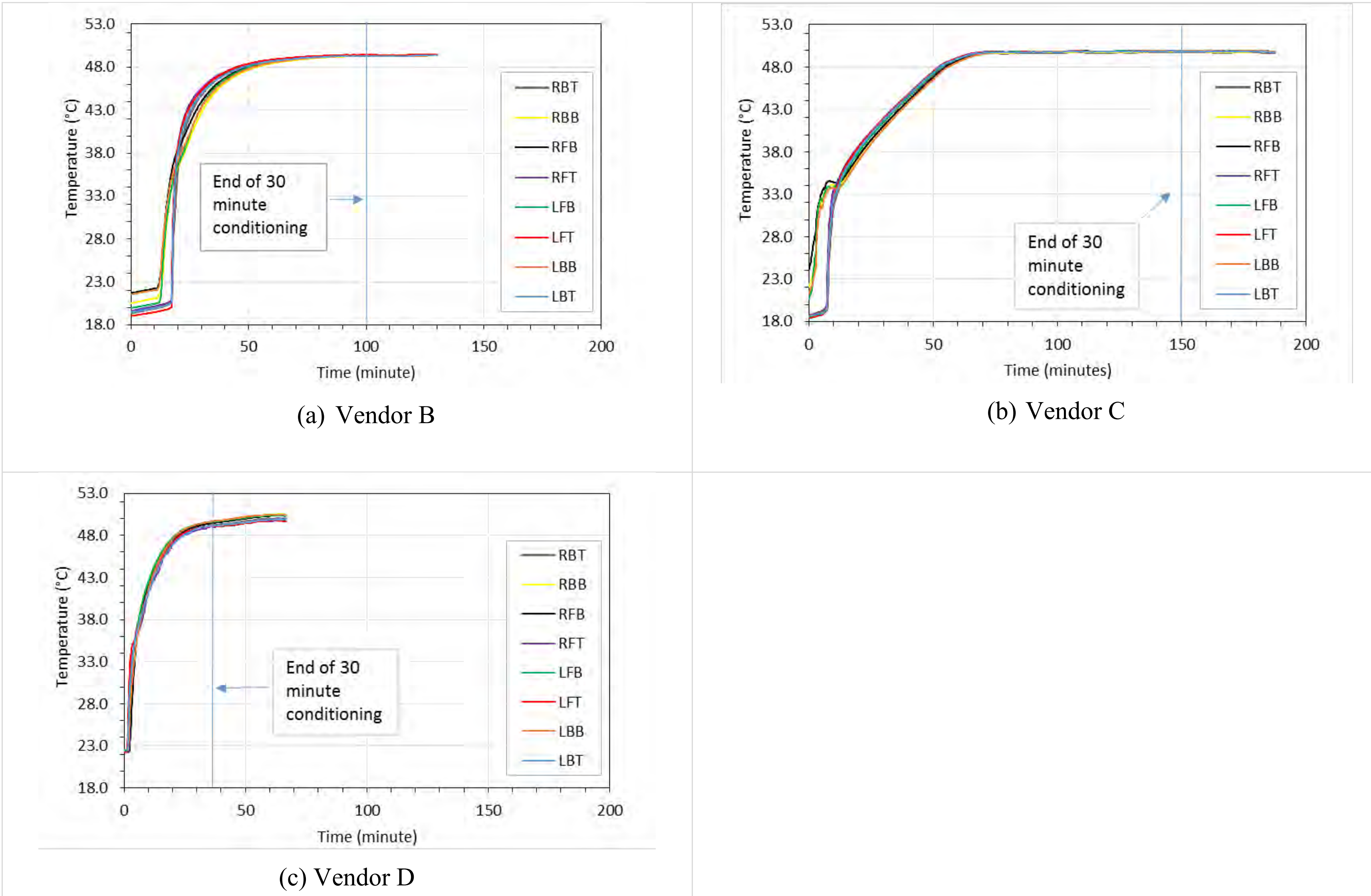


Figure 26
Temperature versus time graphs at 50°C (Vendors B, C, and D)

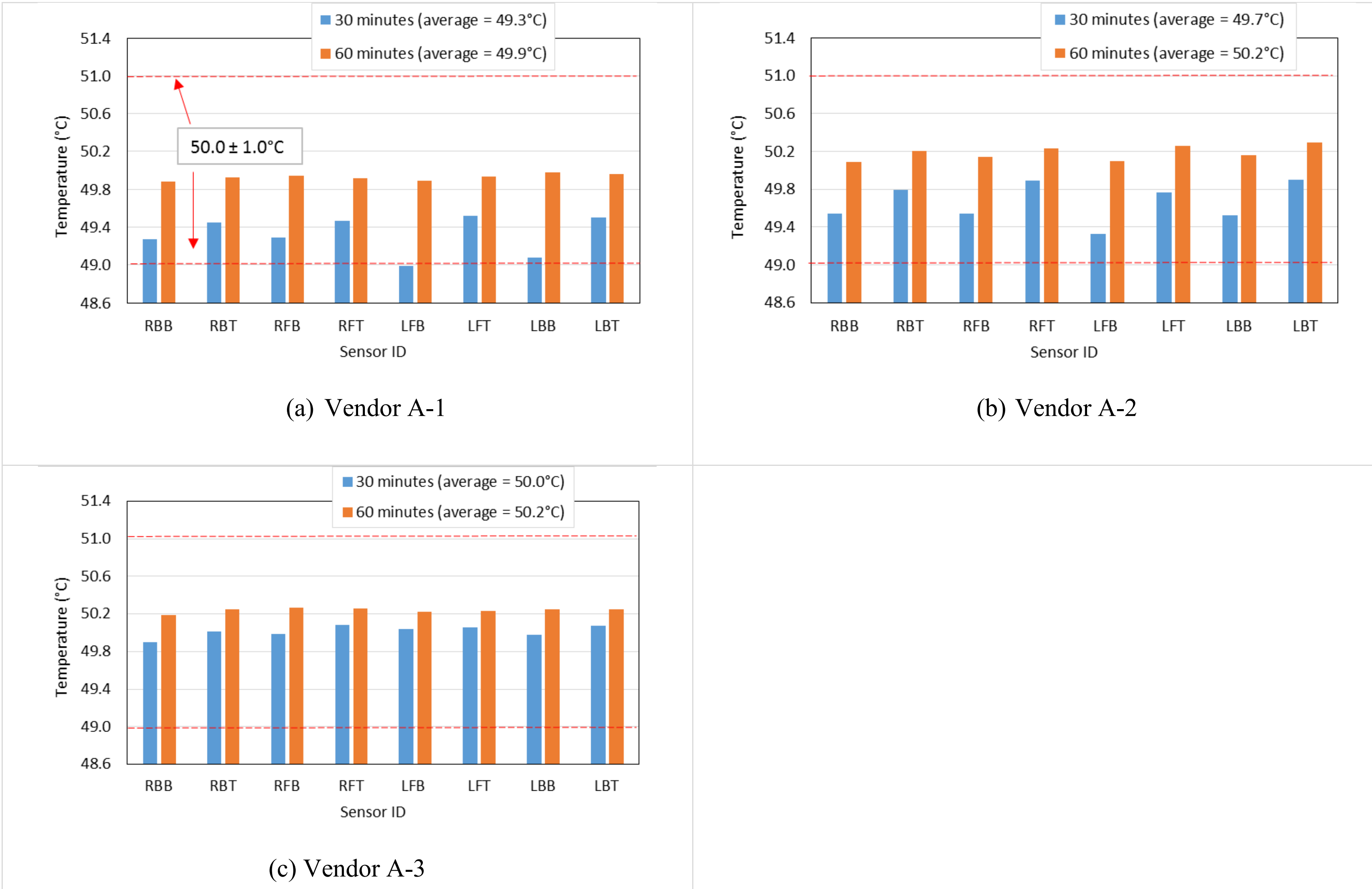


Figure 27
Temperatures after 30 and 60 minutes of conditioning, 50°C (Vendor A)

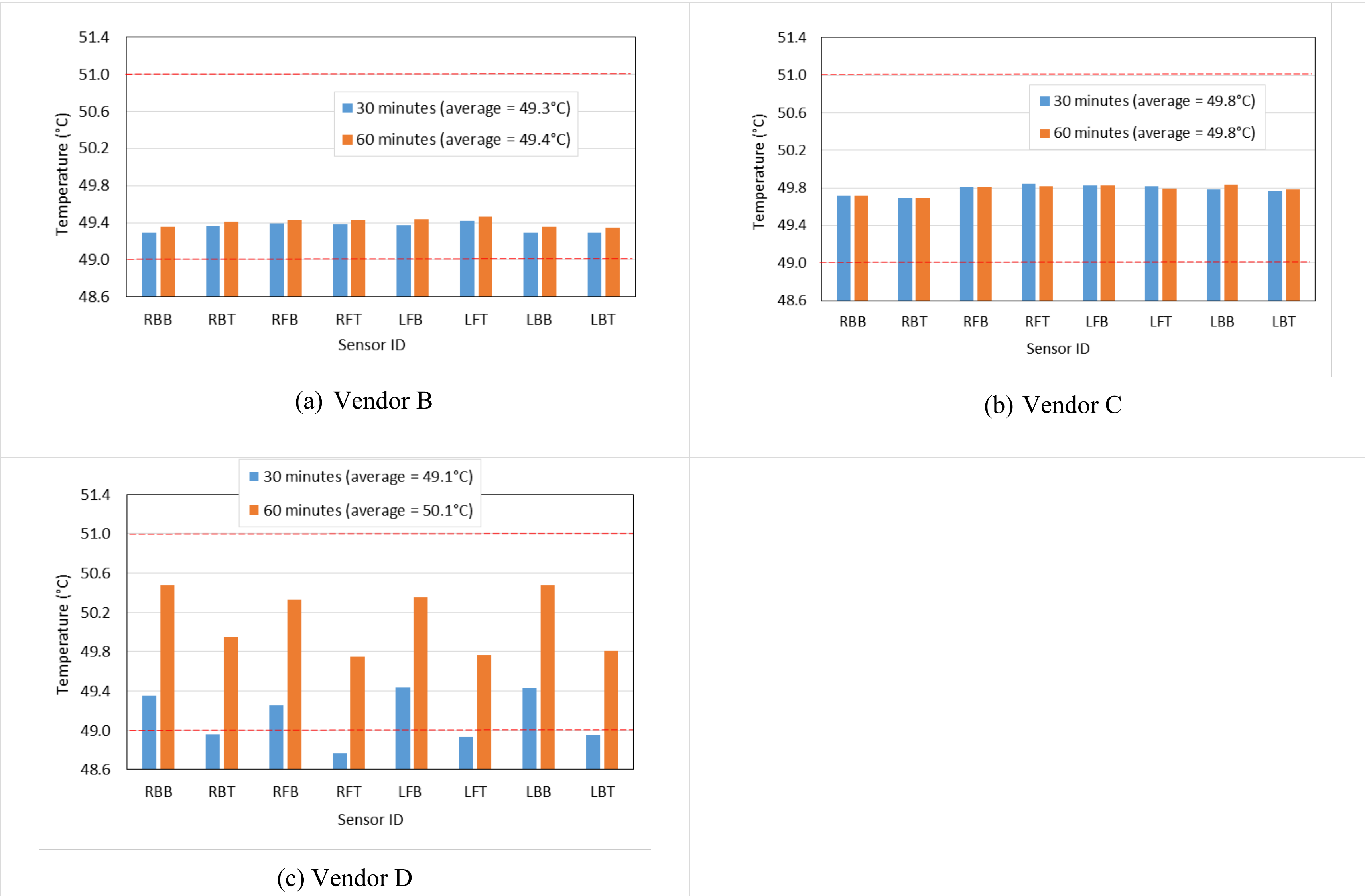
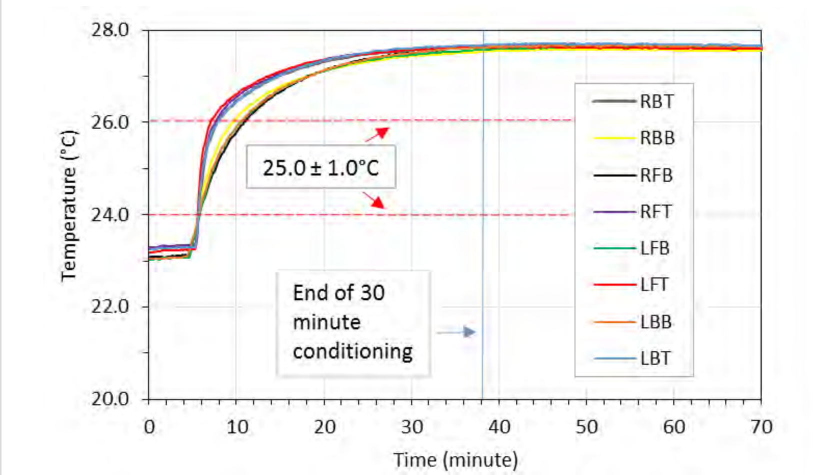


Figure 28
Temperatures after 30 and 60 minutes of conditioning, 50°C (Vendors B, C, and D)

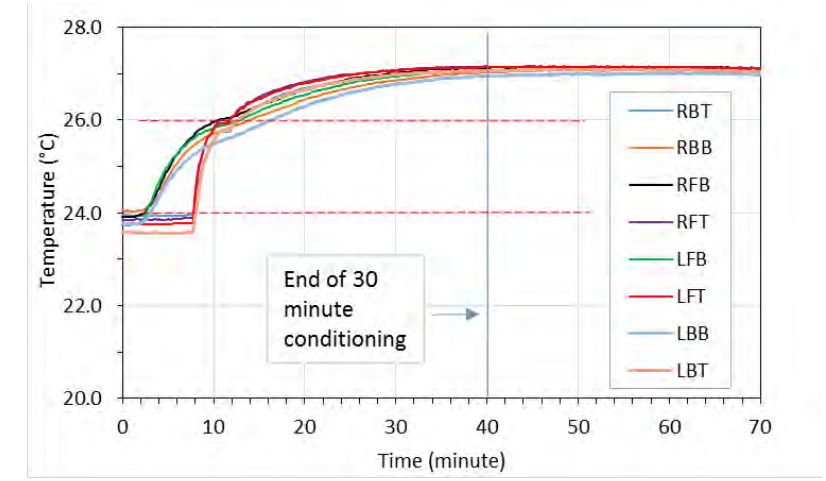
4.7.2 Evaluation at 25°C

Figure 29 presents the results of the temperature evaluation at 25°C. The data acquisition was turned on prior to filling the bath of the HWTs. The hot water inlets were turned off and only water from the cold-water faucets was allowed to fill the bath. In the case of machines from Vendors A and B, the incoming water temperature was 28.3°C. Even after several hours, the ambient air temperature of the laboratory/trailer was not sufficient to cool the water to 25 ± 1°C. For machines from Vendors C and D, the incoming water temperatures were 20 and 24°C, respectively. Therefore, obtaining 25°C in the bath is highly dependent on the incoming water temperature. The machines from Vendors A and B were located in Louisiana, where summertime cold-water temperatures frequently exceed 26°C.

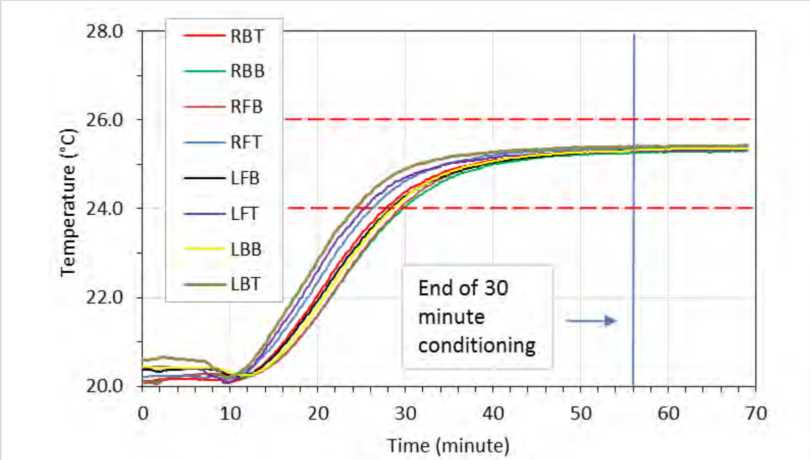
Figure 30 presents snapshots of the temperatures after a conditioning interval of 30 minutes. The machines from Vendors A and B were not able to attain the set target temperature of 25°C due to high incoming water temperature, while machines from Vendors C and D reached their target test temperature after 30 minutes. It should be noted that the HWTs from Vendors A, B, and C do not include a cooling system whereas Vendor D does include a cooling system. However, the cooling system was not functional at the time of the temperature experiment.



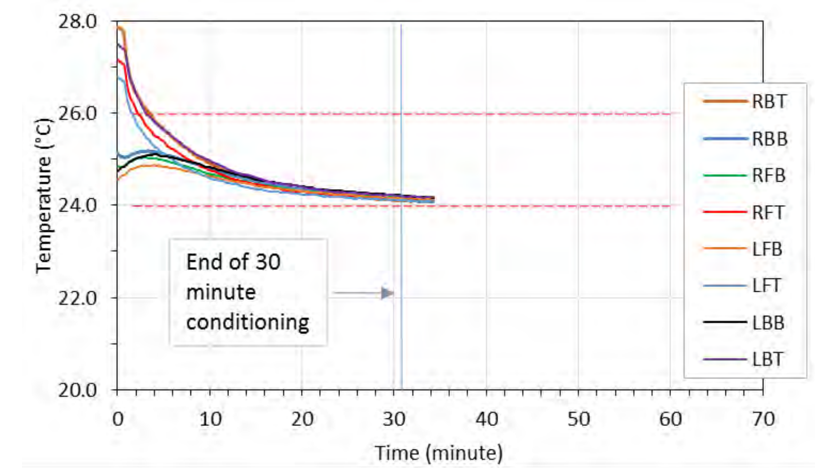
(a) Vendor A



(b) Vendor B

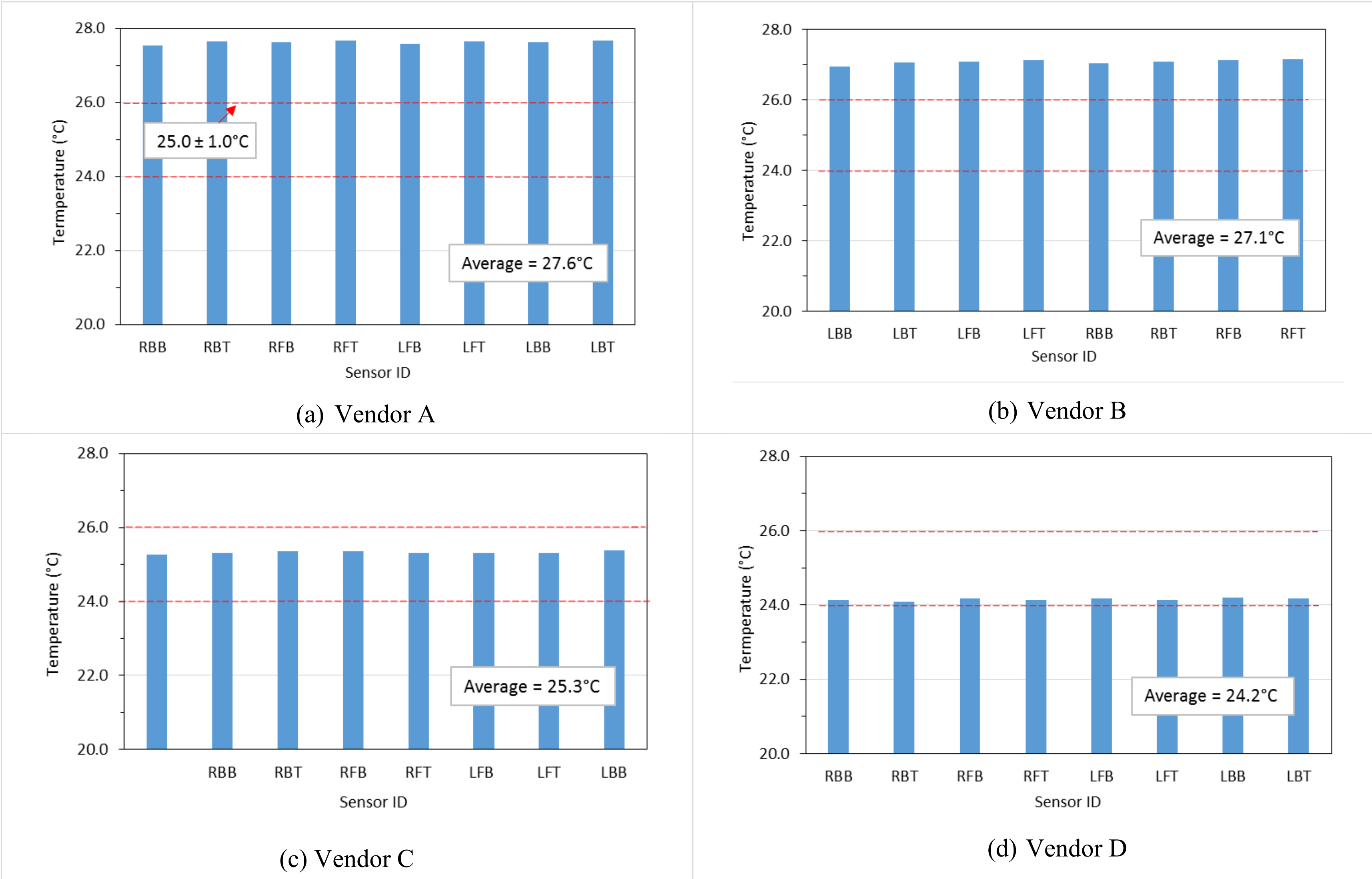


(c) Vendor C



(d) Vendor D

Figure 29
Temperature versus time graphs for various vendors (25°C)



(a) Vendor A

(b) Vendor B

(c) Vendor C

(d) Vendor D

Figure 30
Temperatures after 30 minutes of conditioning (25°C)

4.7.3 *Evaluation at 70°C*

Figure 31presents the data gathered from the sensors in the HMA specimens after they were placed in HWT baths. The data collection system was switched on prior to immersing the specimens in the bath. In the case of machines from Vendors A and C, the time required for the bath to heat up to 70°C depended on the temperature of the incoming hot water. The incoming water temperatures were 52.4°C and 50.0°C for the machines from Vendors A and C, respectively. As the water is heated up to test temperature, the specimens also heat up, with a minor delay.

The machine from Vendor B incorporates two tanks, a lower conditioning tank and an upper testing tank. The water is heated up to test temperature in the lower tank and is circulated into the upper tank at the beginning of the test.

Figure 32 shows the specimen temperatures after 30 and 60 minutes of conditioning. At the end of 30 minutes, the average temperatures were 69.1°C, 68.4°C, 69.2°C, and 69.7°C for the machines from Vendors A, B, C, and D, respectively. Two of the sensors showed temperatures less than 69°C for Vendors A and D, while all the sensors for Vendor B were below the lower temperature limit of 69°C. It should be noted that all except one sensor were within the allowable tolerance of 70 ± 1°C at the end of 60 minutes of conditioning. In an effort to increase the water movement in the machine from Vendor D, a small water circulator was added in the water bath after the 60 minutes conditioning. The results, presented in Figure 33, show that all the readings were within the 70±1°C specification after the addition of the circulator.

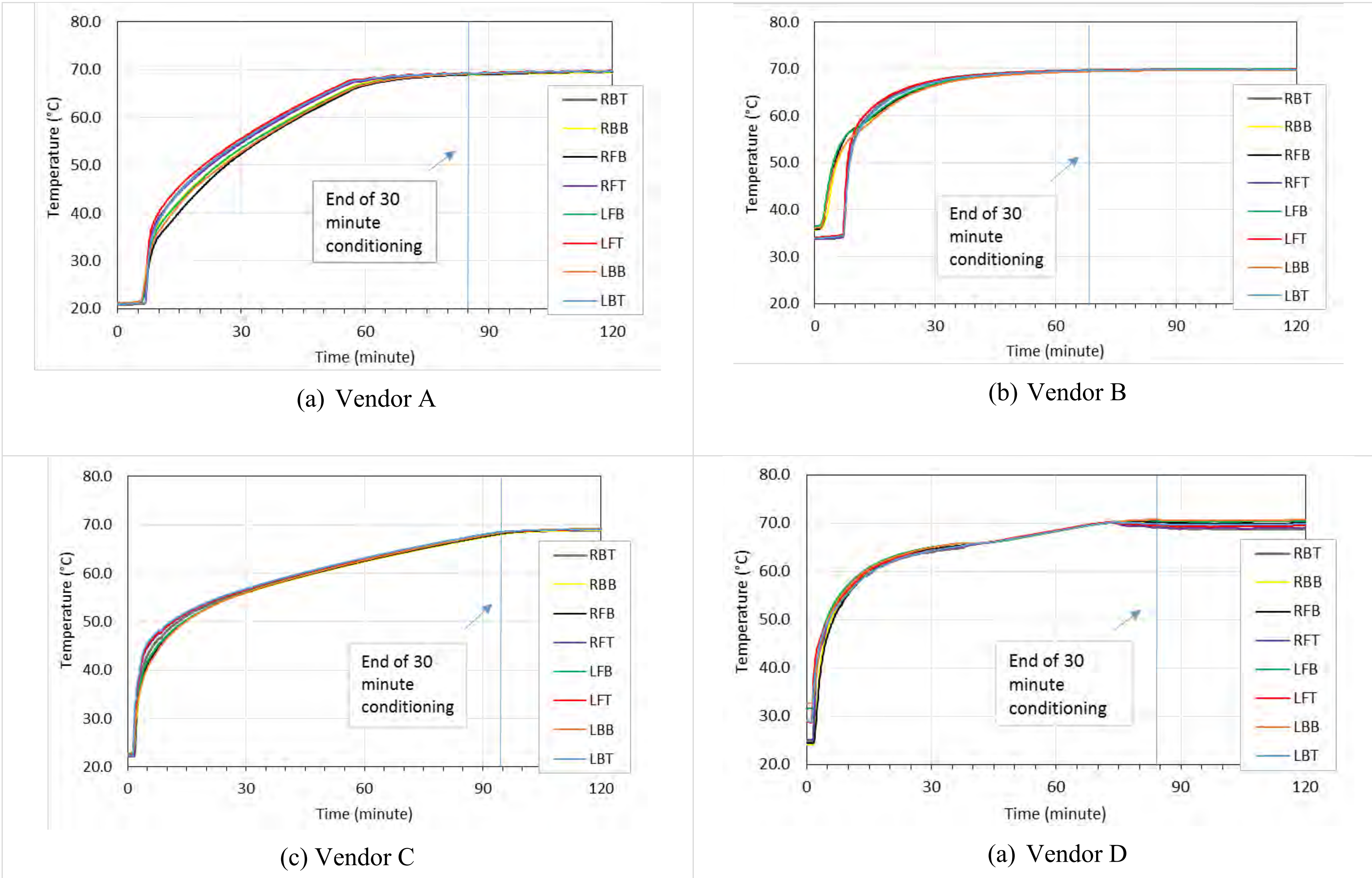


Figure 31
Time versus temperature graphs at 70°C

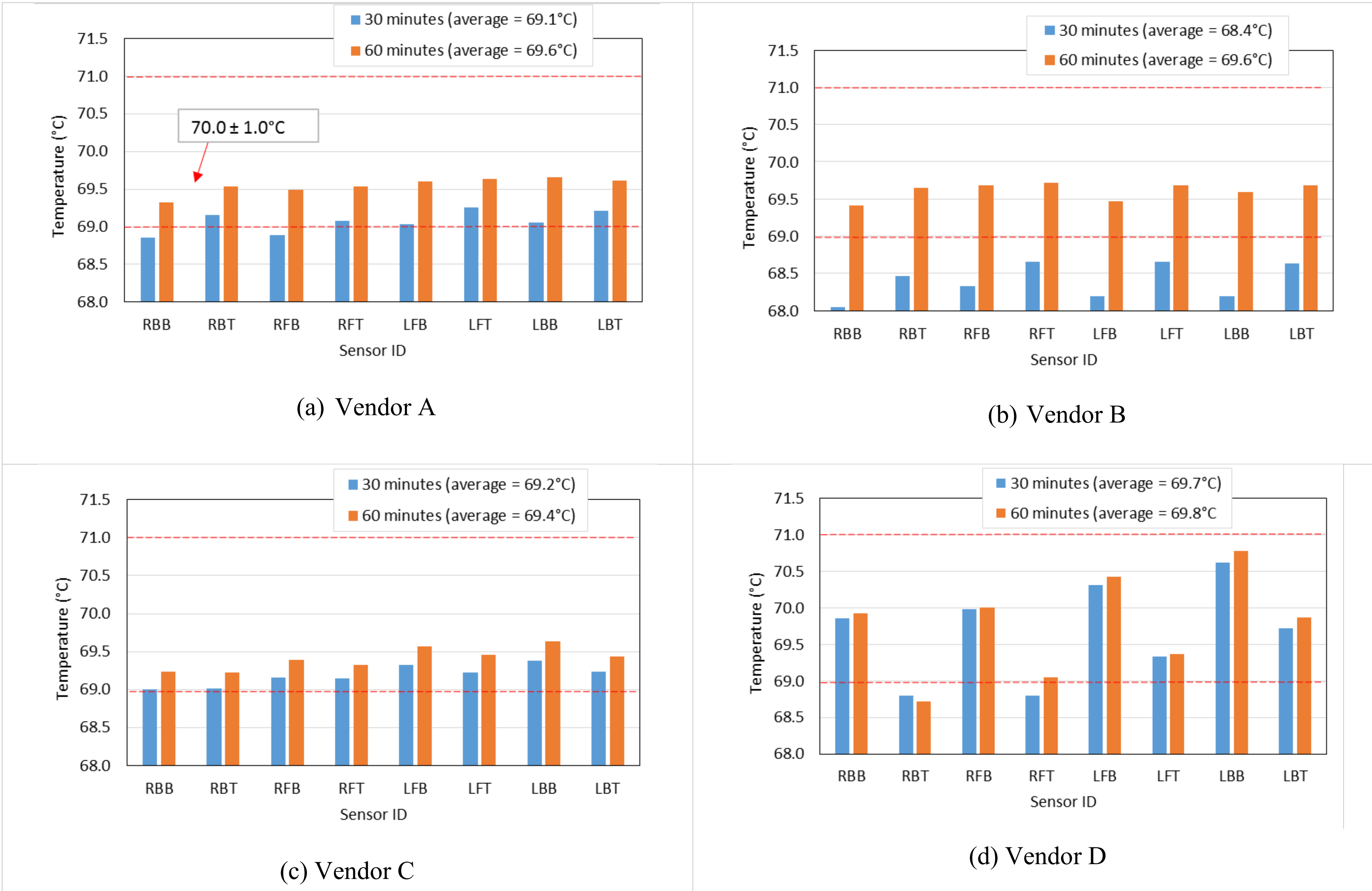


Figure 32
Temperatures after 30 and 60 minutes of conditioning, 70°C

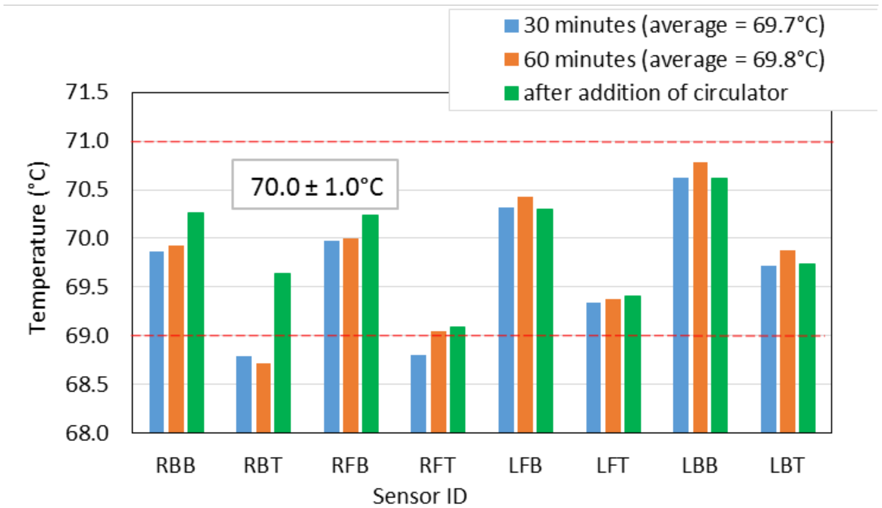


Figure 33
Temperatures at 30 and 60 minutes and after the addition of a water circulator (Vendor D)

4.8. Experiment V – Impression Measurement System

An aluminum specimen with a curvature mimicking a rutted specimen was designed and fabricated to enable verification that the impression readings were being recorded at the locations specified by the vendors. Two metal specimens were fabricated during the course of this study. The first one was used only in the first quarter of the study. The second metal specimen had a longer curved track length to avoid the problem of the wheel "climbing out" of the track. All results presented herein were obtained with the second specimen. The machine drawing of this metal specimen and the analytical solution of the wheel and metal-specimen interaction are presented in Appendix C. Figure 34 presents a picture of this curved specimen. Since the curvature or "rut" of this specimen is machined per the drawing in the appendix, the depression at any location along the track is precisely known. The maximum depression of the manufactured specimen is 19.05 mm (0.75 in.) and is located at the midpoint of the track. The aluminum specimen allows for verification of LVDT readings and confirms if the readings are being recorded at the locations specified by the vendors.

Figure 34
Metal specimen for verifying locations of deformation readings

4.8.1 Test Results

The fabricated metal specimen was used to obtain rut measurements from the HWT machines. The data obtained from the HWT machines were compared to the reference rut profile of the metal specimen. Figure 35 presents the results of the experiment for HWT machines from Vendor A. As can be seen, there are significant deviations from the reference profile, with a marked skew to the right. These results suggest that the deformation readings from the LVDT are not being recorded at the pre-determined locations along the track. The locations of these readings as specified by the manufacturer are -114, -91, -69, -46, -23, 0, +23, +46, +69, +91, and +114 mm with 0 being the midpoint of the track (a total of 11 readings, 22.9 mm (0.9-in.) spacing between readings).

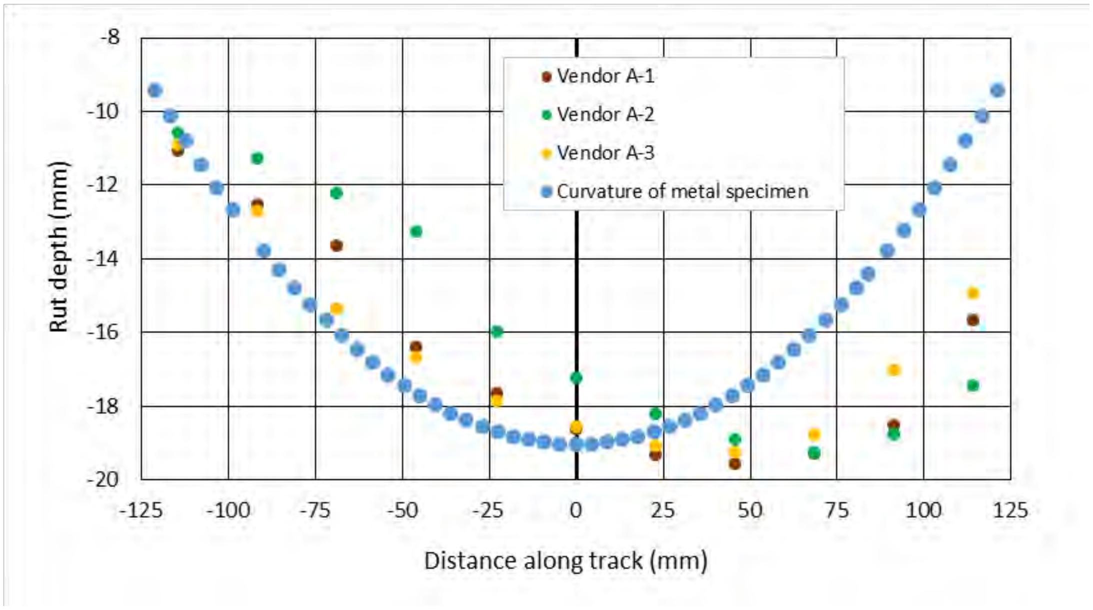


Figure 35
Impression measurement system results from HWT machine (Vendor A)

Figure 36 presents the results for the HWT machine from Vendor B. The vendor-specified locations of the readings are -97, -32, 0, +32, and +99 mm, with zero being the midpoint of the track. The results show a reasonably good agreement with the expected rut depths.

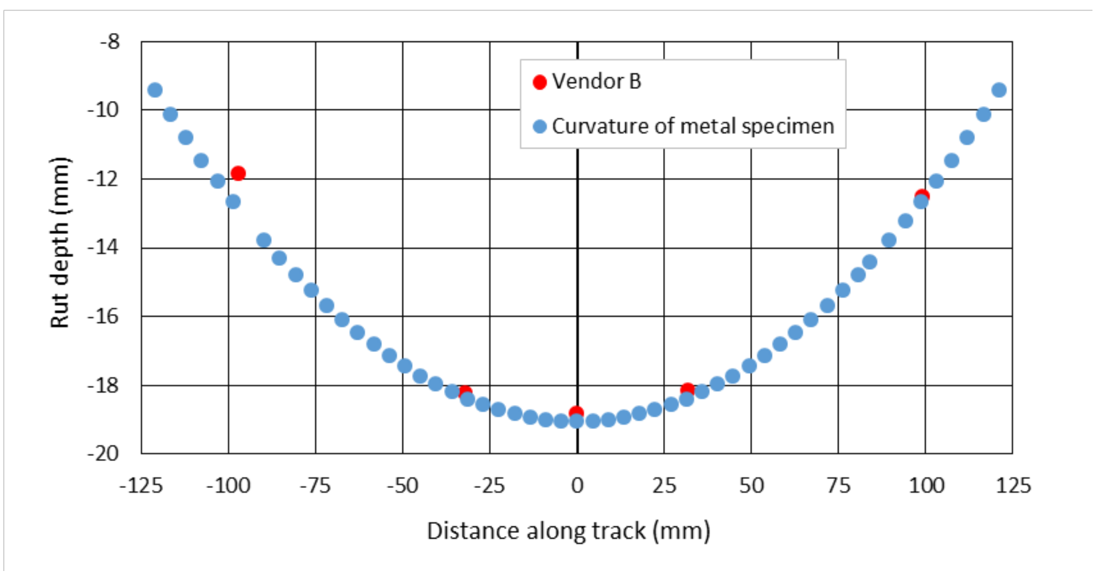


Figure 36
Impression measurement system results from HWT machine (Vendor B)

Figure 37 shows the results of the evaluation for the machine from vendor C. This machine records data at 23 equally-spaced locations across the track (-110, -100, -90, -80, -70, -60, -50, -40, -30, -20, -10, 0, +10, +20, +30, +40, +50, +60, +70, +80, +90, +100, and +110 mm). The data shows good agreement with the metal-profile in the region from -80 to +80 mm. Outside of this region; the readings seem to deviate slightly from the expected rut-depths.

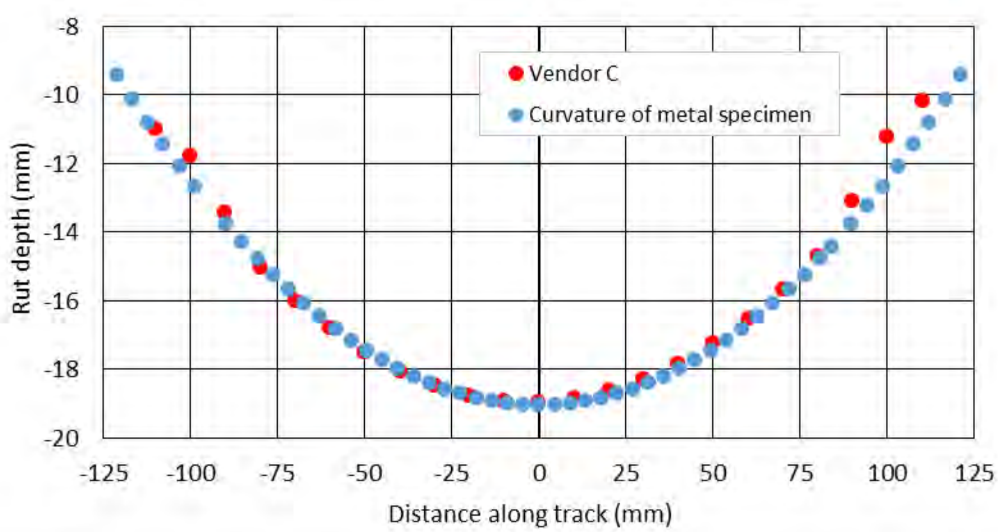


Figure 37
Impression measurement system results from HWT machine (Vendor C)

Figure 38 shows the results of the evaluation for the machine from vendor D. For this machine, the readings were spaced 1 mm apart and were taken from -113 to +113 mm along the track, resulting in 227 readings. The readings are very close to the expected metal-profile, with a slight deviation towards the right end of the graph. It is possible that the metal specimen was not completely level with respect to the deformation measuring system.

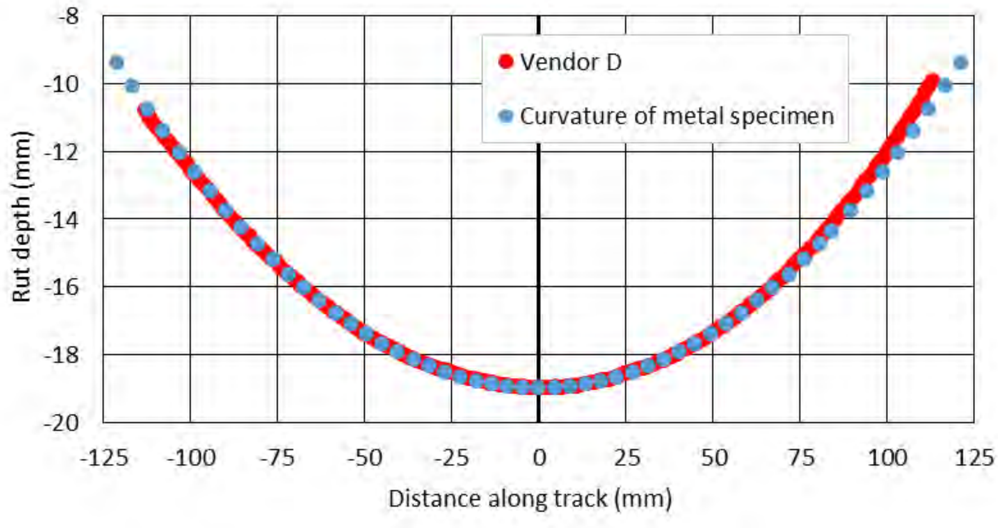


Figure 38
Impression measurement system results of HWT machine (Vendor D)

In an effort to quantify the deviations of the readings from the metal profile, the root mean square error (RMSE) was computed for measurements from each machine. Table 11 shows the RMSE values for each of the four vendors. In line with the visual observations, the RMSE values for Vendors B, C, and D, were lower compared to that for Vendor A, with the lowest value obtained for Vendor D's machine.

Table 11. RMSE values for impression measurements of metal profile

Vendor	RMSE (in.)	AMD (in.)
A-1	0.10	0.08
A-2	0.14	0.12
A-3	0.08	0.06
B	0.02	0.01
C	0.02	0.01
D	0.01	0.00

4.9. Data Collection and Reporting

AASHTO T 324 requires the following five parameters to be collected and reported to quantify the performance of a mix to rutting and moisture susceptibility (stripping):

1. ***Number of Passes at Maximum Impression*:** At a fixed maximum impression value (e.g., 12.5mm), an asphalt mixture with a larger number of passes is more resistant to rutting *(13).*
2. ***Maximum Impression*:** The maximum impression obtained at the completion of the test is reported to quantify the rutting resistance.
3. ***Creep Slope*:** The creep slope is the inverse of the deformation rate in the creep phase. The creep phase starts after the consolidation phase and ends before the stripping starts. In this phase, the rut depth starts to increase steadily due to viscous flow. A mixture with a larger creep slope value is more sensitive to rutting *(14).*
4. ***Strip Slope*:** The strip slope is the inverse of the deformation rate at where the rut depth increases tremendously as moisture damage occurs. A mixture with a larger strip slope value is more sensitive to moisture damage. Furthermore, the ratio of the creep slope to the strip slope has been used to quantify moisture sensitivity in some states *(15, 16).*
5. ***Stripping Inflection Point (SIP)*:** The stripping inflection point is usually reported in wheel passes. This point occurs where the curve has a sudden increase in rut depth and reflects the phase where the asphalt binder starts to strip from the aggregate. Graphically, the SIP is the intersection of the creep slope and the strip slope *(17, 18).*

Upon review of the current requirements detailed in AASHTO T 324, one may note that not enough specifics are provided to allow for consistent analysis and reporting of the five aforementioned performance indicators. For example, AASHTO T 324 does not define how to find the "steady-state portion" to plot the creep slope. At least seven computer programs, developed by four manufacturers and two state DOTs, were identified for analyzing HWT test data and reporting the necessary parameters. The methods are briefly discussed below:

- In vendor A's software, the user specifies the locations of the creep and strip regions. In this approach, the user chooses the "start" and "end" pass numbers for the creep and strip regions and the software draws straight lines using these points to obtain the creep and strip lines.
- For vendor B, the user specifies a "criterion of change" defined as a given amount of change over a certain number of passes, e.g., 1 mm over 1,000 passes. The program then computes the stripping inflection point and subsequently draws the creep and strip lines.
- Vendor C's program truncates the data to 15 mm rut depth and fits a fourth-degree polynomial through the rut data. The location of the minimum of the first derivative of the curve-fit is then determined. A tangential line is drawn at this location to obtain the creep slope. The maximum value of the first derivative between this point and the end of the data is used to obtain the strip slope.
- Vendor D's analysis program involves finding the minimum error from a fitting line. At the request of Vendor D, details of the approach are not to be presented. However, the results obtained from this approach will be presented in the next section.

In addition to the HWT manufacturers, several state DOTs and research institute are developing their own analysis programs to process the data. Iowa DOT has developed a method to determine the SIP, the details of which are published in Iowa DOT specification "*Moisture Sensitivity Testing of Asphalt Mixture*" *(2).* Oklahoma DOT uses a modification of the Iowa DOT test method *(7).* Texas DOT has adopted a new method based on research published by Yin et al. *(19)* and uses a program developed by Thunderhead Testing, LLC that implements this approach. These methods are briefly described below:

- Iowa DOT's program uses a 6-degree polynomial to fit the rut data. The minimum of the first derivative of this fitted curve nearest the end of the test is obtained. The tangent line at that point is the strip slope. The creep slope is located by equating the second derivative to zero where prior to the strip pass point. It should be noted that the program calculates the strip slope prior to the creep slope *(2).*
- The procedure used by Oklahoma DOT is similar to Iowa's method. However, a sixth-degree polynomial is used to fit the data. Next, the rut depth at a 1000 passes is determined. The program then adds 1 mm to this rut depth and finds the number of passes where this second rut depth occurs. A line drawn through these two points is defined to be the creep line. To find the strip line, the program determines the minimum value of the first derivative between 1,000 passes and the end of data. The tangent at this point is defined to be the strip line *(7).*
- Texas DOT defines three new parameters in its analysis approach: LC_{SN}, LC_{ST}, and $\Delta\varepsilon_{10,000}^{vp}$. The number of passes at which the second derivative is equal to zero is defined to be LC_{SN}. Then, the rut depth is separated after LC_{SN} to two parts: accumulation of viscoplastic strain from reciprocate load cycles and from stripping. Viscoplastic strain from loading can be predicted using Tseng-Lytton model. As a result, the deformation from stripping is the total rut depth (natural log fitted curve) minus the deformation under loading (Tseng-Lytton model). In this approach, the number of passes needed to reach the predicted stripping strain after LC_{SN} is defined as LC_{ST}. In Texas DOT, the predicted stripping strain is 12.5mm. The third parameter is determined by taking the derivative of the projected viscoplastic strain using the Tseng-Lytton model at 10,000 cycles *(19).* Since the TTI method of analyzing moisture sensitivity is not consistent with the performance parameters defined in AASHTO T 324, the results of this approach are not discussed in this report.

4.9.1 Test Materials

Two mixes, which were tested using the HWT manufactured by Vendor A, were selected for analysis by the various methods. While Vendor A recorded rut data at 11 points across the wheel track, the rut data corresponding to the center reading, or Point Number 6, was used in the analysis and is presented in Figure 39. As shown in Figure 39, two contrasting mixes were selected; a poor performing mix that stripped during testing and a good performing mix that did not strip during testing.

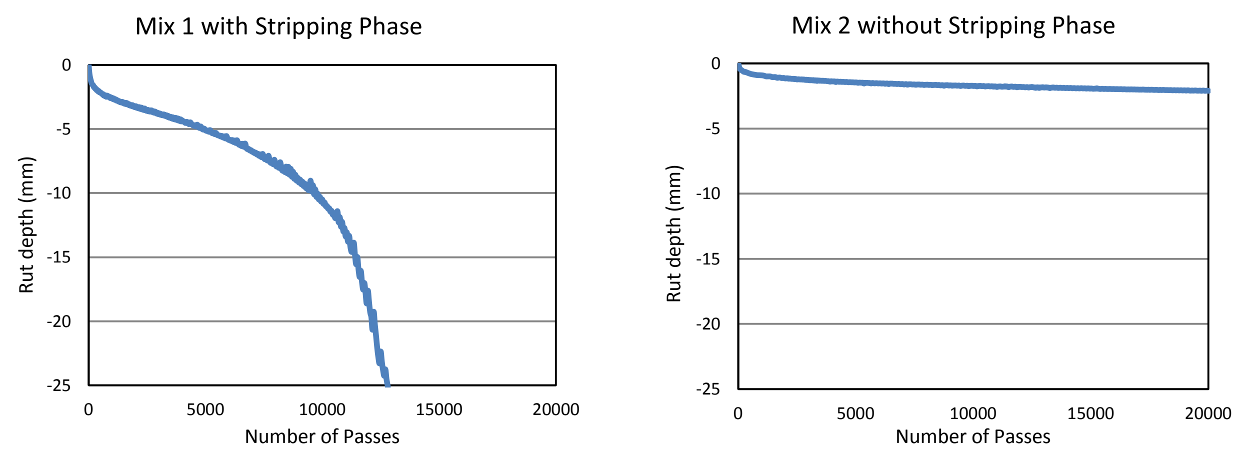


Figure 39
Rut Depth versus Number of Passes for the Selected Mixes

4.9.2 Results and Analysis

Section 9 of AASHTO T 324 requires the following parameters to be reported: the maximum impression, the number of passes at the maximum impression, creep slope, strip slope, and the stripping inflexion point. However, the specification leaves the details of the determination of these parameters up to the vendor/user. The absence of clear definitions for these parameters could lead to widely varying results being reported. The following summarizes the results obtained by processing the selected data sets using the various analysis methods.

The analysis techniques used to obtain SIP location from the HWT data were obtained by requesting details from each of the four vendors. This involved several email communications with each of the vendors to get a better understanding of the algorithms used. In each of these cases, the analysis procedures were independently verified by performing the individual steps of the procedure. The analysis results for Mix 1 are presented in Figure 40.

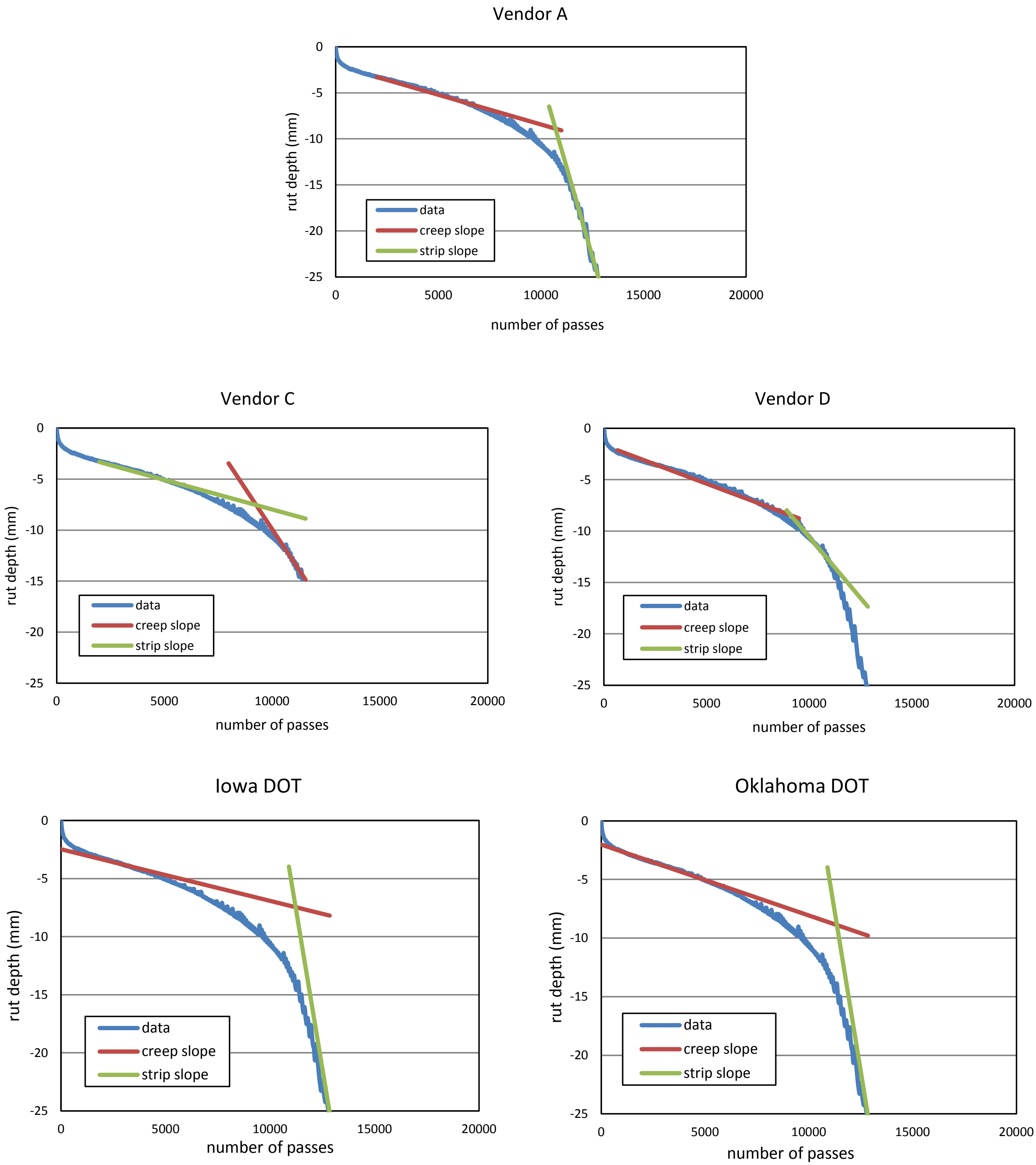
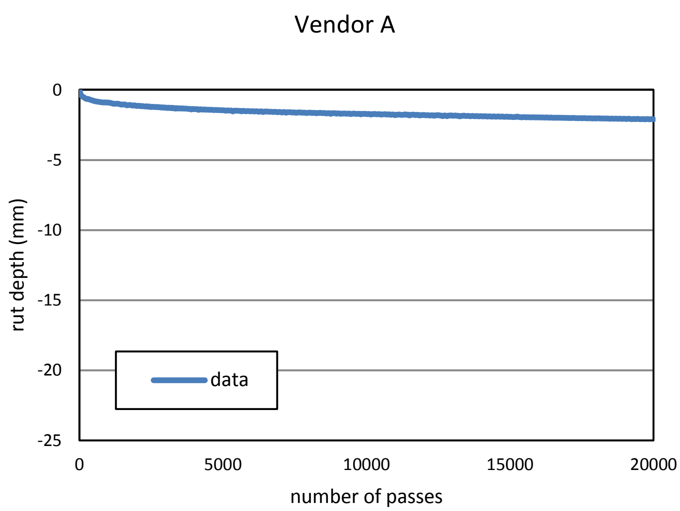


Figure 40
Data Analysis for Mix 1 Based on Different Approaches

As shown in Figure 40, for Vendor A, the creep region ranged from 2,000 to 6,000 passes and the strip region from 11,500 to 12,800 passes. Since these regions are not automatically determined by the program, the results reported could vary by the user. Vendor C's program truncates the data to 15 mm rut depth so the curve is shorter than the rest. Vendor D's program also truncates 50% of data set after the SIP based on the user input. As a result, the SIP location for Vendor D had lower number of passes than the other methods. Iowa DOT and Oklahoma DOT methods are very similar and the methods for obtaining the strip slope are the same.

Results for the non-stripping mix (Mix 2) are presented in Figure 41. Vendor A requires the user to identify the creep and strip region. Because the no-stripping data set has no strip region, the analyze results is not classified here. Vendor C's program locates the SIP at the end of the data set. It should be noted that Vendor D clearly identifies the data set with no stripping, as shown in the graph. In addition, if the ratio of the creep to strip slopes is less than two, the Iowa DOT program concludes that no stripping occurred, as is shown in Figure 41. ODOT method identifies the SIP at the beginning of the data set. It should be noted that the Vendor C and ODOT procedures reported a SIP even though stripping did not occur.



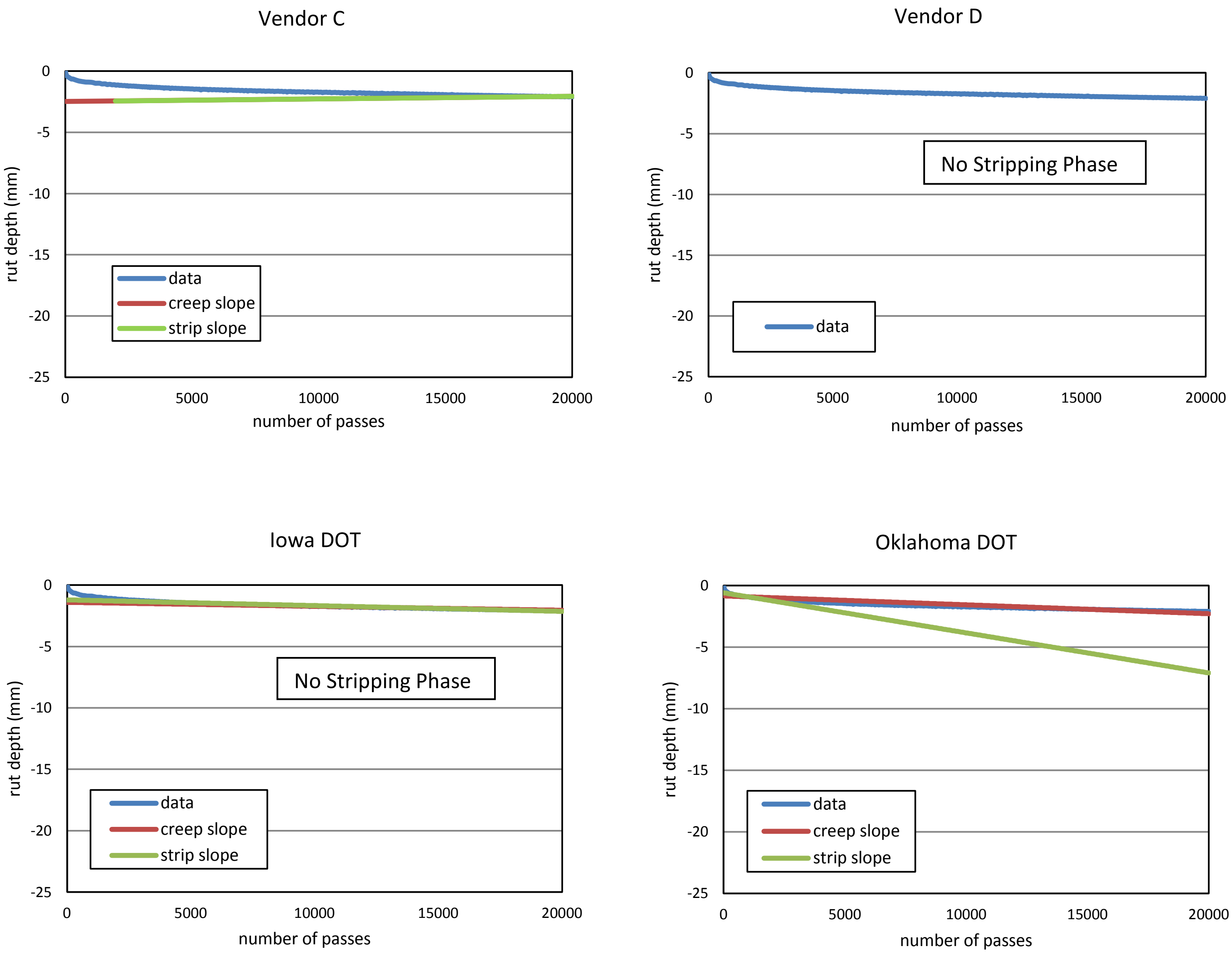


Figure 41
Data Analysis for Mix 2 Based on Different Approaches

Table 12 and Table 13 summarize the stripping and no-stripping data sets results from the different analysis methods. For Mix 1, substantial differences were observed in the reported SIP. Furthermore, a number of methods could not identify a non-stripping mix such as Mix 2. In addition to these discrepancies, the approach adopted by Iowa DOT can only analyze HWT results obtained from the machine manufactured by Vendor A. It is also noted that all programs provide the rut depth at a 5,000 passes interval. However, two approaches, which are Vendor B and Oklahoma DOT, did not report the maximum impression and the number of passes at the maximum impression as required by AASHTO T-324. Furthermore, Iowa program only reports the rut depth as an average of all 11 data points. For the non-stripping mix, because the maximum number of passes was 20,000 passes and all seven programs were able to report the rut depth at every 5,000 passes, number of passes at maximum impression was the same for all seven approaches. AASHTO T 324 also requires reporting the creep slope and the strip slope. The program provided by Vendors A and B do not report the creep and strip slopes. As shown in **Table 13**, only the program provided by Vendor D and the approach adopted by Iowa DOT successfully identified this mix as a non-stripping mix.

Table 12. Summary of Programs Reporting Parameters (Mix 1)

	Number Of Passes at max impression	Max Impression (mm)	Creep Slope (*10^{-4})	Strip Slope (*10^{-4})	SIP
Vendor A	12,800	25	N/A	N/A	10,712
Vendor B	N/A	N/A	N/A	N/A	473
Vendor C	12,800	25	64	34	9,471
Vendor D	12,850	26	8	25	9,104
Iowa DOT	12,806	25	4	53	10,552
Oklahoma DOT	N/A	N/A	6	107	11,295

Table 13. Summary of Programs Reporting Parameters (Mix 2)

	Number Of Passes at max impression	Max Impression (mm)	Creep Slope (*10^{-4})	Strip Slope (*10^{-4})	SIP
Vendor A	20,000	2.1	N/A	N/A	N/A
Vendor B	20,000	2.1	N/A	N/A	-3,211
Vendor C	20,000	2.1	0.07	0.07	19,892
Vendor D	20,000	2.1	No stripping	No stripping	No stripping
Iowa DOT	20,000	1.9	0.3	0.4	No stripping
Oklahoma DOT	20,000	2.1	1	3	180

Table 14 compares the seven approaches in terms of the reporting parameters that are required by AASHTO T 324. As shown in Table 14, Vendor C, Vendor D, and Iowa DOT report all five indices, as required by AASHTO T 324. However, Vendor B and Oklahoma DOT do not report the maximum impression and final passes values. Vendor A and B do not provide the creep and strip slopes.

Table 14. Summary of Seven Programs Reporting Parameters

	Number Of Passes	Max Impression (mm)	Creep Slope	Strip Slope	SIP
Vendor A	Y	Y	N	N	Y
Vendor B	N	N	N	N	Y
Vendor C	Y	Y	Y	Y	Y
Vendor D	Y	Y	Y	Y	Y
Iowa DOT	Y	Y	Y	Y	Y
Oklahoma DOT	N	N	Y	Y	Y

Y: The program provides this parameter
N: the program does not provides this parameter

4.10. Proposed Modifications to AASHTO T324 Specifications

Based on the results of the experimental program, revisions to AASHTO T 324 are proposed to incorporate the equipment capabilities, components, or design features that ensure proper testing and accurate, reproducible results. The key elements of AASHTO T 324 specifications to conduct the Hamburg Wheel Track (HWT) test were identified to be the loading mechanism, temperature measurement and control system, impression measurement system, test specimen size, and data collection and reporting sections. The following issues need to be addressed in the current specification:

- **Section 5.1:** It is proposed to define a tolerance for the wheel dimensions. Based on the results of the experimental program and assuming an acceptable deviation of 1% around the mean value, it is recommended to specify a 203.2 ± 2 mm diameter, 47.0 ± 0.5 mm wide steel wheel. It is noted that wheel dimensions tend to change with wear and deviation from the recommended specifications will necessitate the replacement of the loading wheel.
- **Section 5.1:** AASHTO T 324 specifies that the wheel be required to reciprocate over the specimen such that its position varies sinusoidally over time. Since not all the machines available in the market are able to produce a perfectly sinusoidal wave, a maximum level of deviation from a perfectly sinusoidal wave should be specified in AASHTO T 324. Based on the results of the experimental program, the greatest root-mean square error (RMSE) should be set at 2.54 mm.
- **Section 5.1:** AASHTO T 324 does not set a tolerance for the maximum speed of the wheel. It is recommended to add a tolerance of ± 0.02 m/s.
- **Section 5.2:** AASHTO T 324 specifies the use of a water bath capable of controlling the temperature within ±1.0°C over a range of 25 to 70°C (34°F over a range of 77°F to 158°F). Results of the temperature experiment revealed major shortcomings in this part of the specification:

    - Since three of the four machines available on the market do not have a cooling system, it is virtually impossible to set the target temperature to 25°C, especially during summer time. It is recommended to modify the low range to 35°C (95°F).
    - The upper range of 70°C is too high and is not encountered in any region of the US. Test temperature is usually selected based on the 50% reliability 7-day average maximum high pavement temperatures computed using the LTPPBind software *(20)*. In NCHRP Project 9-29, the highest pavement temperature was calculated based on LTPPBind to be 58°C for Phoenix, AZ *(21)*. Furthermore and based on the results of the survey, the highest test temperature used by the states was 56°C. Therefore, the recommended upper range should be changed to 64°C.
    - The 30-min preconditioning time specified in Section 8.9.2 is not sufficient to ensure that all areas of the test specimen have reached the specified temperature within ±1.0°C. It is recommended to increase the preconditioning time to 45 min.

- **Section 5.3:** AASHTO T 324 does not currently specify the locations of the deformation readings or the number of deformation readings. Current specification has resulted in major discrepancies among manufacturers, as some machines record deformations at only five locations while others record deformations at 227 locations. Results also suggest that the deformation readings are sometimes not being recorded at the pre-determined locations along the track. To this end, two major modifications are recommended:
    - Specify that deformation readings should be recorded at 11 locations along the length of the track. These locations should be set at -114, -91, -69, -46, -23, 0, +23, +46, +69, +91, + 114 mm with zero being the midpoint of the track. The midpoint of the track should be marked by the different manufacturers to assist the user. While a manufacturer may elect to record deformations at more than 11 locations, these locations should be kept consistent to allow for comparisons between the measured rut depths among different LWT machines.
    - Specify that the locations of the deformation readings should be verified experimentally using the aluminum apparatus developed in this study and presented in Figure 33. The maximum total RMSE at the 11 pre-set locations should be set at 1.27 mm.
- **Section 9.2:** A coherent method of reporting the measured rut depth is needed and is currently not provided in AASHTO T 324. The availability of a consistent method of reporting the rut depth would allow for comparisons between the measured rut depths among different vendors. To this end, it is recommended that the average rut depth be calculated based on the five middle deformation sensors (i.e., sensors located at -46, -23, 0, + 23, and + 46 mm). This recommendation is similar to the work reported by Schram, Williams, and Buss *(22)*. This study suggested reporting the average measurements of locations 5 through 9 when the average rut depth at the final pass is greater than 12 mm. Results were based on statistical analysis over 135 test runs on cylinder specimens.
- **Section 9.3:** The recommended method to calculate the stripping inflection point (SIP) and other reporting parameters is not clearly defined in the current specification. Furthermore, it may result in discrepancies in calculating this parameter. It is recommended that an approach similar to the one adopted by Iowa DOT be implemented in the revised AASHTO T 324 specifications.

4.11. Laboratory Experimental Plan for Validation of Proposed Changes

A laboratory experimental plan was developed to validate the proposed equipment modifications and specifications proposed in this study. The objective of the proposed laboratory plan is to evaluate proposed modifications to the Hamburg test equipment as well as the modified AASHTO T 324 developed in this study. The research team envisions that results obtained from all Hamburg test equipment should be comparable. Currently, there is no guarantee that this is the case as the methods of measurement and calculation are different. After addressing the proposed modifications to the equipment configurations and to the specifications, a laboratory experimental program shall be conducted to compare statistically the results obtained with different Hamburg test equipment from various manufacturers when testing the same asphalt mixture. The experimental program should test contrasting asphalt mixtures using the four main types of Hamburg test equipment available in the US market. Furthermore, the selected mixes shall include good and poor performers against rutting. To this end, the following factors should be considered in the proposed laboratory plan:

- **Mixture Characteristics:**
  - Four contrasting dense-graded asphalt mixture types (small and large NMAS, low and high binder contents, two binder types [e.g., PG 58-22 and PG 76-22])
- **Specimen Types and Sizes:**
  - Plant-mixed laboratory-compacted (PL) and plant-mixed field-compacted (PF) specimens;
  - Two specimen configurations (core and slab specimens).
- **Test Conditions:**
  - Three test temperatures (35, 50, and 64°C)
- **Test Protocols:**
  - Original and modified AASHTO T 324 specifications
- **Equipment Manufacturer:**
  - Four brands of Hamburg test equipment that conform to the revised specification

Considering that a minimum number of three replicates would be required for each test condition, it is clear that a complete factorial design for the proposed test matrix will not be achievable given possible time and financial restrictions. Therefore, a fractional factorial statistically based design should be developed in order to consider the most important combinations, which will allow the proposed experimental plan to characterize the accuracy, repeatability, and proposed test configurations. To minimize variability due to mix preparation, a single technician shall be fabricating all specimens in the experimental program.

Upon finalization of the specifications for the Hamburg test equipment, the research team envisions that a protocol that complies with ASTM E1169, Standard Guide for Conducting Ruggedness Tests, will be used for systematic evaluation of the Hamburg test equipment available from different manufacturers. The results of the five performance parameters obtained with different HWT equipment would be compared statistically to assess whether observed differences are statistically significant.

5. CONCLUSIONS AND RECOMMENDATIONS

After performing a comprehensive evaluation of the machines conforming to AASHTO T 324, it is concluded that there are differences between commercially available HWT machines in the US market. Furthermore, available HWT machines do not meet all the requirements set forth in AASHTO T 324 including requirements for the waveform, the temperature range, and the reporting parameters. One should acknowledge, however, that some of the observed differences are due to the ambiguity of the specification and the lack of detailed requirements for every aspect of the test method. The following represents a summary of the main shortcomings identified during the testing program.

Waveform: Results of the experimental program showed that not all the machines available in the market are able to produce a sinusoidal wave. AASHTO T 324 specifies that the wheel be required to reciprocate over the specimen such that its position varies sinusoidally over time. In the case of a pure-sinusoidal machine, the wheel spends equal amounts of time on the front and back halves of the track. However, in the case of the non-sinusoidal machine, the wheel spends more time on the back half of the track as compared to the front half.

Temperature control system: AASHTO T 324 specifies the use of a water bath capable of controlling the temperature within ±1.0°C over a range of 25 to 70°C (34°F over a range of 77°F to 158°F). Since the majority of the HWT machines do not have a cooling system, obtaining 25°C in the bath is highly dependent on the incoming water temperature and was not possible when the water temperature was warmer than 25°C. When tested at 50°C, even though the average temperatures at the end of 30 minutes of conditioning were within the specification limit of 50 ± 1°C, some locations in the HMA specimen were not within the specified range. Therefore, a longer pre-conditioning time is deemed necessary. When tested at 70°C, all machines were able to heat the specimen; however, some locations in the HMA specimen were not within the required range. The upper range of 70°C is too high and is not encountered in any region of the US. Based on the results of the survey, the highest test temperature used by the states was 56°C.

Deformation measurements: AASHTO T 324 does not currently specify the locations of the deformation readings or the number of deformation readings. Current specification has resulted in major discrepancies among manufacturers, as some machines record deformations at only five locations while others record deformations at 227 locations. Results also suggest that the deformation readings are sometimes not being recorded at the pre-determined locations along the track. Furthermore, the researchers located the center of wheel travel for each of the machines before performing the evaluations, it is important that the specimen molds be centered with respect to the travel of the wheel. Therefore, the vendors should mark the center of travel on the machines to allow users to line up the molds with that mark.

Data collection and reporting: AASHTO T 324 requires five parameters to be collected and reported to quantify the performance of a mix to rutting and moisture susceptibility: number of passes at maximum impression, maximum impression, creep slope, strip slope, and Stripping Inflection Point (SIP). Upon review of the current requirements detailed in AASHTO T 324, one may note that not enough specifics are provided to allow for consistent analysis and reporting of the five aforementioned performance indicators. For example, AASHTO T 324 does not define how to find the “steady-state portion” to plot the creep slope.

At least seven computer programs, developed by four manufacturers and two state DOTs, were identified for analyzing HWT test data and reporting the necessary parameters. Two mixes, which were tested using the HWT manufactured by Vendor A, were selected for analysis by the various methods. Mix 1 was a poor performing mix that stripped during testing and Mix 2 was a good performing mix that did not strip during testing. For Mix 1, substantial differences were observed between the different analysis methods especially in the reporting of the SIP. Furthermore, some of the available methods do not report the five performance parameters specified by AASHTO T 324. For Mix 2, only two of the seven methods successfully identified this mix as a non-stripping mix. In addition to these discrepancies, the approach adopted by Iowa DOT can only analyze HWT results obtained from the machine manufactured by Vendor A.

5.1. Recommendations

Based on the results of the experimental program, revisions to AASHTO T 324 and to the configurations of the available HWT machines are necessary. Modifications were proposed to address equipment capabilities, components, or design features in order to ensure proper testing and accurate, reproducible results. The key elements of AASHTO T 324 specifications to conduct the Hamburg Wheel Track (HWT) test were identified to be the loading mechanism, temperature measurement and control system, impression measurement system, test specimen size, and data collection and reporting sections. Proposed modifications are discussed in this report to ensure repeatable measurements and that the results from different manufacturers are comparable. These modifications include change to temperature measurement and range, impression measurement system, data collection, and data analysis and reporting. In addition to the proposed modifications to the AASHTO T 324 specifications, the vendors are expected to modify their equipment to meet the new requirements.

Based on the findings of the experimental program, it is concluded that there are differences between commercially available HWT machines in the US market. After addressing the proposed modifications to the equipment configurations and to the specifications, a laboratory experimental program shall be conducted in order to compare the results obtained with HWT devices from various manufacturers when testing the same asphalt mixture. The experimental program recommended testing a range of contrasting asphalt mixtures using the four main types of Hamburg test equipment available in the US market and to compare the five performance parameters statistically according to ASTM E1169, Standard Guide for Conducting Ruggedness Tests.

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7. APPENDIX A

Louisiana Transportation Research Center

Sponsored jointly by the Louisiana Department of Transportation and Development and Louisiana State University

Survey Questionnaire for NCHRP Research Project 20-07/Task 361, "Hamburg Wheel-Track Test Equipment Requirements and Improvements to AASHTO T 324"

The Louisiana Transportation Research Center (LTRC) is conducting a national research project titled, "Hamburg Wheel-Track Test Equipment Requirements and Improvements to AASHTO T 324" for the National Cooperative Highway Research Program (NCHRP). The objective of this study is to document the available Hamburg test equipment capabilities, specifications, and similarities and differences among the different U.S. vendors.

This information will be used to help develop a recommended practice for state DOTs to incorporate these results in specifications. Your input is greatly appreciated.

If you need additional information, please contact Louay Mohammad:
Louay Mohammad
LSU / LTRC
Phone: (225) 767-9126
e-mail: Louaym@lsu.edu

Please return the questionnaire by November 12, 2014. We appreciate your timely response.

Name:
Title:
Agency:
Address:
City:
State: Select One...
Zip:
Email:
Phone:

1. What type of LWT do you use? (Please mark one or more manufacturers)

Manufacturer	Mark if applicable	Model number	Date acquired
Troxler Electronic Laboratories, Inc. (formerly Precision Machine & Welding)	☐		
Pavement Technology, Inc.	☐		
James Cox and Sons, Inc.	☐		
InstroTek, Inc.	☐		
Cooper Research Technology Ltd.	☐		
Other			

2. Does your machine have a single wheel or two wheels?

- Single Wheel
- Two Wheels

3. Which specification do you use? (Please choose one)

Specification	Mark if applicable
AASHTO T-324 (Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA))	
Modified AASHTO T-324 (please provide copy with response)	
State specific specification (please provide a copy)	

4. How often do you calibrate your LWT device (months)?

5. What does the calibration include?

Items	Mark if applicable
Load	
LVDT or deformation sensor	
Temperature	
Wheel Frequency	
Horizontal level check at start of test	

6. Is your laboratory AMRL certified for AASHTO T-324?

Yes No

7. What test temperature(s) do you use? (°C)

8. What is the acceptance criteria used in your state? Please email a copy of your specifications to Louaym@lsu.edu.

Acceptance criteria	Mark if applicable
Maximum allowable rut depth at specified number of wheel passes	☐
Post compaction	☐
Stripping inflection point	☐
Others, please specify	

9. What type of specimens do you use?

Items	Mark if applicable
Slabs	☐
Pucks (Cylindrical samples)	☐

10. Does you agency specify requirements for the Hamburg test specimen fabrication?

○ Yes ○ No

If yes, please email a copy of your requirements to Louaym@lsu.edu.

11. Do you have test data that you can share? (Please choose one)

Items	Mark if applicable
Electronic data files can be made available for NCHRP 20-07/Task 361 purposes	○
Files unavailable, only one final rut depth number available	○

12. How is the result of the Hamburg test reported?

Mid-point depression	☐
Maximum depression	☐
Average depression	☐
If an average is reported, how many data points are averaged?	
If you answered yes to the previous question, please provide the locations of the data points	
Other (please specify)	

13. How do you use the data you obtain from the machine?

Rutting	☐
Moisture Sensitivity	☐
Performance	☐
Other	

14. Do you have any additional comments?

Submit

Table A-1. List of State Specifications

Asphalt Binder Grade	Minimum Number of Passes at 0.5 inch Rut Depth*	
California DOT		
PG 58	10000	
PG 64	15000	
PG 70	20000	
PG 76 or higher	25000	
Illinois DOT		
PG 58 or lower	5000	
PG 64	7500	
PG 70	15000	
PG 76 or higher	20000	
Louisiana DOT		
PG 58	12000	
PG 64	20000	
PG 70 (OGFC)	7500	
Montana DOT		
	Produced Plant Mix	Mix Design
PG 58	10000	15000
PG 64	10000	15000
PG 70	10000	15000
Texas DOT		
PG 64 or lower	10000	
PG 70	15000	
PG 76 or higher	20000	
Wisconsin DOT		
PG 58	20000	
PG 64	15000	
PG 70	10000	
PG 76	5000	
Colorado DOT		
maximum rut depth > 4mm before 10,000 passes is considering a failure		

*: the test temperature is based on the tables below

Table A-2. Test Temperatures

Asphalt Binder Grade	Test temperature (°C)
California DOT	
PG 58	45
PG 64	50
PG 70	55
Colorado DOT	
PG 58	45
PG 64	50
PG 70	55
PG 76	55
Montana DOT	
PG 58	44
PG 64	50
PG 70	56
Utah DOT	
PG 58	46
PG 64	50
PG 70	54

*: States Iowa, Illinois, Louisiana, Oklahoma, Texas, Washington and Wisconsin DOTs are using 50°C for all the tests.

8. APPENDIX B

Table B-115. Types of rulers evaluated

Material	Metal												Paper	
Background	Black								White				Black	
Width (inch)	1				1/2				1				1	
Subdivisions	1/8	1/16	1/32	1/64	1/8	1/16	1/32	1/64	1/8	1/16	1/32	1/64	1/8	1/16

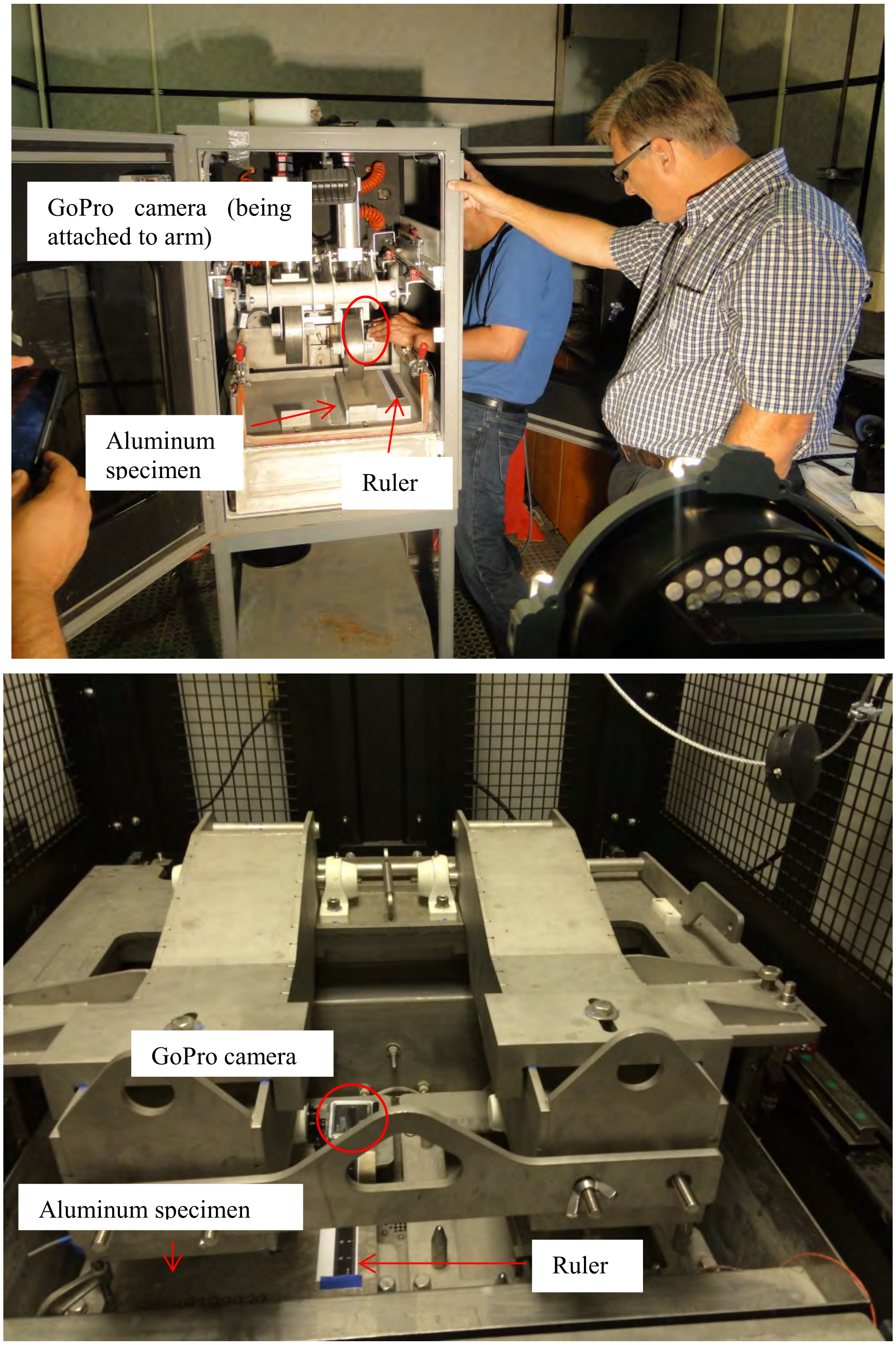


Figure 42
Setups on other machines evaluated for position analysis

9. APPENDIX C

The following discussion presents the analytical solution of the wheel and metal-specimen interaction. Figure 43 shows the drawing of the metal specimen used in this study (curvature with radius R) with a HWT wheel (with radius r) placed over it at a distance of γ_c from the center. As can be seen from the figure, the wheel will come in contact with the metal specimen tangentially at the point γ. Therefore, the rut depth reported by the machine LVDT will be less than the actual rut in the metal specimen at all points except the center. The following steps present the mathematical derivation to obtain the difference in rut depth reported by the machine LVDT and the impression of the metal specimen $(\alpha_0 - \alpha_c)$. It should be noted that the center of the curvature of the metal specimen is at (0, R).

1. The equation of the circle with radius R is:

$$x^2 + (y - R)^2 = R^2 \tag{1}$$

   Therefore,

$$(y - R) = \pm\sqrt{R^2 - x^2} \tag{2}$$

2. Since we are dealing with only the bottom half of the circle

$$(y - R) = -\sqrt{R^2 - x^2} \tag{3}$$

3. Assume a γ

$$y = R - \sqrt{R^2 - \gamma^2} = \alpha \tag{4}$$

$$y' = \frac{+\gamma}{\sqrt{R^2 - \gamma^2}} = \beta \tag{5}$$

4. Use r and β to find γ_c

$$\gamma_c = \gamma - r \times \sin(tan^{-1}\beta) \tag{6}$$

5. Use R and γ_c to find α_c

$$\alpha_c = R - \sqrt{R^2 - \gamma_c^2} \tag{7}$$

6. Use r and ($\theta = tan^{-1}\beta$) to find f

$$f = r \times \cos(\theta) \tag{8}$$

7. Find α_R and α_0

$$\alpha_R = \alpha + f \tag{9}$$

$$\alpha_0 = \alpha_R - r \tag{10}$$

Maximum speed location computation for the non-sinusoidal configuration

The position of the wheel in the non-sinusoidal machine is described as follows:

$$x = rcos(\theta) + \sqrt{l^2 - r^2 sin^2(\theta)} \tag{11}$$

where,

θ = crank angle,

r = radius of the crank circle, and

l = length of the connecting rod.

The speed of the wheel is obtained by taking the derivative of the position and is shown below:

$$x' = -rsin(\theta) - \frac{r^2 \sin(\theta)\cos(\theta)}{\sqrt{l^2 - r^2 sin^2(\theta)}} \tag{12}$$

The maximum value of speed is obtained by taking the derivative of speed and equating it to zero. i.e.

$$x'' = -rcos(\theta) - \frac{r^2\left(cos^2(\theta) - sin^2(\theta)\right)}{\sqrt{l^2 - r^2 sin^2(\theta)}} - \frac{r^4 sin^2(\theta) cos^2(\theta)}{\left(\sqrt{l^2 - r^2 sin^2(\theta)}\right)^3} = 0 \tag{13}$$

MATLAB software (MuPAD) was used to numerically solve this equation to obtain θ. The resulting θ was plugged back into the distance equation to obtain position. The position of the maximum velocity was thus found to be 0.61 in. from the midpoint of the track. It should be noted that the values of r and l used were 4.5 and 13.0 in., respectively.

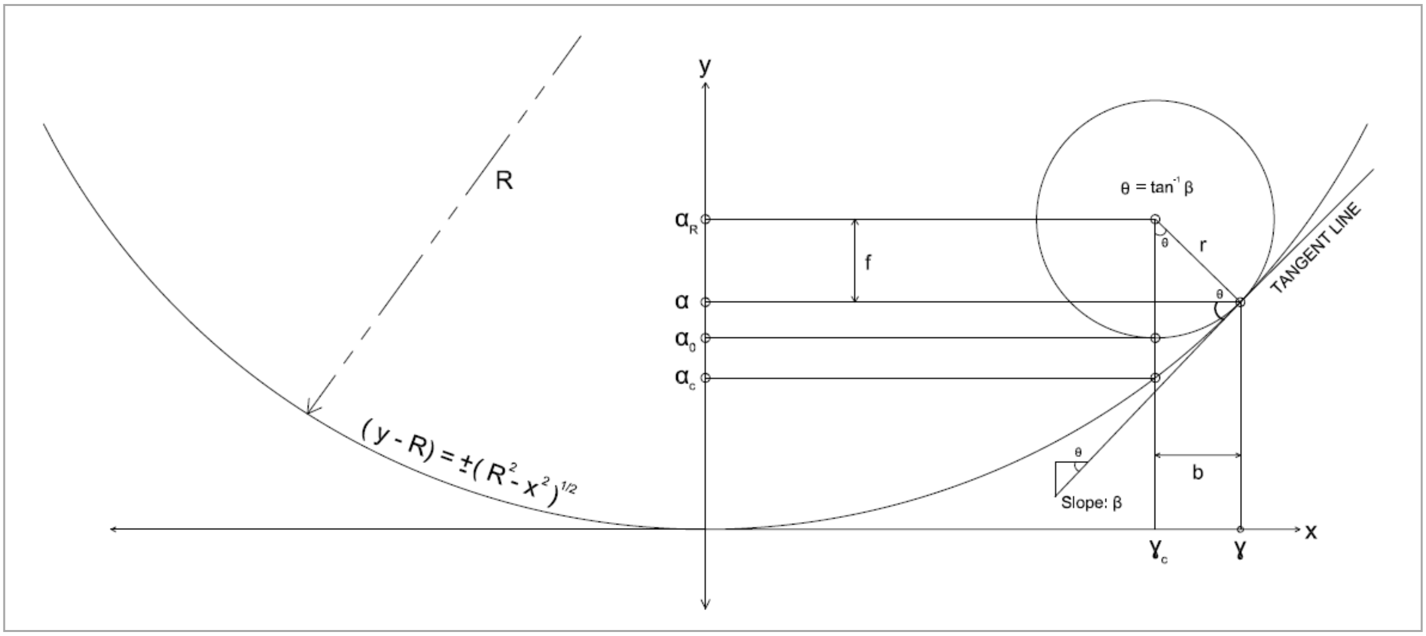


Figure 43
Geometry of metal specimen and wheel

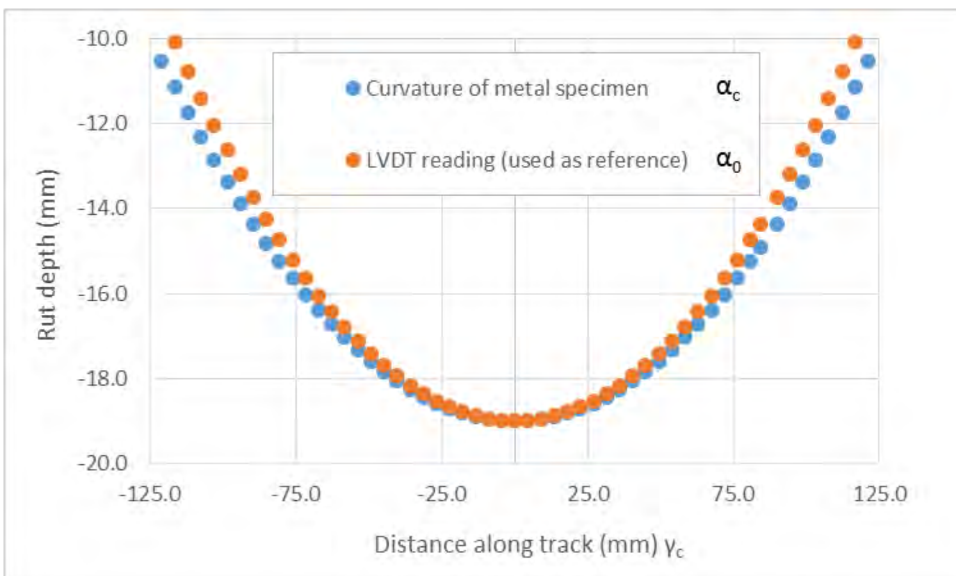


Figure 44
Difference between the rut of the metal specimen and the LVDT reading

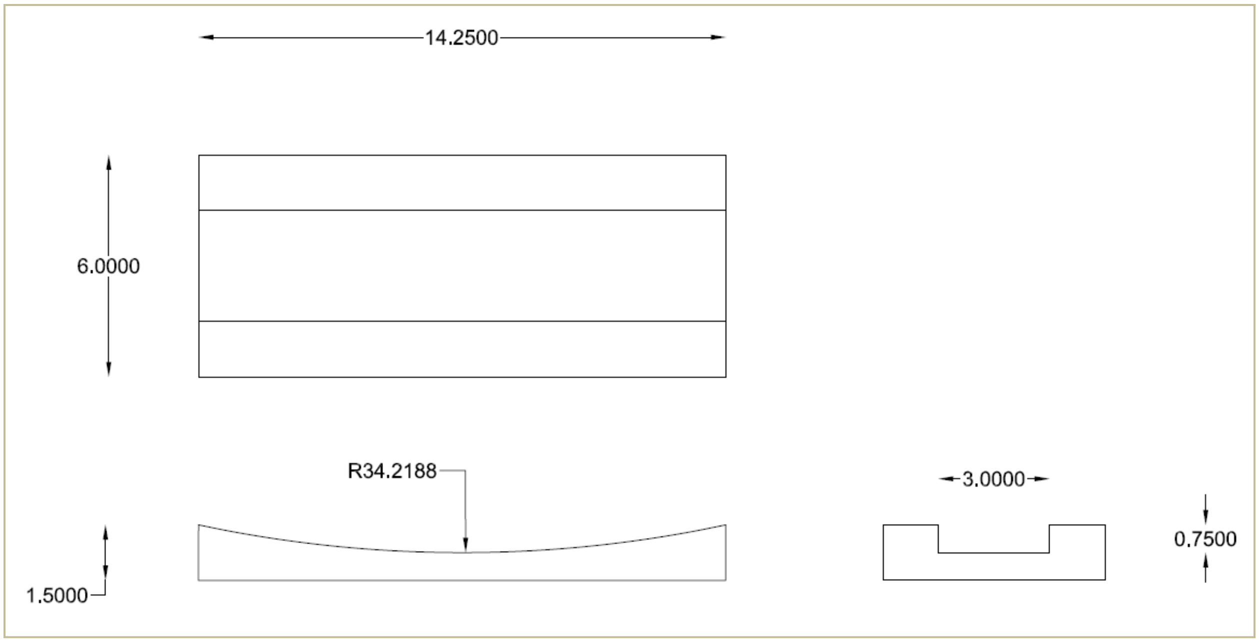


Figure 45
Details of the metal specimen (all dimensions are in inches)

10. APPENDIX D

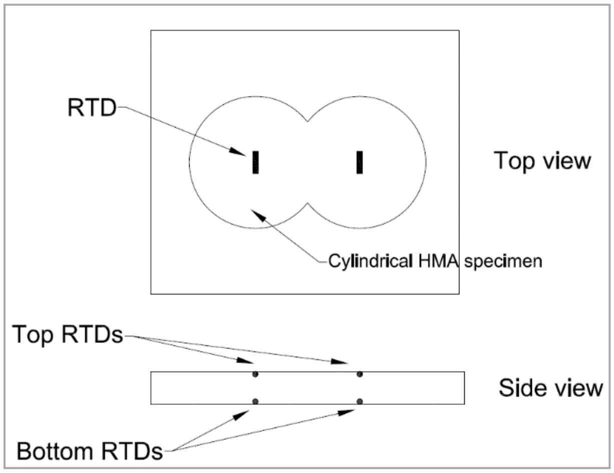


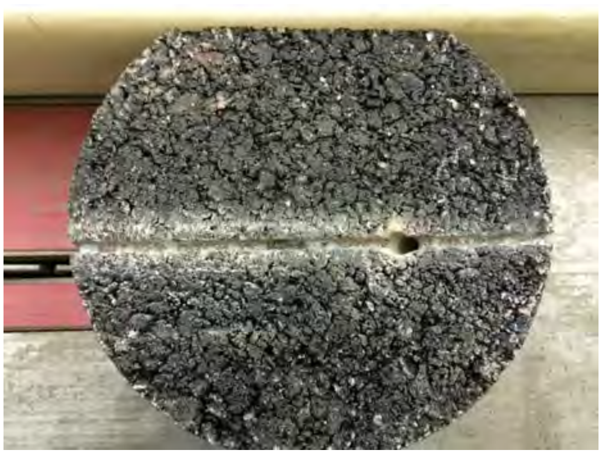
Figure 46
Locations of the embedded RTDs

Table 16. Sensor labelling convention

	Side	Specimen	Sensor position	Sensor ID
1	Left	Front	Top	LFT
2	Left	Front	Bottom	LFB
3	Left	Back	Top	LBT
4	Left	Back	Bottom	LBB
5	Right	Front	Top	RFT
6	Right	Front	Bottom	RFB
7	Right	Back	Top	RBT
8	Right	Back	Bottom	RBB

Specimen preparation for temperature verification

Cylindrical HMA specimens were fabricated in the laboratory and a table saw was used to cut grooves 0.25-inch wide x 0.25-inch deep, for installation of the RTDs and lead wires. Next, the RTDs were placed in the grooves and centered with respect to the width of the specimen. Finally, plumber's putty was used to seal the grooves and keep the RTDs in place. Each of these steps is shown in **Error! Reference source not found.**. It should be noted that through-holes for the bottom RTDs were drilled at an angle of 45° to avoid sharp bends of the lead wire.



(a) Grooves cut and holes drilled

(b) Drill press used for holes for bottom RTDs

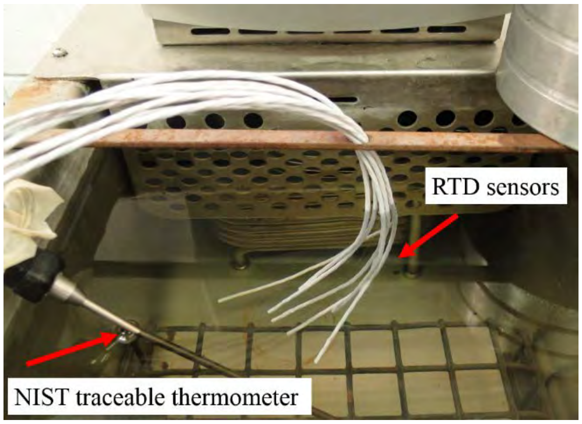
(c) Plumber's putty used to seal grooves after RTD placement

(d) Instrumented specimens in machine

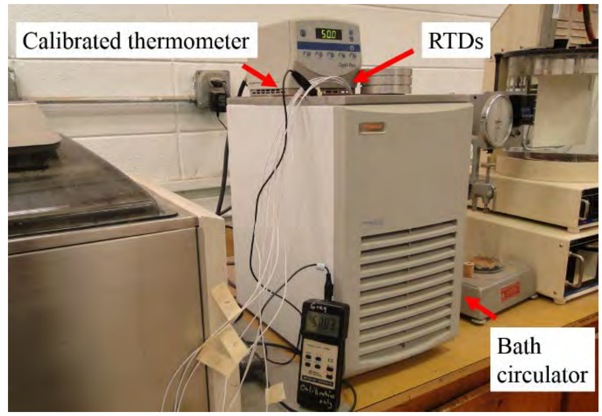
Figure 47
Instrumented specimen preparation

RTD and signal conditioner specifications

The RTDs were purchased after evaluating the temperature range and accuracy requirements. Model HSRTD (class A) RTDs from Omega Engineering, Inc. were found suitable for this application. Next, signal conditioners to interface these RTDs with data acquisition equipment were selected and acquired. The signal conditioners excite and amplify 100-ohm platinum, 4-wire RTDs that are based on the 0.00385 ohm/ohm/°C curve. The RTDs and the data acquisition system were calibrated by using a NIST-traceable thermometer and a ±0.01°C bath circulator. Figure 44 presents the details of the calibration setup. All the RTDs were calibrated to be within ±0.1°C.



(a) Top view of RTDs in bath



(b) Neslab model RTE 17 Bath circulator

(c) Overall setup

Figure 48
RTD calibration setup