DEPARTMENT OF TRANSPORTATION

Standardization of SIP Calculation for Hamburg Wheel Tracking Test

Fan Yin, Principal Investigator
National Center for Asphalt Technology
Auburn University

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16. Abstract (Limit: 250 words)

This project aimed to develop software to standardize and automate the calculation of stripping inflection point (SIP) from the Hamburg Wheel Tracking Test (HWTT) for evaluating the moisture susceptibility of asphalt mixtures. A survey of state highway agencies (SHAs) was conducted to collect information on their use of HWTT to evaluate asphalt mixtures. Based on the survey responses and consultations with HWTT equipment manufacturers, seven SIP calculation methods were identified, synthesized, and critically reviewed for comparison. These efforts resulted in selecting the most robust method for software development. Finally, a web-based program, named *HWTTXpert*, was developed through alpha testing at the National Center for Asphalt Technology (NCAT) at Auburn University and beta testing with 12 SHAs and three equipment manufacturers. The program is now accessible at http://HWTTXpert.eng.auburn.edu, with login credentials available upon request.

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Final Report

Prepared by:

Fan Yin
National Center for Asphalt Technology at Auburn University

Chen Chen
National Center for Asphalt Technology at Auburn University

Qi Li
Fisk University

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List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
COMP	Committee on Materials and Pavements
DOT	Department of Transportation
HWTT	Hamburg Wheel Tracking Test
LaDOTD	Louisiana Department of Transportation and Development
NCAT	National Center for Asphalt Technology
NRRA	National Road Research Alliance
RMSE	Root Mean Square Error
SHA	State Highway Agency
SIP	Stripping Inflection Point
SN	Stripping Number

Executive Summary

The stripping inflection point (SIP) is a widely recognized parameter derived from the Hamburg Wheel Tracking Test (HWTT) to assess the moisture susceptibility of asphalt mixtures. Although its definition is well established in the American Association of State Highway and Transportation Officials (AASHTO) T 324-23, the method for calculating SIP remains unspecified. Consequently, different calculation methods have been developed by equipment manufacturers and asphalt practitioners, often yielding inconsistent results. This inconsistency may lead to disputes between state highway agencies (SHAs) and asphalt contractors when evaluating SIP results for mix design approval and production acceptance.

The objective of this project was to develop software to standardize and automate the calculation of SIP. The project commenced with a survey of SHAs to gather information on their use of HWTT. Responses indicated that 32 agencies use HWTT, including 18 for mix design approval, six for production acceptance, 19 for forensic analysis, and 26 for research evaluation. Of these 32 agencies, 13 use HWTT for rutting evaluation, one for moisture evaluation, and 18 for both purposes. SIP is among the three most commonly used HWTT parameters, alongside the rut depth at a specific number of passes and the number of passes to reach a 12.5mm rut depth. Only two SHAs specify the calculation method for SIP, while the others rely on manufacturer-provided results but acknowledge potential discrepancies between different manufacturers.

Following survey responses and consultations with HWTT equipment manufacturers, seven SIP calculation methods were identified, synthesized, and critically reviewed for their advantages and disadvantages. These methods were also compared by analyzing three sets of HWTT data corresponding to asphalt mixtures exhibiting no stripping failure, marginal stripping failure, and severe stripping failure. While the various methods yielded reasonably consistent results, certain discrepancies were noted. Based on the critical review, the most robust method was selected for software development.

Finally, a web-based program called *HWTTXpert* was developed using the selected SIP calculation method. It is compatible with data files from three equipment manufacturers: InstroTek, Inc., Pavement Technology Inc., and Troxler Electronic Laboratories, Inc. The program underwent alpha testing with over a hundred data files from the National Center for Asphalt Technology (NCAT) at Auburn University for initial development and troubleshooting, followed by beta testing with 12 SHAs and three equipment manufacturers. Based on the feedback, the program was finalized and can be accessed at http://HWTTXpert.eng.auburn.edu, with login credentials available upon request.

Chapter 1: Introduction

1.1 Background

The Hamburg Wheel Tracking Test (HWTT) is widely utilized by state highway agencies (SHAs) to evaluate the rutting resistance of asphalt mixtures. Additionally, because the test is conducted in water, it enables the evaluation of moisture susceptibility based on the stripping inflection point (SIP). According to the American Association of State Highway and Transportation Officials (AASHTO) T 324-23, SIP is graphically identified as the intersection of slopes derived from fitted lines corresponding to the creep and stripping phases of the HWTT curve. Despite the straightforward definition of SIP, accurately determining it can be challenging because HWTT data often do not present a well-defined SIP, particularly in cases of marginal stripping failure. Over the years, various methods for calculating SIP have been developed by HWTT equipment manufacturers and asphalt practitioners; however, these methods do not consistently produce uniform results. The absence of standardized SIP calculation procedures may lead to disputes among SHAs when evaluating HWTT results for mix design approval and production acceptance.

1.2 Objectives

The project aimed to develop HWTT analysis software to standardize and automate the calculation of SIP. This will help SHAs to make well-informed and consistent decisions on HWTT results. The software will be compatible with various HWTT devices to facilitate direct reading and processing of raw data files without subjective data manipulation or interpretation.

1.3 Organization of the Report

This report is structured into five chapters. Chapter 1 outlines the motivation and objectives of the project. Chapter 2 presents survey results from SHAs regarding the use of HWTT for evaluating asphalt mixtures. Chapter 3 provides a synthesis and critical review of existing SIP calculation methods, along with the selection of the most robust method for software development. Chapter 4 outlines the development of the *HWTTXpert* software and its user manual. Finally, Chapter 5 summarizes the major findings of the project.

Chapter 2: Survey of State Highway Agencies

An online survey was conducted to gather information from SHAs on their use of HWTT for evaluating asphalt mixtures. The survey was sent to 50 SHAs in the United States through the American Association of State Highway and Transportation Officials (AASHTO) Committee on Materials and Pavements (COMP). Responses from 43 SHAs were received, resulting in an 86% response rate.

Of the 43 respondents, 32 use HWTT for asphalt mixture evaluation, while 11 do not (Figure 1). Specifically, 18 SHAs use HWTT for mix design approval, 6 for production acceptance, 19 for forensic analysis, and 26 for research evaluation (Figures 2-5).

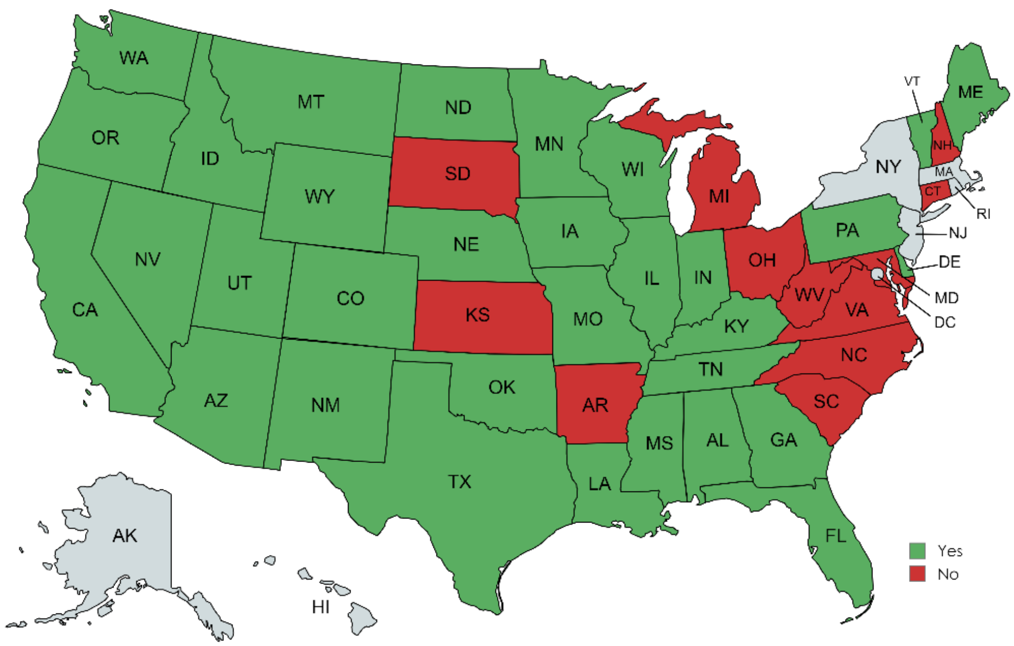


Figure 1. U.S. SHAs using HWTT for Evaluating Asphalt Mixtures (total number of survey respondents: 43)

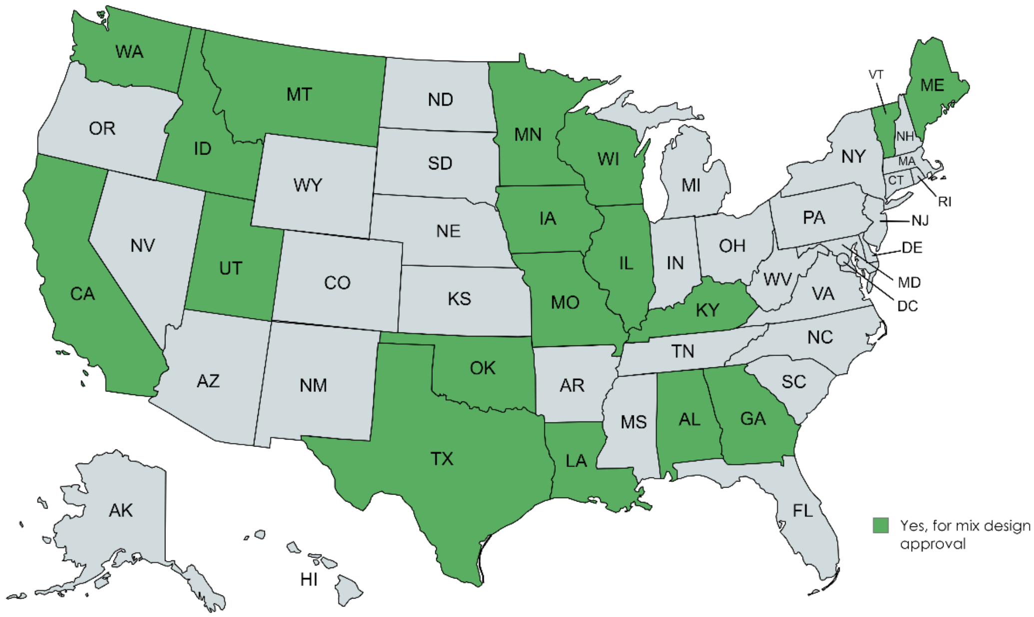


Figure 2. U.S. SHAs using HWTT for Mix Design Approval (answered by 18 out of 43 survey respondents)

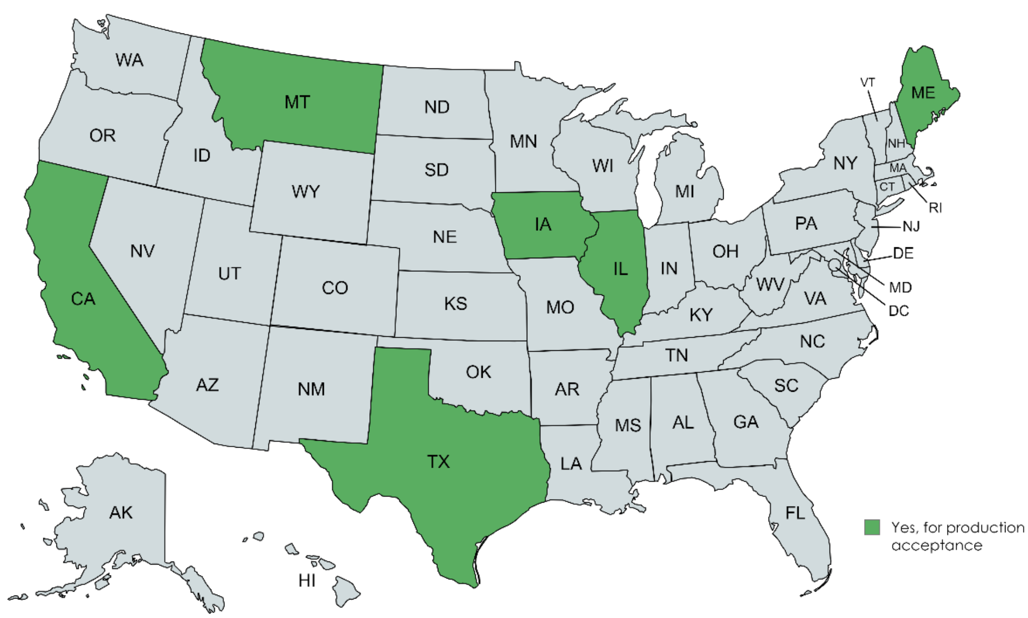


Figure 3. U.S. SHAs using HWTT for Production Acceptance (answered by 6 out of 43 survey respondents)

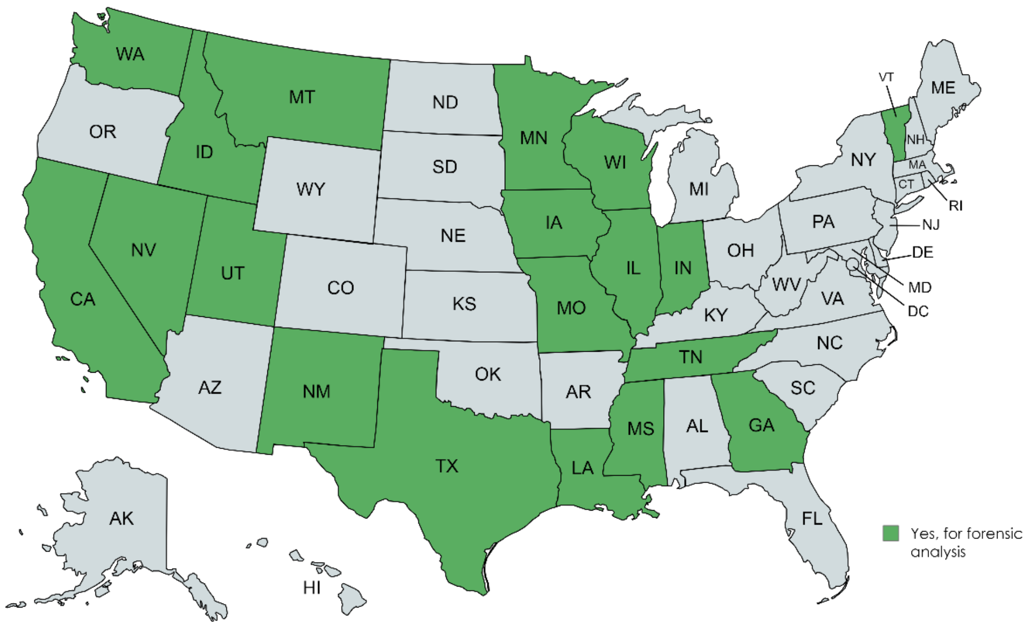


Figure 4. U.S. SHAs using HWTT for Forensic Analysis (answered by 19 out of 43 survey respondents)

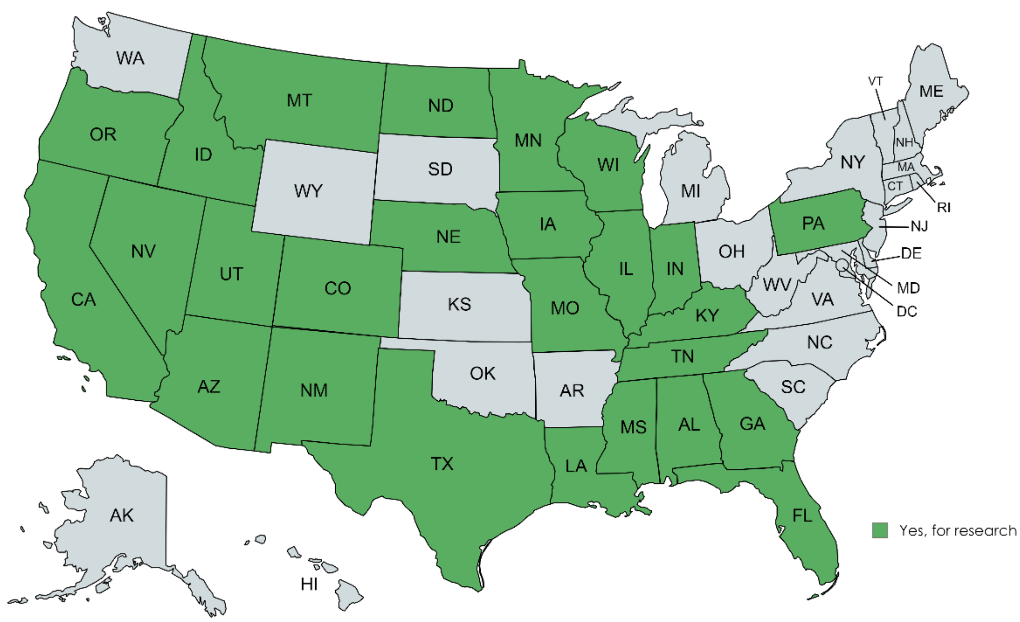


Figure 5. U.S. SHAs using HWTT for Research Evaluation (answered by 26 out of 43 survey respondents)

Of the 32 SHAs using HWTT, 13 assess rutting resistance, one evaluates moisture resistance, and 18 evaluate both (Figure 6). All agencies conduct HWTT on lab-compacted gyratory cylindrical specimens, three allow lab-compacted slab specimens, and 16 allow field cores. No agency requires additional moisture conditioning of the specimens before testing, though the Louisiana Department of Transportation and Development (LaDOTD) is considering it for future mix design approval.

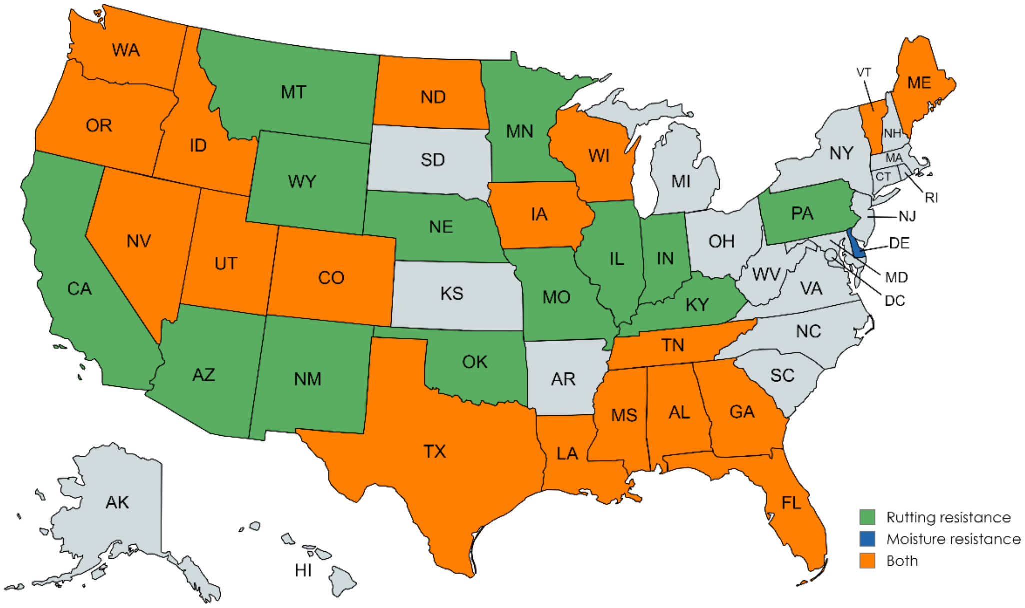


Figure 6. U.S. SHAs using HWTT for Evaluating Rutting and/or Moisture Resistance of Asphalt Mixtures (answered by 32 out of 43 survey respondents)

Figure 7 presents an overview of various HWTT parameters employed by the 32 SHAs. The three most commonly utilized parameters are rut depth at a specific number of passes, SIP, and the number of passes to reach a 12.5 mm rut depth. Additional parameters include creep slope, stripping slope, corrected rut depth, stripping number (SN), and stripping/creep slope ratio. Figure 8 indicates that among the 17 SHAs utilizing SIP, only the Iowa and Maine DOTs specify the calculation method for SIP. The remaining 15 agencies use SIP values provided by the HWTT manufacturer, although it is acknowledged that different manufacturers employ varying methods to calculate SIP.

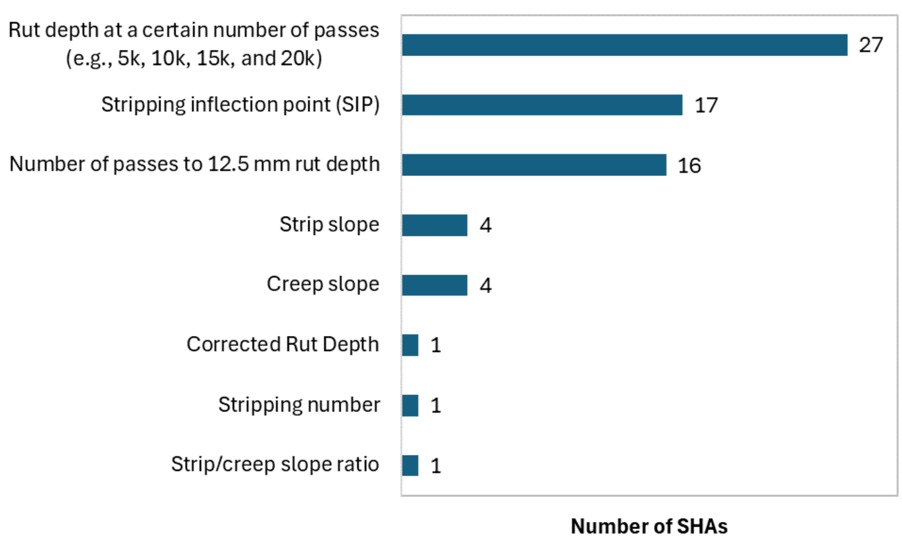


Figure 7. HWTT Test Parameters Used by U.S. SHAs (answered by 32 out of 43 survey respondents)

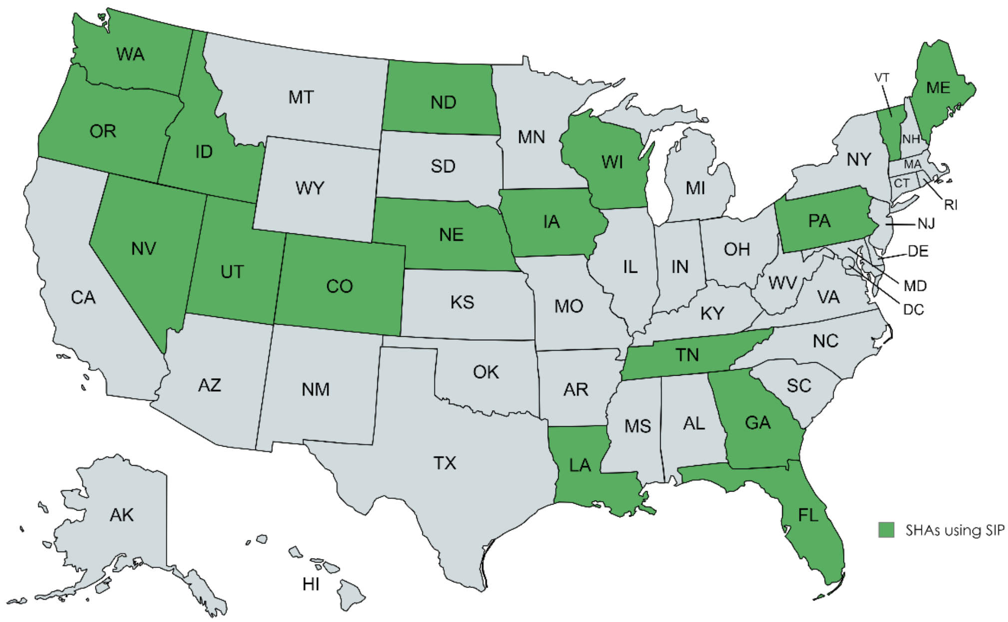


Figure 8. U.S. SHAs using HWTT SIP as a Test Parameter (answered by 17 out of 43 survey respondents)

There are discrepancies among the 32 SHAs in the number and location of deformation sensors used to report the HWTT rut depth. As shown in Figure 9, 19 agencies average five middle locations (i.e., 46mm, -23mm, 0mm, +23mm, and +46mm) per AASHTO T 324-23, four agencies average all locations, two average seven middle locations, one averages three middle locations, and one uses the maximum value of all locations. Additionally, three SHAs use alternative methods: Illinois DOT averages the maximum location and two adjacent ones; Iowa DOT averages locations three through nine out of eleven; and Utah DOT uses the maximum but excludes two inches at each end of the wheel path.

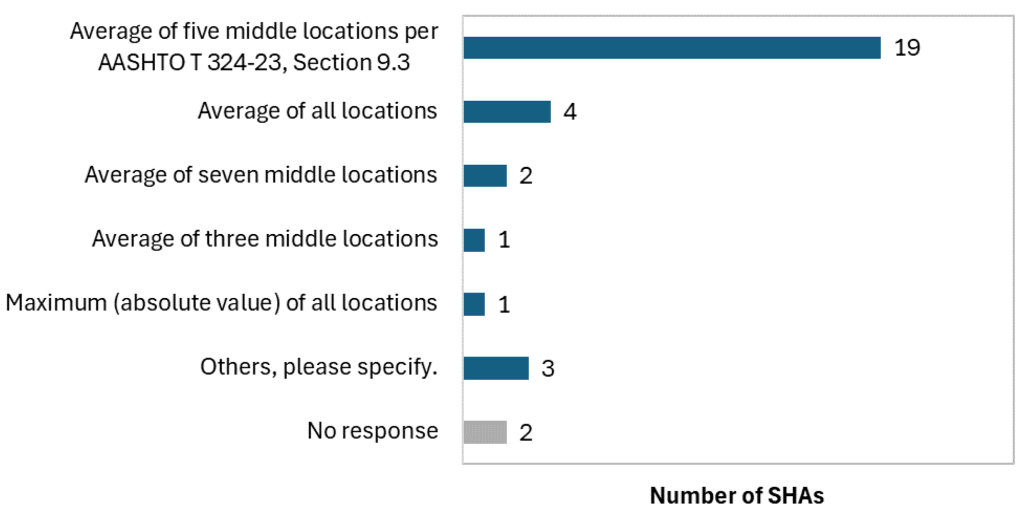


Figure 9. Deformation Locations for Reporting HWTT Rut Depth Used by U.S. SHAs (answered by 32 out of 43 survey respondents)

Figure 10 summarizes the various HWTT devices employed by the 32 SHAs. The three most commonly used devices are the InstroTek SmarTracker™, Cox & Sons Hamburg Wheel Tracker, and Troxler Hamburg Wheel Tracker. Additional devices include the PTI Asphalt Pavement Analyzer Junior (APA Jr.) and the PMW (currently Troxler) Hamburg Wheel Tracker.

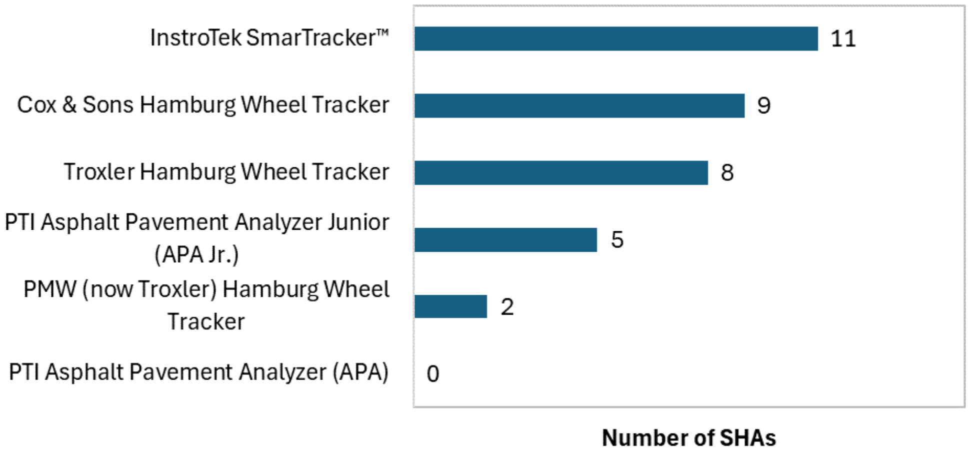


Figure 10. HWTT Devices Used by U.S. SHAs (answered by 32 out of 43 survey respondents)

Finally, of the 32 SHAs using HWTT, 29 are willing to provide raw data files for NCAT to use as templates in developing the HWTT analysis software, and 25 have expressed interest in participating in beta testing of the software.

Chapter 3: SIP Calculation Methods

3.1 Synthesis of SIP Calculation Methods

Based on the SHA survey and consultations with HWTT equipment manufacturers, seven distinct methods for calculating SIP from HWTT results have been identified. The details of each method are provided below.

3.1.1 Method A

This method, used by one of the HWTT equipment manufacturers, instructs the user to determine whether the stripping phase is present by visually assessing the shape of the HWTT curve. If the stripping phase is observed, the user manually selects the start and end points on the curve to define the creep and stripping phases, as shown in Figure 11. Two straight lines connecting the start and end points are plotted on the HWTT curve, representing the creep and stripping lines. Finally, SIP is calculated as the number of passes at the intersection point of the creep and stripping lines in accordance with AASHTO T 324-23. If the user determines that the stripping phase is not present, SIP will not be calculated.

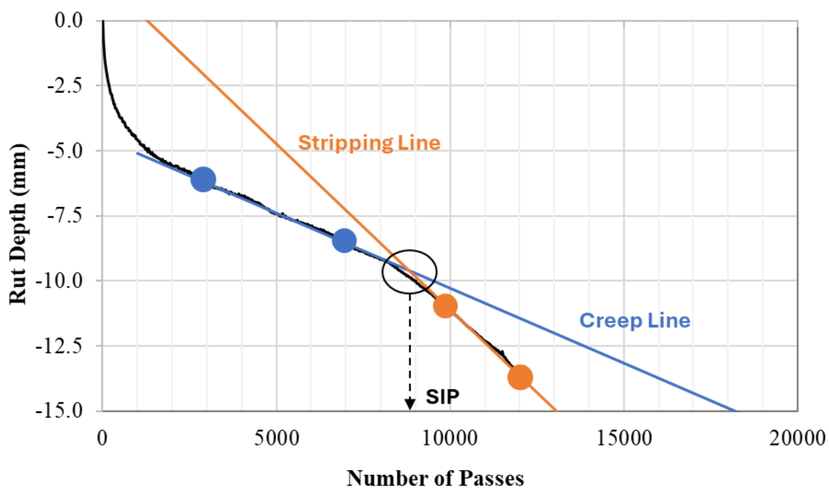


Figure 11. Graphic Illustration of Method A

3.1.2 Method B

This method is utilized by one of the HWTT equipment manufacturers. Similar to Method A, it requires the user to determine the presence of the stripping phase by visually inspecting the shape of the HWTT curve. If the stripping phase is identified, the user must define a “criterion of change” (i.e., slope) for rut depth change over a specified number of passes (e.g., 1 mm over 2,000 passes) that best fits the creep and stripping phases based on the visual assessment of the HWTT curve. The creep line is determined from the rut depth at 1,000 passes (indicating the end of the post-compaction phase and the beginning of the creep phase) and the defined slope for the creep phase, as depicted in Figure 12. For instance, if the rut depth at 1,000 passes is 1.5 mm and the defined slope for the creep phase is 1.0 mm over 2,000 passes, the creep line is established by connecting two points: 1.5 mm rut depth at 1,000 passes and 2.5 mm (i.e., 1.5 mm + 1.0 mm) rut depth at 3,000 passes (i.e., 1,000 passes + 2,000 passes). Similarly, the stripping line is determined based on the endpoint of the HWTT curve and the predetermined slope for the stripping phase, also shown in Figure 12. Finally, SIP is calculated as the number of passes at the intersection point of the creep and stripping lines in accordance with AASHTO T 324-23. If the stripping phase does not exist, SIP will not be calculated.

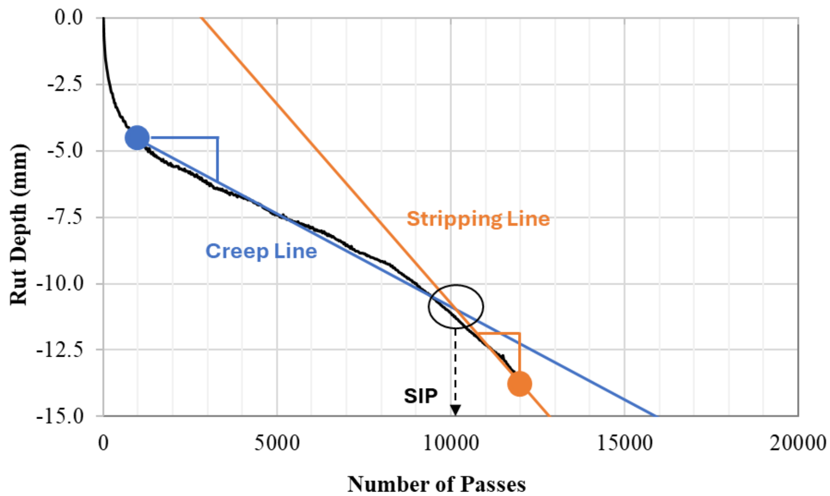


Figure 12. Graphic Illustration of Method B

3.1.3 Method C

This method, utilized by one of the HWTT equipment manufacturers, employs a simple derivative filtering technique to determine the steady-state tangent approximations of the HWTT curve (Macon, 2023). First, the HWTT curve is processed through a monotonic filter to eliminate irregularities of the HWTT curve caused by aggregate loss from the specimen during testing. Subsequently, the steady-state tangent D_i is calculated with a half-spacing (n) selected according to Table 1 using Equation 1. The generated D_i values are illustrated in Figure 13 (a). The minimum smoothed derivative D_i is identified as the creep slope, and the creep line is then fitted using the creep slope (i.e., minimum D_i) and the corresponding point on the HWTT curve. It should be noted that the number of passes corresponding to the minimum Di is comparable to the SN defined in Method G, which is discussed later in this report.

$$D_i^{(n)} = \frac{R_{i+n} - R_{i-n}}{2n} (n < i < N - n) \quad \text{Equation 1}$$

Where R_i is the HWTT rut depth at the number of passes i; N is the number of passes; and n is the half-spacing chosen for the numerical derivative.

Table 1. Spacing Filter Parameter Adjustment for Non-standard Length Tests using Method C

Number of Wheel Passes	Half-spacing (n) for Creep Slope Determination	Half-spacing (n) for Stripping Slope Determination
≥ 20,000	2,000	1,000
10,000 to 20,000	1,000	500
5,000 to 10,000	500	250

The stripping slope is determined by identifying the steady-state tangent for the post-creep phase of the HWTT curve, utilizing a half-spacing selected according to Table 1 that has the maximum D_i, as shown in Figure 13(b). The stripping line is established using the stripping slope (i.e., maximum D_i) and the corresponding point on the HWTT curve. Subsequently, SIP is calculated as the number of passes at the intersection point of the creep and stripping lines, following AASHTO T 324-23 guidelines. For this method, SIP is valid only if the difference between the stripping slope and creep slope exceeds 2 mm per 10,000 passes.

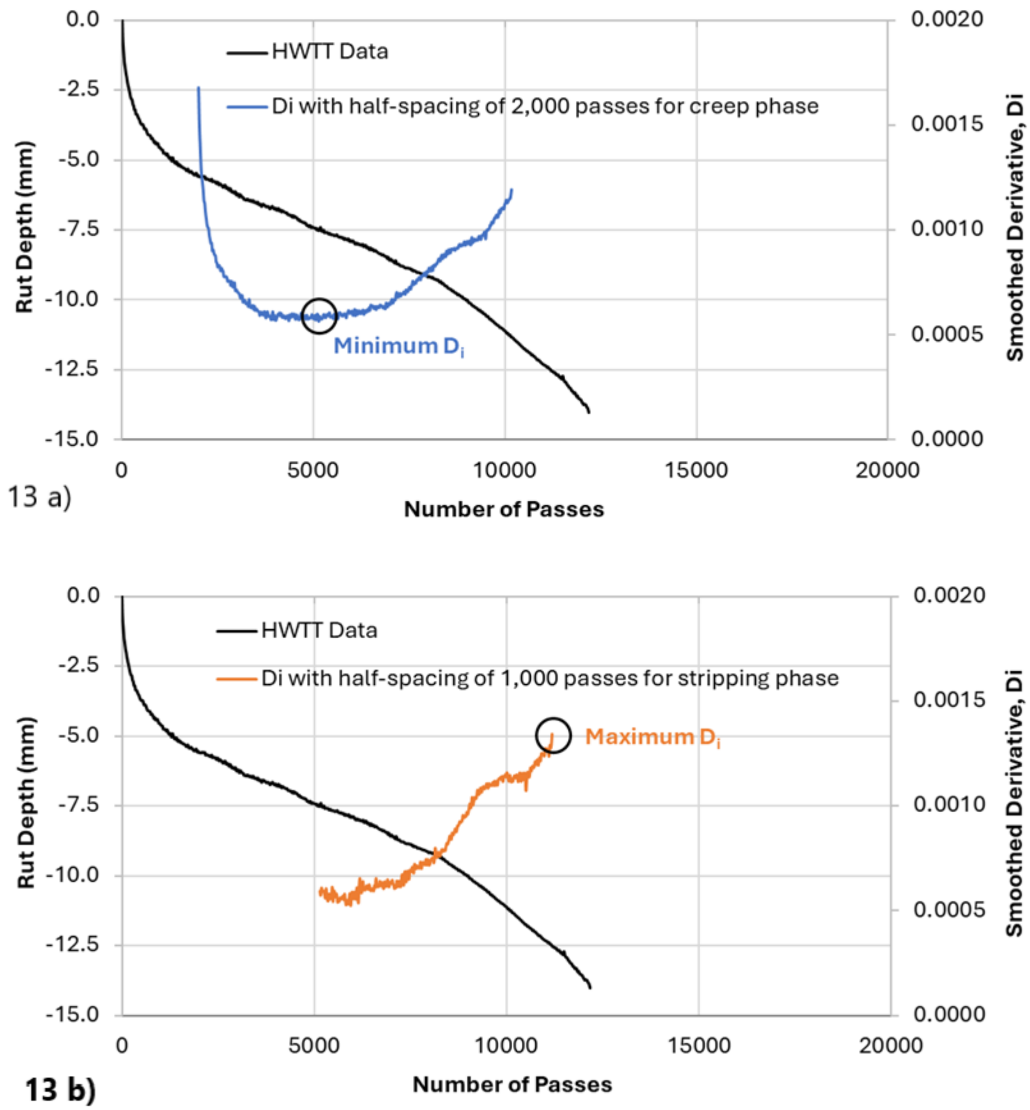


Figure 13. Determining Smoothed Derivative D_i for Method C: (a) using a Half-spacing of 2,000 Passes for Creep Phase, (b) using a Half-spacing of 1,000 Passes for Stripping Phase

3.1.4 Method D

This method, utilized by one of the HWTT equipment manufacturers, begins by fitting a straight line to the HWTT curve starting at 100 or 200 passes, thereby excluding data from the post-compaction (initial densification) phase. The difference between the measured and fitted rut depth is then calculated, as illustrated by the red curve in Figure 14. The number of passes corresponding to the minimum and maximum differences – referred to as the “Min” and the “Max” difference points, respectively – are defined as the start and end points of the creep phase. The creep line is then determined by connecting these points on the HWTT curve. If the “Max” difference point falls within the last five percent of the HWTT test endpoint, the method assumes that the stripping phase does not exist, and SIP will not be calculated. Otherwise, the stripping line will be determined by fitting a straight line to part of the HWTT curve from the "Max" difference point to the middle point between the "Max" difference point and the endpoint. Finally, SIP is calculated as the number of passes at the intersection point of the creep and stripping lines following AASHTO T 324-23.

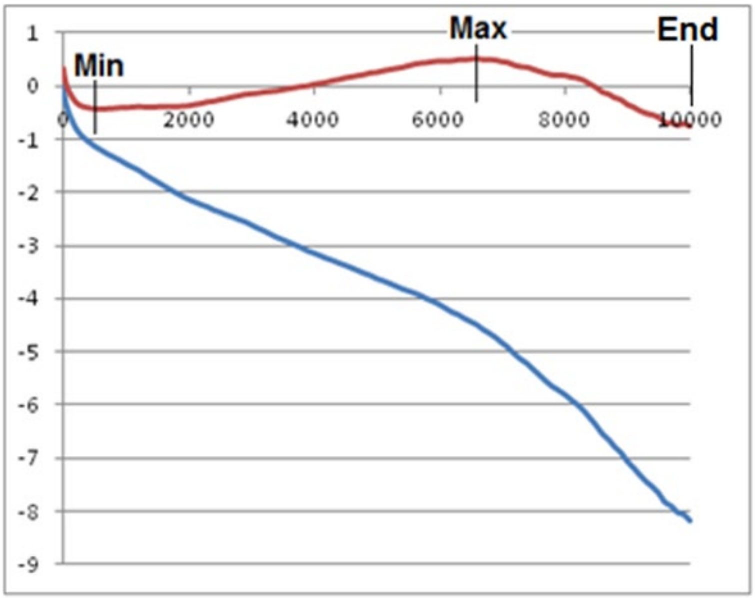


Figure 14. Determining "Min" and "Max" Difference Points for Method D (Cooper, 2023)

3.1.5 Method E

This method, implemented by the Iowa Department of Transportation (DOT) (Iowa DOT, 2024), begins by fitting the HWTT curve with a 6^{th}-degree polynomial determined through least-squares multiple regression. If the curve has an R^2 of 90% or higher, it undergoes additional processing to determine the creep slope, stripping slope, and SIP. Otherwise, the HWTT data is considered invalid and discarded. Next, the first derivative values (i.e., slope) of the fitted polynomial curve are calculated, and the absolute slope values are plotted against the number of passes, as shown in Figure 15. The stripping slope is identified as the maximum absolute derivative value near the end of the fitted polynomial curve, corresponding to the point with the most negative first derivative (defined as the strip pass), as shown in Figure 15. The stripping line is then determined based on the strip pass and the stripping slope. Subsequently, the creep slope is established by identifying the creep pass with the minimum absolute slope of the fitted polynomial curve before the strip pass, as shown in Figure 15. The creep line is determined based on the creep pass and the calculated creep slope. Finally, SIP is calculated as the number of passes at the intersection point of the creep and stripping lines following AASHTO T 324-23. For this method, SIP is deemed invalid when the ratio of the stripping slope to the creep slope is less than 2.0.

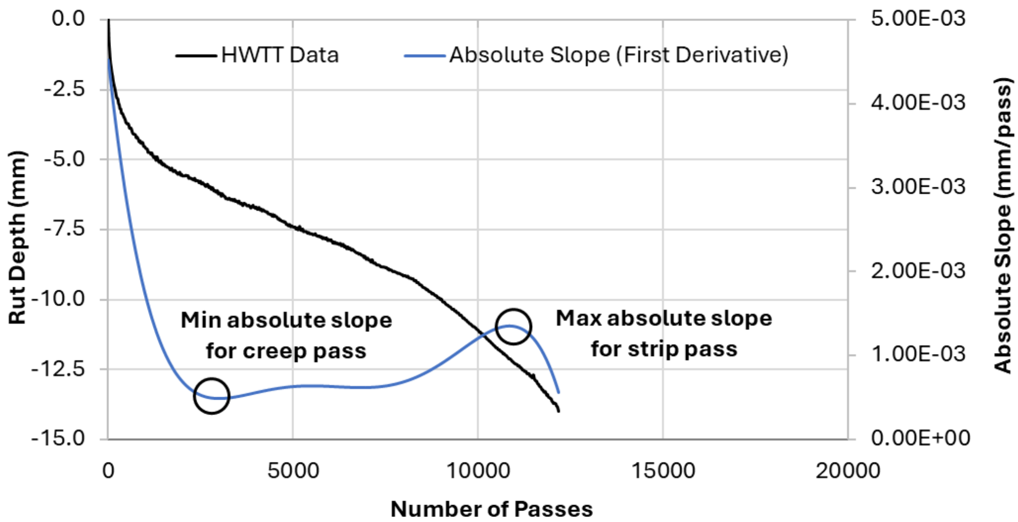


Figure 15. Determining Strip Pass with Maximum Absolute Slope and Creep Pass with Minimum Absolute Slope for Method E

3.1.6 Method F

This method, employed by the Maine DOT (Maine DOT, 2023), begins with fitting the HWTT curve with a 6^{th}-degree polynomial determined via least-squares multiple regression, similar to Method E. The stripping slope is determined by identifying the maximum absolute slope of the fitted polynomial curve from the midpoint to the endpoint of the test. This corresponds to the point exhibiting the most negative first derivative within that range and is defined as the strip pass, as shown in Figure 16. Subsequently, the stripping line is established based on the strip pass and the identified stripping slope. The creep slope is determined by identifying the minimum absolute slope of the fitted polynomial curve between 1,500 passes and the strip pass. The corresponding point on the HWTT curve denotes the creep point, as shown in Figure 16. The creep line is then determined by connecting two adjacent points of the creep point with a 1,000-pass interval on the HWTT curve. For example, if the creep point is 4,000 passes, the creep line is determined by connecting the points at 3,000 (i.e., 4,000 – 1,000) and 5,000 (i.e., 4,000 + 1,000) passes on the HWTT curve. Finally, SIP is calculated as the number of passes at the intersection point of the creep and stripping lines following AASHTO T 324-23. For this method, SIP is deemed invalid under any of the following conditions: (1) the regression model exhibits an R^2 value less than or equal to 0.95; (2) the ratio of the stripping slope to the creep slope falls below 3.0; or (3) the stripping slope is less than 0.63 mm per 1,000 passes.

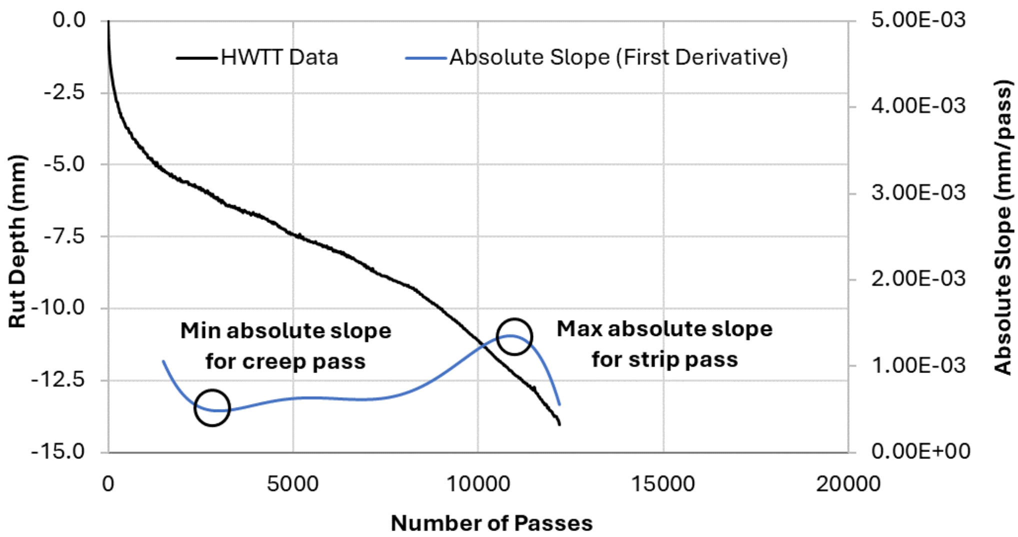


Figure 16. Determining Strip Pass with Maximum Absolute Slope and Creep Pass with Minimum Absolute Slope for Method F

3.1.7 Method G

This method, used by NCAT, begins with fitting the HWTT curve using the Francken model in accordance with Equation 2. This is the same model used to fit the permanent strain versus load cycle curve from the Flow Number test, as specified in AASHTO T 378. Subsequently, the first derivative values (i.e., slope) of the fitted curve are calculated, and the absolute slope values are plotted against the number of passes, as depicted in Figure 17. The inflection point of the fitted HWTT curve is identified by locating the minimum absolute slope. This inflection point is defined as SN, and the tangent of the HWTT curve at the inflection point is defined as the creep line. The stripping line is identified as the tangent of the fitted HWTT curve at the endpoint, which exhibits the maximum absolute slope from the inflection point to the endpoint of the curve (Figure 17). Finally, SIP is calculated as the number of passes at the intersection point of the creep and stripping lines following AASHTO T 324-23. For this method, SN and SIP are distinct parameters, with SN being significantly lower than SIP (Yin et al., 2020).

$$RD = AN^{B} + C(e^{DN} - 1) \quad \text{Equation 2}$$

Where *RD* is the HWTT rut depth; *N* is the number of passes; and *A*, *B*, *C*, and *D* are model coefficients.

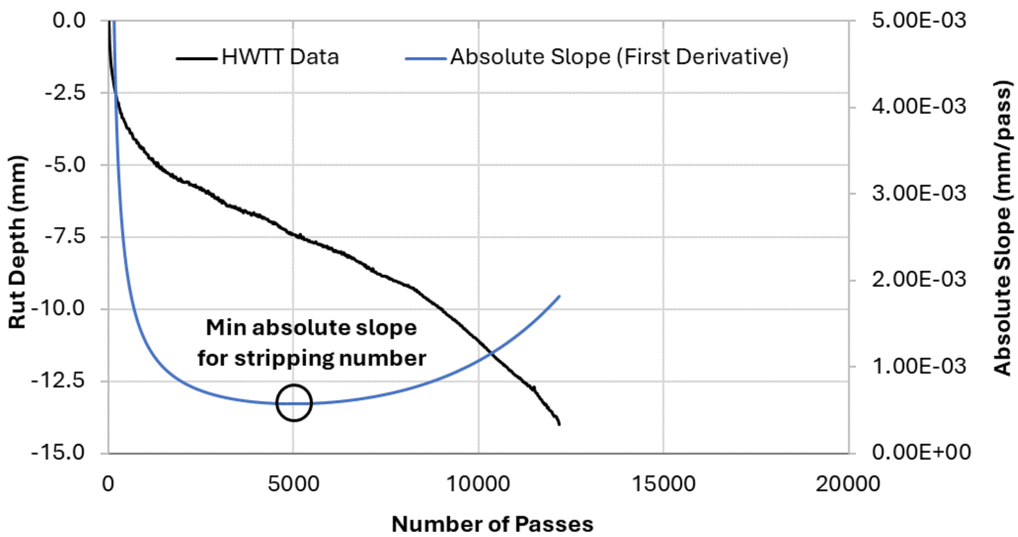
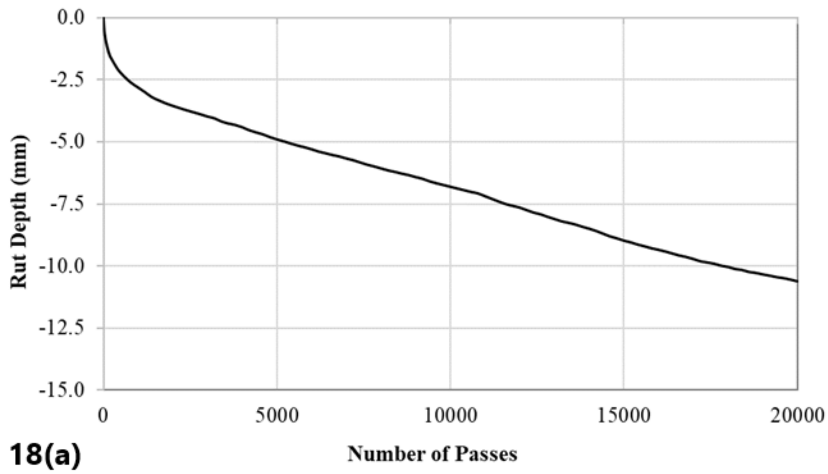


Figure 17. Determining SN for Method G

3.2 Comparison of SIP Calculation Methods using Shared Data

To further illustrate different SIP calculation methods, three sets of HWTT data were analyzed using each method. These data include no stripping failure, marginal stripping failure, and severe stripping failure, as shown in Figure 18(a-c). The analysis outcomes are summarized in Tables 2 through 4 and graphically presented in Figures 19 through 21.



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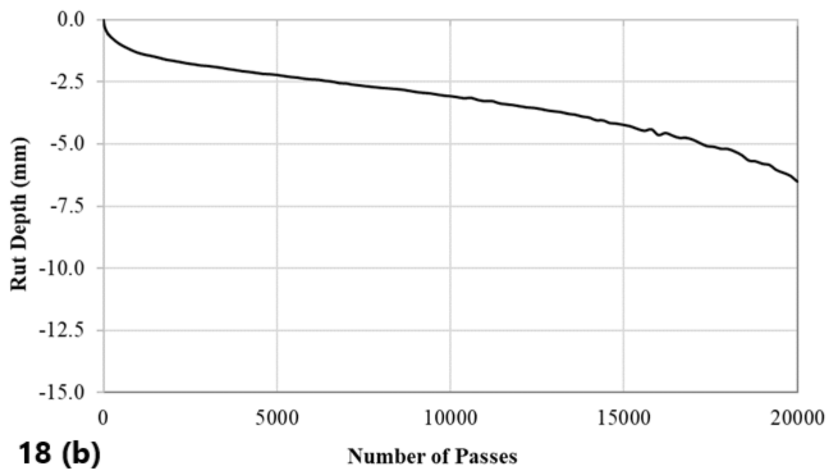

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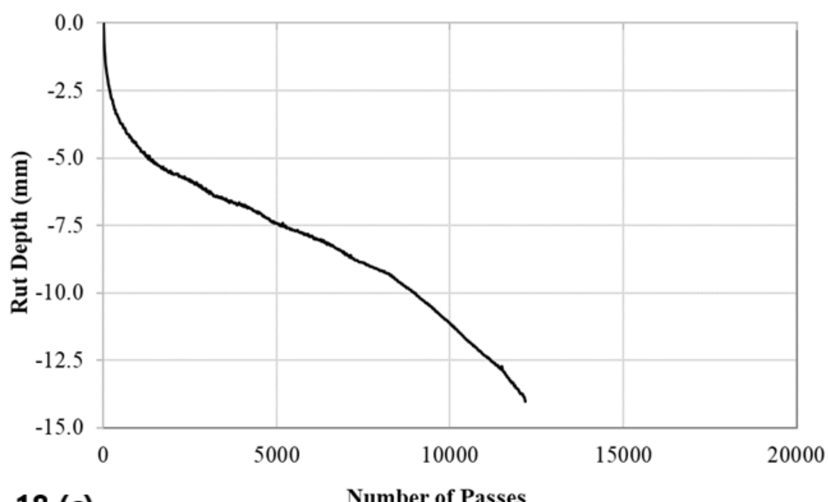


18 (c)

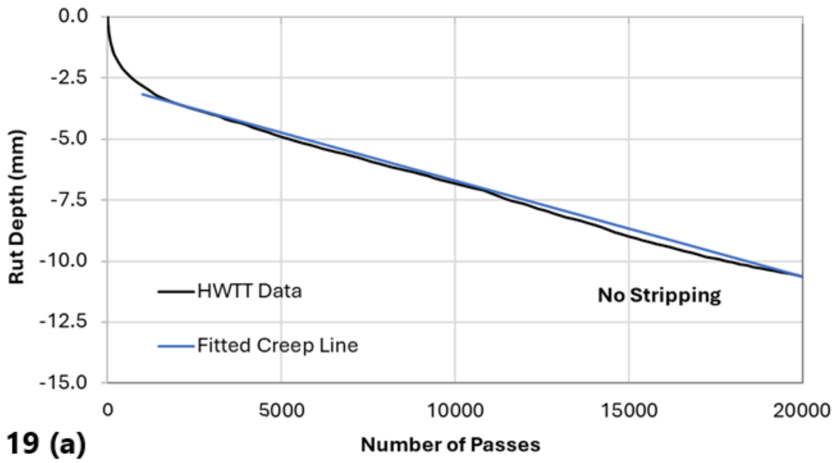
Figure 18. HWTT Results for SIP Method Comparison: (a) with No Stripping Failure, (b) with Marginal Stripping Failure, and (c) with Severe Stripping Failure

Table 2. Comparison of SIP Results for HWTT Result with No Stripping Failure

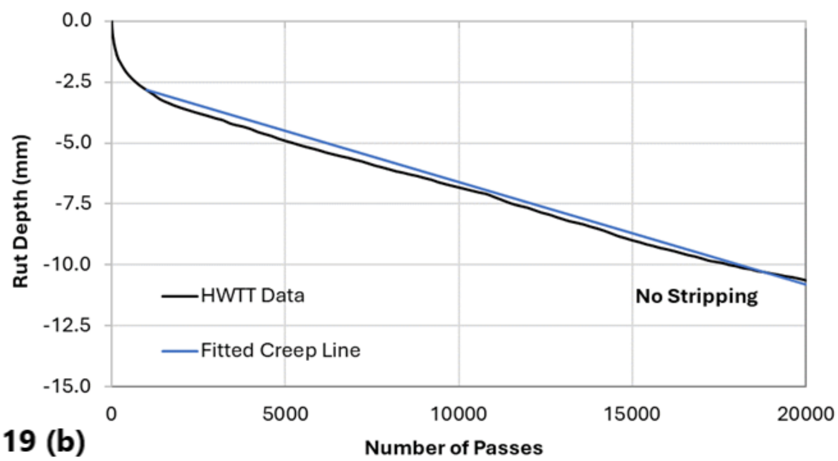
Method	Curve Fitting R^2	Curve Fitting Root Mean Square Error (RMSE)	Creep Slope (mm/1k passes)	Stripping Slope (mm/1k passes)	Slope Ratio	SIP	SN
A	n/a	n/a	0.39	No stripping	No stripping	No stripping	n/a
B*	n/a	n/a	0.42	No stripping	No stripping	No stripping	n/a
C	n/a	n/a	0.32	No stripping	No stripping	No stripping	n/a
D	n/a	n/a	0.38	No stripping	No stripping	No stripping	n/a
E	0.996	0.208	0.27	No stripping (0.46)	No stripping (1.74)	No stripping (8,144)	n/a
F	0.996	0.208	0.28	No stripping (0.46)	No stripping (1.63)	No stripping (8,498)	n/a
G	1.000	0.097	0.36	No stripping	No stripping	No stripping	No stripping

* Based on the HWTT curve, the “criterion of change” was selected as 0.42 mm at 1,000 passes for the creep phase.

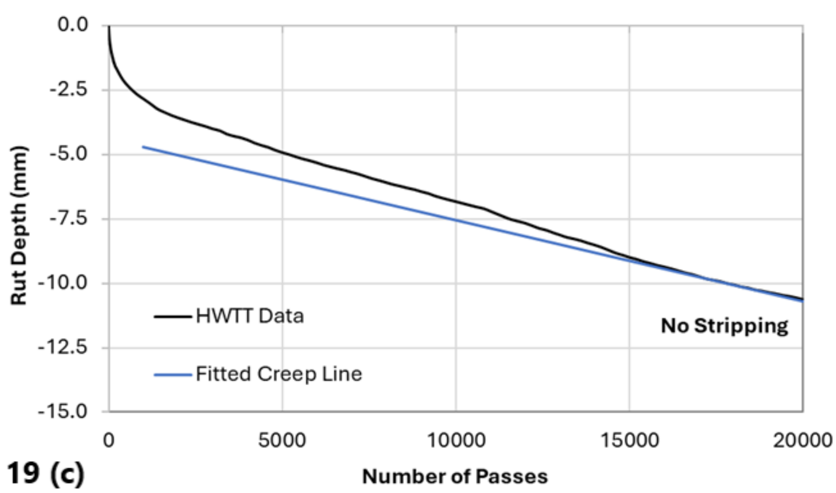
As shown in Table 2, all methods determine that the HWTT data in Figure 18(a) does not exhibit stripping failure. Methods E and F provide a SIP value but deem it invalid due to a low stripping-over-creep slope ratio. As a result, “no stripping” is reported for the stripping slope, slope ratio, and SIP results. Among all the methods, the creep slope ranges from 0.27 mm to 0.42 mm per 1,000 passes, with Method E being the lowest and Method B being the highest.


0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
0
5000
10000
15000
20000
Number of Passes
HWTT Data
Fitted Creep Line
No Stripping

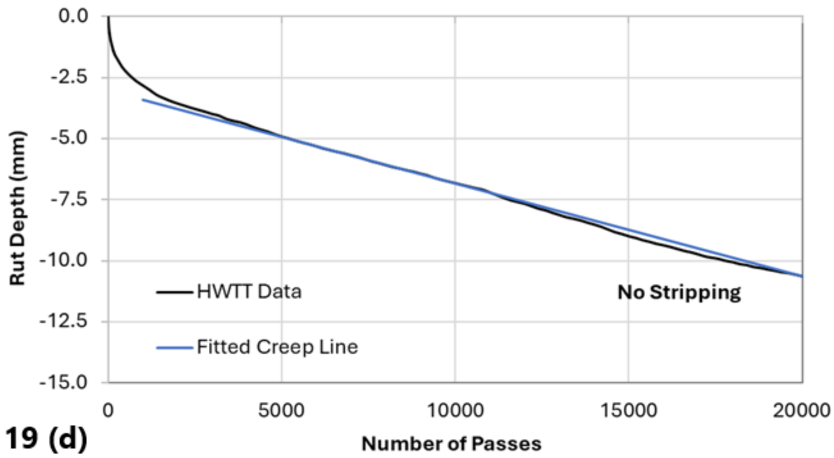
19 (a)


0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
0
5000
10000
15000
20000
Number of Passes
HWTT Data
Fitted Creep Line
No Stripping

19 (b)

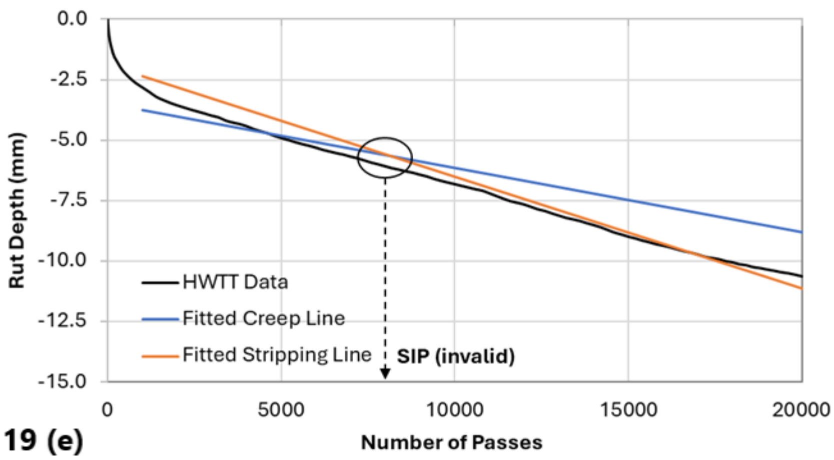

0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
0
5000
10000
15000
20000
Number of Passes
HWTT Data
Fitted Creep Line
No Stripping

19 (c)



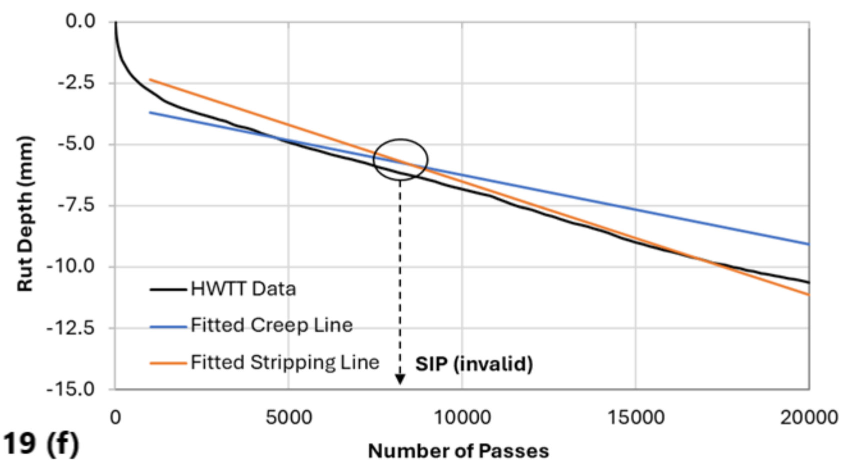
0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
HWTT Data
Fitted Creep Line
No Stripping
0
5000
10000
15000
20000
Number of Passes

19 (d)



0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP (invalid)
0
5000
10000
15000
20000
Number of Passes

19 (e)



0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP (invalid)
0
5000
10000
15000
20000
Number of Passes

19 (f)

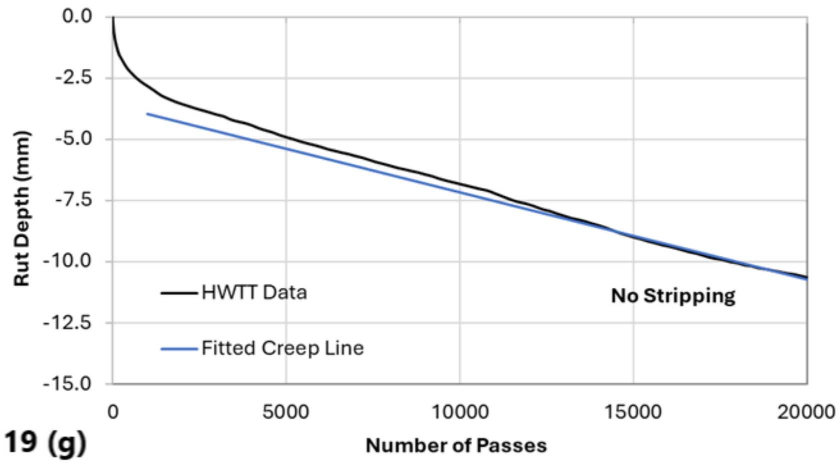


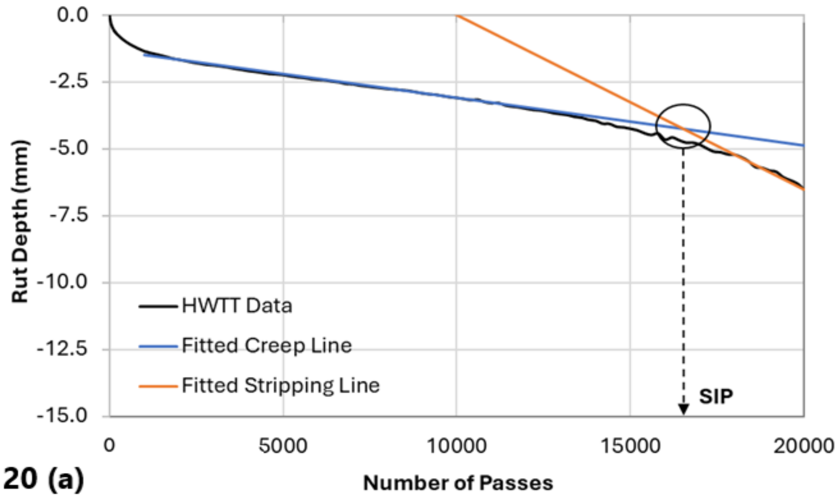
Figure 19. Comparison of SIP Results for HWTT Result with No Stripping Failure: (a) Method A, (b) Method B, (c) Method C, (d) Method D, (e) Method E, (f) Method F, (g) Method G

Table 3. Comparison of SIP Results for HWTT Result with Marginal Stripping Failure

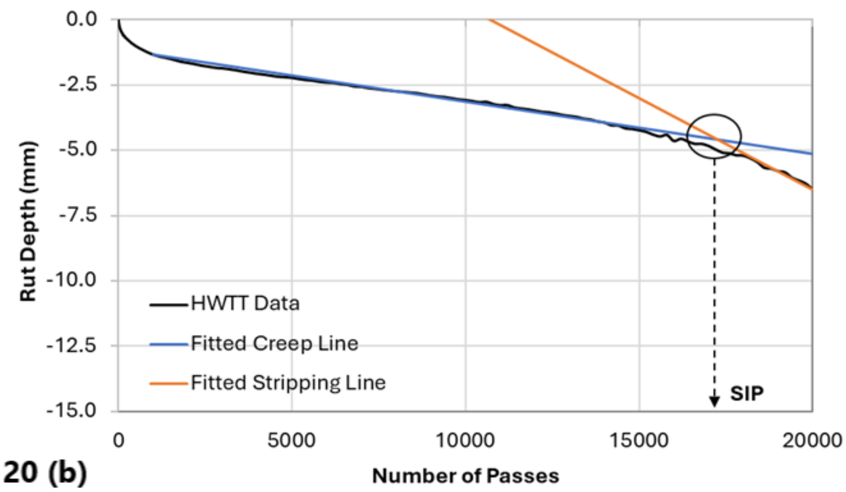
Method	Curve Fitting R^2	Curve Fitting RMSE	Creep Slope (mm/1k passes)	Stripping Slope (mm/1k passes)	Slope Ratio	SIP	SN
A	n/a	n/a	0.18	0.65	3.66	16,524	n/a
B*	n/a	n/a	0.20	0.70	3.50	17,260	n/a
C	n/a	n/a	0.16	0.65	4.14	16,269	n/a
D	n/a	n/a	0.18	0.30	1.67	13,200	n/a
E	0.997	0.088	0.11	0.49	4.53	13,518	n/a
F	0.997	0.088	0.12	0.49	4.23	13,700	n/a
G	1.000	0.431	0.17	0.68	4.08	16,754	8,000

* Based on the HWTT curve, the "criterion of change" was selected as 0.2 mm at 1,000 passes for the creep phase and 0.7 mm at 1,000 passes for the stripping phase.

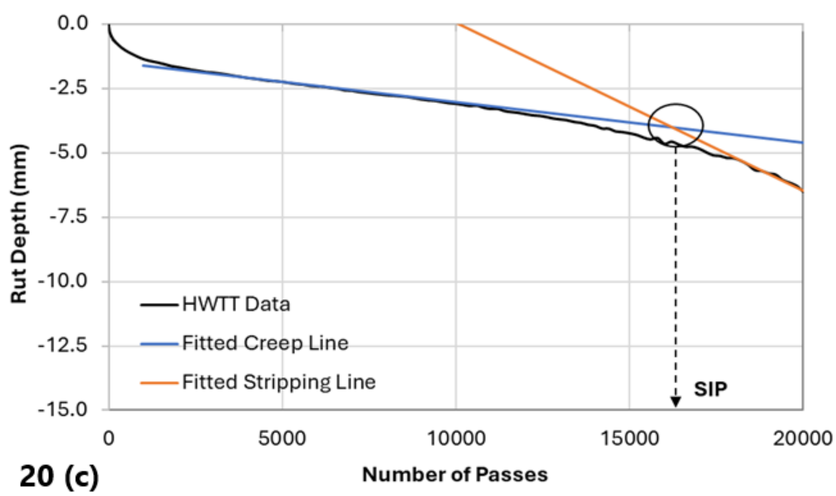
As shown in Table 3, all methods determine that the HWTT data in Figure 18(b) exhibits late marginal stripping failure. Method B produces the highest SIP at 17,260 passes, whereas Method D produces the lowest SIP at 13,200 passes, with other methods falling in between. Method D, despite exhibiting considerably lower creep and stripping slopes, yields a SIP comparable to other methods.


0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP
0
5000
10000
15000
20000
Number of Passes

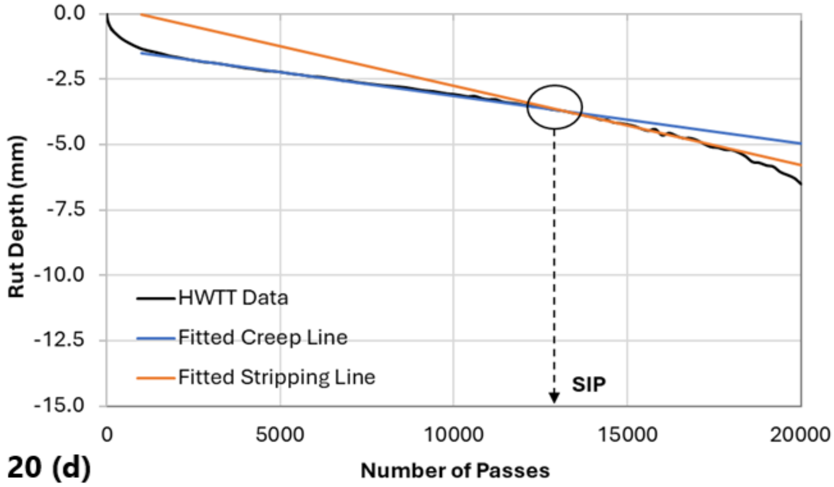
20 (a)


0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP
0
5000
10000
15000
20000
Number of Passes

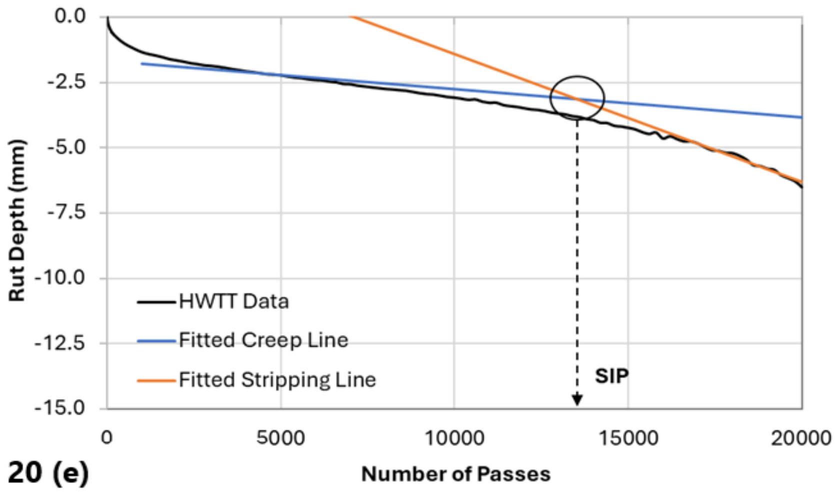
20 (b)


0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP
0
5000
10000
15000
20000
Number of Passes

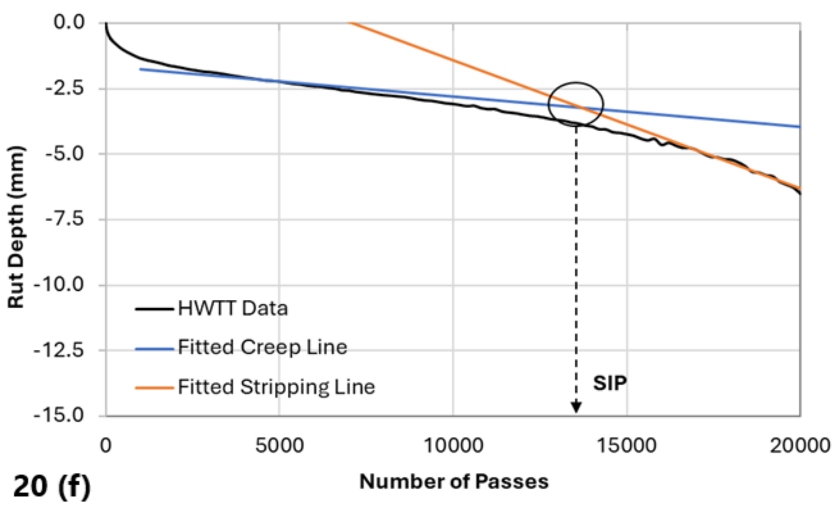
20 (c)


0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP
0
5000
10000
15000
20000
Number of Passes

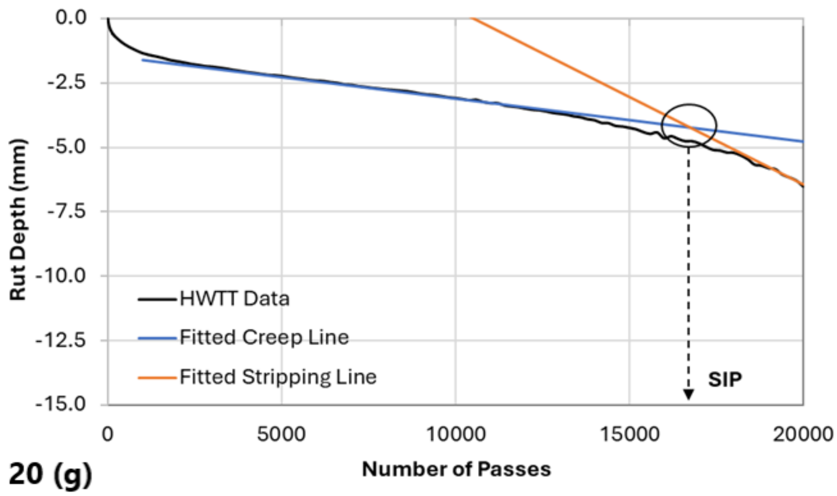
20 (d)


0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP
0
5000
10000
15000
20000
Number of Passes

20 (e)


0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP
0
5000
10000
15000
20000
Number of Passes

20 (f)



20 (g)

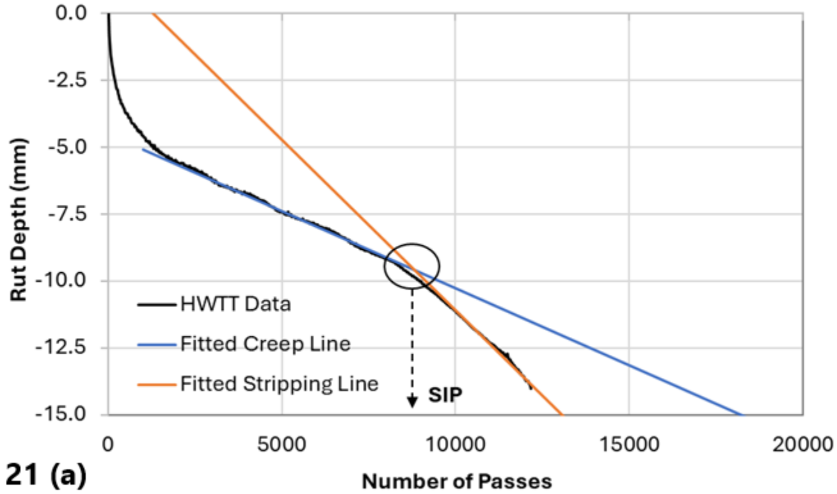
Figure 20. Comparison of SIP Results for HWTT Result with Marginal Stripping Failure: (a) Method A, (b) Method B, (c) Method C, (d) Method D, (e) Method E, (f) Method F, (g) Method G

Table 4. Comparison of SIP Results for HWTT Result with Severe Stripping Failure

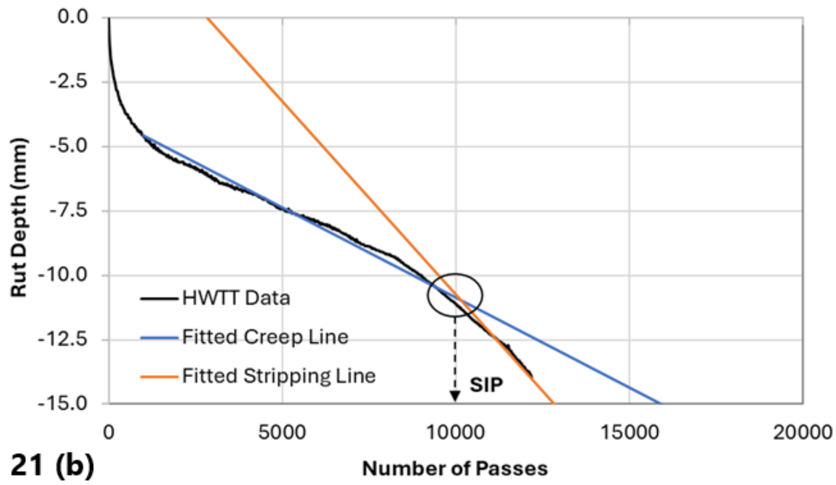
Method	Curve Fitting R^2	Curve Fitting RMSE	Creep Slope (mm/1k passes)	Stripping Slope (mm/1k passes)	Slope Ratio	SIP	SN
A	n/a	n/a	0.58	1.27	2.21	8,817	n/a
B*	n/a	n/a	0.70	1.50	2.14	10,159	n/a
C	n/a	n/a	0.56	1.34	2.38	9,192	n/a
D	n/a	n/a	0.59	1.08	1.82	8,320	n/a
E	0.998	0.124	0.49	1.35	2.78	8,389	n/a
F	0.998	0.124	0.53	No stripping (1.35)	No stripping (2.54)	No stripping (8,663)	n/a
G	0.999	0.112	0.57	1.81	3.19	10,103	5,000

* Based on the HWTT curve, the “criterion of change” was selected as 0.7 mm at 1,000 passes for the creep phase and 1.5 mm at 1,000 passes for the stripping phase.

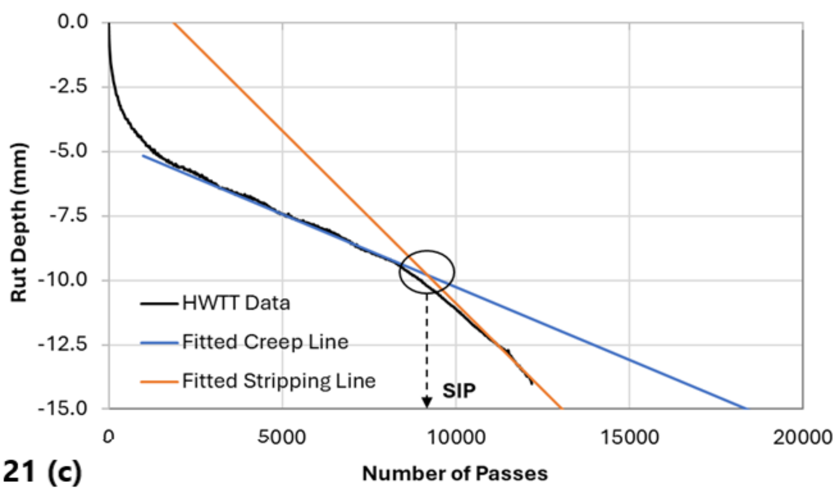
As shown in Table 4, all methods except Method F identify severe stripping failure for the HWTT data in Figure 18(c). Method B has the highest SIP at 10,159 passes, and Method D has the lowest at 8,320 passes. Despite having lower creep and stripping slopes, Method D produces a SIP comparable to other methods. Method F calculates SIP at 8,663 passes but considers it invalid due to a stripping-over-creep slope ratio below the 3.0 limit, reporting “no stripping” in Table 4.



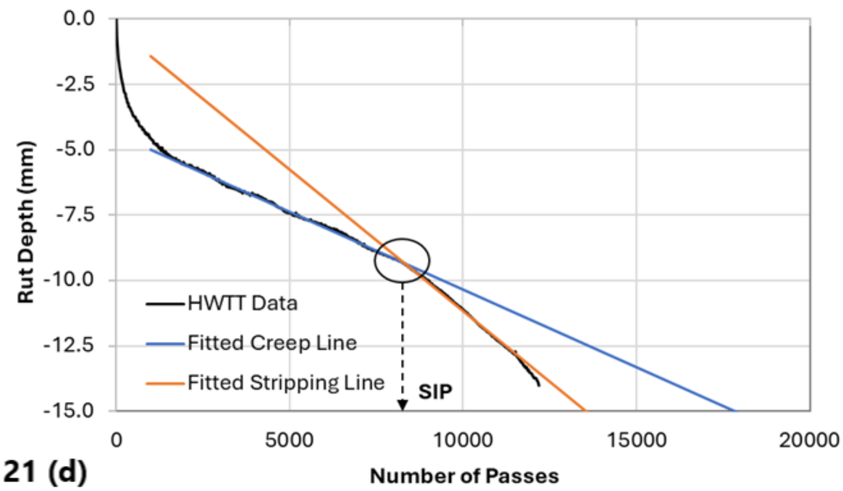
21 (a)



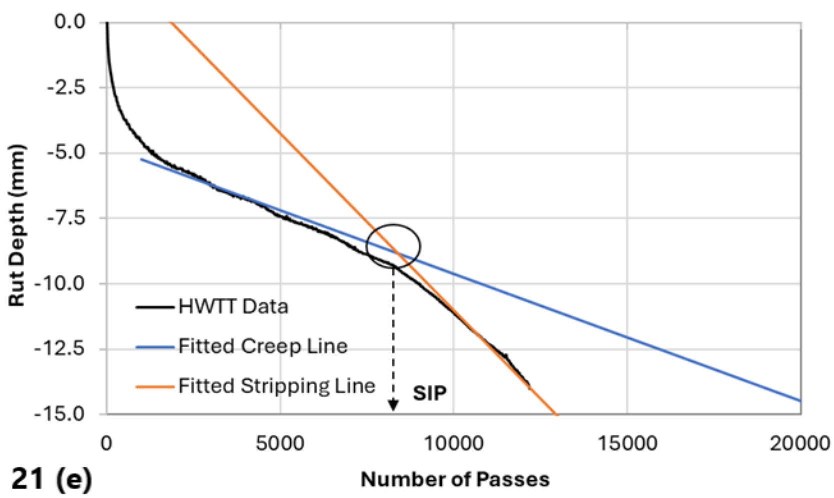
21 (b)



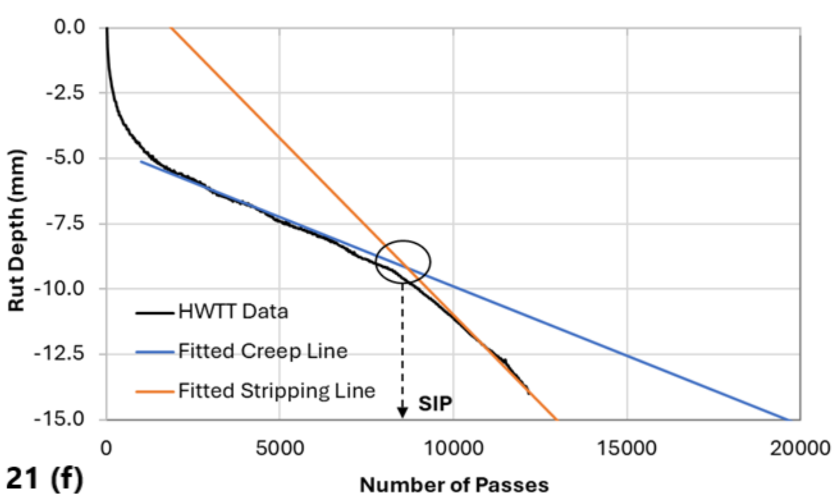
21 (c)


Rut Depth (mm)
0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
0
5000
10000
15000
20000
Number of Passes
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP

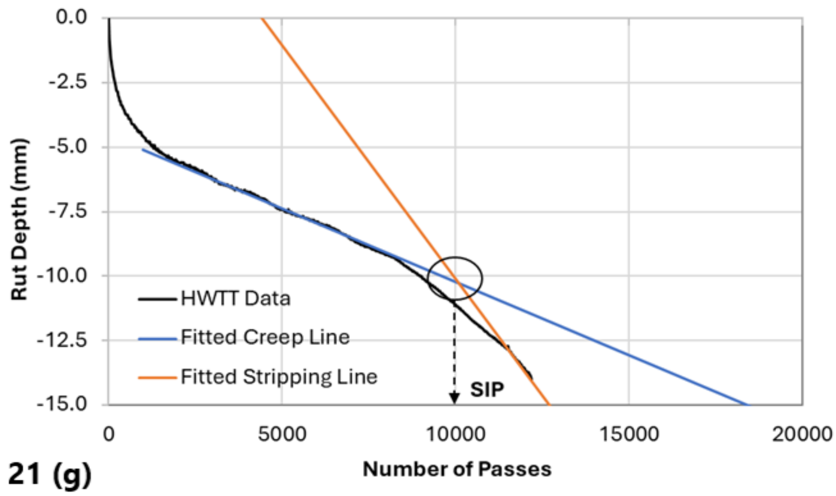
21 (d)


Rut Depth (mm)
0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
0
5000
10000
15000
20000
Number of Passes
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP

21 (e)


Rut Depth (mm)
0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
0
5000
10000
15000
20000
Number of Passes
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP

21 (f)



21 (g)

Figure 21. Comparison of SIP Results for HWTT Result with Severe Stripping Failure: (a) Method A, (b) Method B, (c) Method C, (d) Method D, (e) Method E, (f) Method F, (g) Method G

3.3 Critical Review of SIP Calculation Methods

Each SIP method previously discussed was critically evaluated to identify limitations for standardization in AASHTO T 324-23. A summary of this review is provided below:

- Method A necessitates the user to identify the stripping phase by visually evaluating the shape of the HWTT curve and manually defining the creep and stripping regions for calculating the SIP. This introduces subjectivity, which may hinder its suitability for standardization under AASHTO T 324-23.
- Method B requires users to visually assess the shape of the HWTT curve to determine the presence of the stripping phase and establish a "criterion of change" for assessing rut depth over a specified number of passes to calculate SIP. This approach is subject to interpretation and is not ideal for standardization in AASHTO T 324-23. It assumes that the first 1,000 passes represent the post-compaction phase and that the creep phase follows, which may not be applicable to certain asphalt mixtures.
- Method C identifies the stripping phase by comparing the difference between the stripping and creep slopes against a 2.0 mm rut depth threshold over 10,000 passes. This threshold is based on experience and may not suit all asphalt mixtures, especially those with marginal stripping failure or high susceptibility to both rutting and stripping in the HWTT.
- Method D determines the presence of the stripping phase based on the location of the "Max" difference point relative to the test endpoint, as shown in Figure 14. This approach may not be applicable to asphalt mixtures that exhibit late stripping failure in the HWTT.
- Method E involves fitting the HWTT curve with a 6^{th}-degree polynomial and finding the stripping slope by identifying the maximum absolute slope of the fitted curve near the end of the test. However, "near the end of the test" needs clarification for AASHTO T 324-23. Furthermore, the polynomial is an empirical fit that does not accurately characterize the rutting and stripping

behaviors of the mixture. Finally, this method considers SIP invalid if the ratio of the average slope over the average creep phase falls below 2.0. However, this limit is based on experiential judgement, which may not apply universally, especially to mixtures with marginal stripping failure or those with high susceptibility to both rutting and stripping in the HWTT.

- Method F resembles Method E but clarifies the determination of the stripping slope by using the HWTT curve from the midpoint to the endpoint of the test. This method shares the same limitations noted for Method E. The 6^{th}-degree polynomial is an empirical fit that does not accurately characterize the rutting and stripping behaviors of the mixture in the HWTT. The method considers SIP invalid if the stripping-over-creep slope ratio is below 3.0 or the stripping slope is less than 0.63 mm per 1,000 passes. These criteria are based on experience and may not be applicable to all asphalt mixtures, particularly those with marginal stripping failure or high susceptibility to both rutting and stripping in the HWTT.
- Method G uses the Francken model to fit the HWTT curve, determining the stripping phase solely by the shape and curvature of the fitted HWTT curve without subjective data interpretation. If the fitted curve has no inflection point, it assumes no stripping failure in the mixture, so SN and SIP are not calculated.

3.4 Selection of a SIP Calculation Method for Software Development

Based on the comparison and critical review of SIP methods previously presented, it was recommended that Method G be utilized for the development of the HWTT software in this project. This method leverages an existing asphalt mixture permanent deformation model – specifically, the Francken model – and identifies the presence of the stripping phase solely by analyzing the shape and curvature of the fitted HWTT curve. This approach eliminates the need for subjective data interpretation of creep and stripping slope results against empirical thresholds, which may not be universally applicable to certain asphalt mixtures. Furthermore, as shown in Tables 2 through 4, the SIP results for Method G are reasonably consistent with those produced by other methods currently used by HWTT equipment manufacturers, Iowa DOT, and Maine DOT.

Chapter 4: Software Development and User Manual

4.1 Software Development

A web-based program, termed *HWTTXpert*, was developed for SIP calculation using Method G as previously discussed, along with other data analysis guidelines from AASHTO T 324-23. The logo for *HWTTXpert* is presented in Figure 22. The program is designed to be compatible with data files from three equipment manufacturers: InstroTek, Inc., Pavement Technology Inc., and Troxler Electronic Laboratories, Inc. Each manufacturer provided a data file template to assist with code development. The alpha version of the program was tested using over a hundred data files from NCAT for initial development and troubleshooting. Subsequently, the beta version was distributed to three equipment manufacturers and 25 SHAs for testing, with 12 participating (Figure 23). Based on the feedback, the program was refined to improve the user interface and functionality. The final version of the program is now accessible on Auburn University's server at http://HWTTXpert.eng.auburn.edu, with login credentials available upon request.

Figure 22. *HWTTXpert* Logo

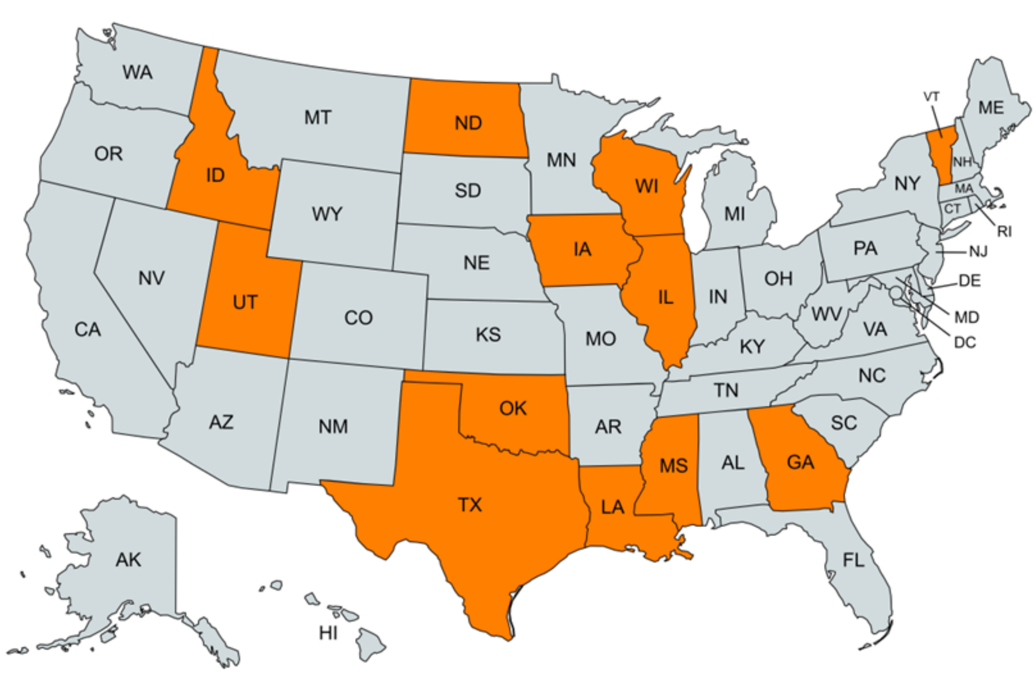


Figure 23. Map of SHAs that Participated in *HWTTXpert* Beta Testing

4.2 User Manual

HWTTXpert is a web program designed to standardize the analysis of Hamburg Wheel Tracking Test (HWTT) results for evaluating the rutting and moisture resistance of asphalt mixtures. This program was developed by the National Center for Asphalt Technology (NCAT) at Auburn University through the National Road Research Alliance (NRRA) project, *Standardization of SIP Calculation for Hamburg Wheel Tracking Test*. This initiative also received cost-sharing support from three HWTT equipment manufacturers: InstroTek, Inc., Pavement Technology, Inc., and Troxler Electronic Labs, Inc.

HWTTXpert allows users to upload and process raw data files directly from the supported equipment manufacturers. The analysis conforms to AASHTO T 324-23, utilizing the average rut depth for the middle five deformation locations: -46, -23, 0, +23, and +46 mm. Furthermore, *HWTTXpert* facilitates the custom analysis of rut depth data using other deformation locations specified by individual state highway agencies, leveraging a pre-formatted Excel spreadsheet template.

HWTTXpert provides outputs for both the traditional test parameters, as specified in AASHTO T 324-23, and additional research parameters. These include:

- **AASHTO Test Parameters**
  - Final number of passes
  - Final rut depth
  - Measured rut depth at 5,000, 10,000, 15,000, and 20,000 passes (if available)
  - Creep slope
  - Stripping slope

- Stripping/creep slope ratio
  - Stripping inflection point (SIP)
- **Additional Research Parameters**
  - Stripping number (SN)
  - Corrected rut depth at 5,000, 10,000, 15,000, and 20,000 passes.

The final number of passes, final rut depth, and measured rut depths at various pass intervals are directly reported from the raw data. The creep slope, stripping slope, stripping/creep slope ratio, and SIP are calculated utilizing the methodology recommended in the Task 1 report of the project (Yin and Chen, 2024). Additionally, SN and corrected rut depths are determined following the approaches outlined by Yin et al. (2014; 2020). These parameters aim to isolate the rutting and stripping behavior of the asphalt mixture in the HWTT, with a higher SN indicating better moisture resistance and a lower corrected rut depth signifying better rutting resistance.

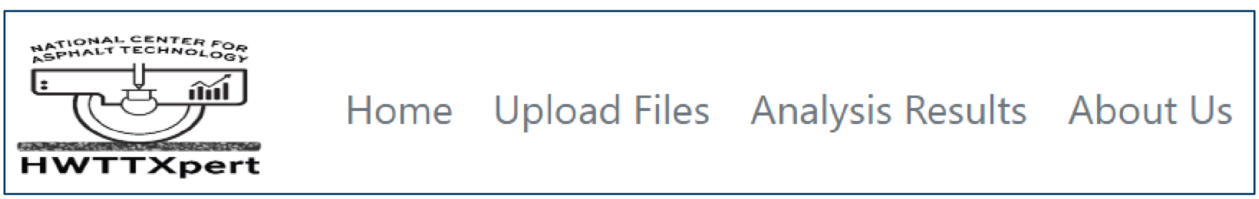
Program Access

HWTTXpert is available for access through Auburn University's website: https://hwttxpert.eng.auburn.edu.

Program Layout

HWTTXpert encompasses four primary sections:

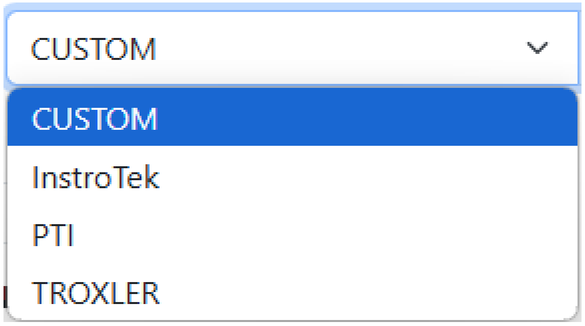
- **Home**: Provides an overview of all data files in the program.
- **Upload Files**: Enables users to upload and process data files.
- **Analysis Results**: Allows users to review and export analysis results.
- **About Us**: Contains information regarding the ownership and development of the program.



Steps for Uploading and Processing Data

1) Navigate to the "Upload Files" section from the menu at the top of the webpage.

2) Utilize the drop-down menu to select the equipment manufacturer for the data file(s). Select "CUSTOM" to analyze data using the provided Excel spreadsheet template.



(listed in alphabetical order)

3) Click on “Choose Files” to select one or multiple data files from your computer. (**Note: Ensure your data files adhere to the same format as the example files at** https://auburn.box.com/s/kktnm3p3potpelxcevic4i0kpvj60u8d**.** If your files are in a different format, please contact the manufacturer for format conversion.)

4) Click on “Upload” to initiate the upload of the selected data file(s).

5) Locate your uploaded data file in the table at the bottom of the webpage, where data files can be sorted by “File Name,” “Data File Format,” and “Date Created.” Alternatively, use the “Search” function to find the file by name.

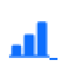
6) Click on the Cloud icon  to process the data. (Note: Processing PTI data may take up to a minute due to the file size exceeding 25 MB.)

7) Wait for the confirmation message: “*Your file {file name} has been processed!*” displayed at the top of the webpage.

Steps for Reviewing and Exporting Results

1) Proceed to the “Analysis Results” section from the menu at the top of the webpage.

2) Locate your processed data file within the table at the bottom of the webpage. The files can be sorted by “File Name,” “Data File Format,” “Date Created,” and “Date Analyzed,” or alternatively, you may use the “Search” function to locate them by name.

3) Click on the Bar Chart icon  to review the analysis results.

4) Examine the displayed figure to ensure the accuracy and reasonableness of the analysis.

Figure Customization Options

The figure can be customized by interacting with the data legends below the chart:

- *Measured Rut Depth:* displays the average rut depth data.
- *Fitted Rut Depth:* displays the fitted rut depth using the Francken model.
- *Creep Line:* displays the best-fit line representing the creep phase of the rut depth data.
- *Stripping Line:* displays the best-fit line representing the stripping phase of the rut depth data.
- *SIP:* displays the intersection of the Creep Line and Stripping Line.
- *Number of Passes to SIP:* displays a vertical line at the SIP intersection.
- *SN:* displays the inflection point of the *Fitted Rut Depth* data.
- *Number of Passes to SN:* displays a vertical line at the SN intersection.
- *Fitted Corrected Rut Depth:* displays the projected rut depth using the Tseng-Lytton model, based on the creep phase of the rut depth data.

5) Click on “Export to PDF” or “Export to Excel” to export the results.

Chapter 5: Summary of Project Findings and Outcomes

The key findings and outcomes of the project are summarized as follows:

- Thirty-two SHAs use HWTT to evaluate asphalt mixtures, including 18 for mix design approval, six for production acceptance, 18 for forensic analysis, and 26 for research evaluation.
- Out of these 32 SHAs, 13 use HWTT for rutting evaluation, one for moisture evaluation, and 18 for both purposes.
- SIP is among the three most commonly used HWTT parameters, alongside the rut depth at a specific number of passes and the number of passes to reach a 12.5mm rut depth. Only two SHAs specify the calculation method for SIP, while the others rely on manufacturer-provided results but acknowledge potential discrepancies between different manufacturers.
- There are seven existing methods to calculate SIP, and these methods do not always provide consistent results for identical data sets. A critical review of these methods identifies Method G as the most robust approach.
- A web-based program, named *HWTTXpert*, has been developed based on Method G, aimed at standardizing and automating the calculation of SIP and other traditional test parameters specified in AASHTO T 324-23 and additional research parameters, including the SN and corrected rut depth.

References

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Appendix A
State Highway Agency Survey Questionnaire

Survey Questions

The National Center for Asphalt Technology (NCAT) at Auburn University is conducting a research project titled "Standardization of SIP Calculation for Hamburg Wheel Tracking Test." The objective of the project is to develop Hamburg Wheel Track Tracking (HWTT) analysis software to standardize and automate the calculation of stripping inflection point (SIP) for evaluating the moisture susceptibility of asphalt mixtures. More details of the project can be found on the NRRA website at https://www.dot.state.mn.us/mnroad/nrra/structure-teams/flexible/standardization-sip-hwtt.html.

This survey, including a maximum of 11 questions, seeks to synthesize the current practice for using HWTT to evaluate the rutting and moisture resistance of asphalt mixtures and identify the existing methods of calculating SIP among state highway agencies. Your participation is greatly appreciated.

If you have any questions about the survey or the project, please contact Fan Yin of NCAT at f-yin@auburn.edu.

Name:
Agency:
Email:
Phone:

1. Does your agency use the Hamburg Wheel Tracking Test (HWTT) (select all that apply)?

- Yes, for mix design approval
- Yes, for production acceptance
- Yes, for forensic analysis
- Yes, for research evaluation
- Yes, for other purposes (please specify).
- No (survey will end)

If "Yes" is selected, the survey continues.

If "No" is selected, the survey ends.

2. Does your agency use HWTT to evaluate the rutting and/or moisture resistance of asphalt mixtures?

- Rutting resistance
- Moisture resistance
- Both

3. What type(s) of specimens does your agency use for HWTT testing (select all that apply)?

- Lab-compacted gyratory cylindrical specimens
- Lab-compacted slab specimens
- Field cores

4. Does your agency require moisture conditioning of the HWTT specimens before testing?

- Yes, please specify the moisture conditioning procedure (e.g., freeze-thaw, MiST, or others)
- No

5. What test parameters does your agency use for HWTT (select all that apply)?

- Number of passes to 12.5 mm rut depth
- Rut depth at a certain number of passes (e.g., 5k, 10k, 15k, and 20k)
- Stripping inflection point (SIP)
- Creep slope
- Strip slope
- Others, please specify.

If "stripping inflection point (SIP)" is selected, the survey proceeds to Question 6.

Otherwise, the survey proceeds to Question 7.

6. Does your agency specify how SIP should be calculated?

- No, use SIP reported by the Hamburg software.
- Yes, please specify (and provide references, if available).

7. When reporting the rut depth, how many deformation (sensor) locations does your agency use?

- Average of five middle locations (i.e., located at -46mm, -23mm, 0mm, +23mm, and +46mm) per AASHTO T 324-23, Section 9.3
- Average of all locations
- Maximum (absolute value) of all locations
- Others, please specify.

8. What type of Hamburg device does your agency use (select all that apply)?

- Cox & Sons Hamburg Wheel Tracker: https://www.jamescoxandsons.com/hamburg-wheel-tracker/
- InstroTek SmarTracker™: https://www.instrotek.com/products/smartracker
- PTI Asphalt Pavement Analyzer (APA): https://pavementtechnology.com/index.php/asphalt-payment-analyzer/
- PTI Asphalt Pavement Analyzer Junior (APA Jr.): https://pavementtechnology.com/index.php/aspahalt-pavement-anayzer-jr/
- Troxler Hamburg Wheel Tracker: https://troxlerlabs.com/premium-wheeltracker-model-5949/
- Others, please specify.

9. Would you be willing to provide raw data files from your Hamburg device(s) for NCAT to use as templates to develop the software? All mix-specific information in those files will be kept confidential.

- Yes
- No

10. Would you like to participate in the beta testing of the HWTT analysis software?

- Yes
- No

11. Please provide additional comments regarding your responses.