Standardization of SIP Calculation for Hamburg Wheel Tracking Test (Task 1 Report)

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This report serves as Task 1 report of the National Road Research Alliance (NRRA) project, "*Standardization of SIP Calculation for Hamburg Wheel Tracking Test*." The project's objective is to develop software for analyzing Hamburg Wheel Tracking Test (HWTT) results to standardize the calculation of the stripping inflection point (SIP) for evaluating the moisture susceptibility of asphalt mixtures. Task 1 focused on information gathering, including conducting a survey of state highway agencies (SHAs) and consulting with HWTT equipment manufacturers to identify existing SIP calculation methods. All existing methods were critically reviewed and compared to determine the most suitable method for potential standardization in AASHTO T 324 and incorporation into the HWTT software development process.

SHA Survey on Using HWTT for Evaluating Asphalt Mixtures

An online survey was conducted to collect information from SHAs regarding their utilization of HWTT to evaluate asphalt mixtures. The survey questionnaire was distributed to 50 SHAs across 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, achieving a response rate of 86%.

Among the 43 responding SHAs, 32 reported using the HWTT for asphalt mixture evaluation, while the remaining 11 agencies did not employ this test method (Figure 1). Specifically, 18 SHAs utilize the HWTT for mix design approval, 6 for production acceptance, 19 for forensic analysis, and 26 for research evaluation, as shown in Figure 2 through Figure 5.

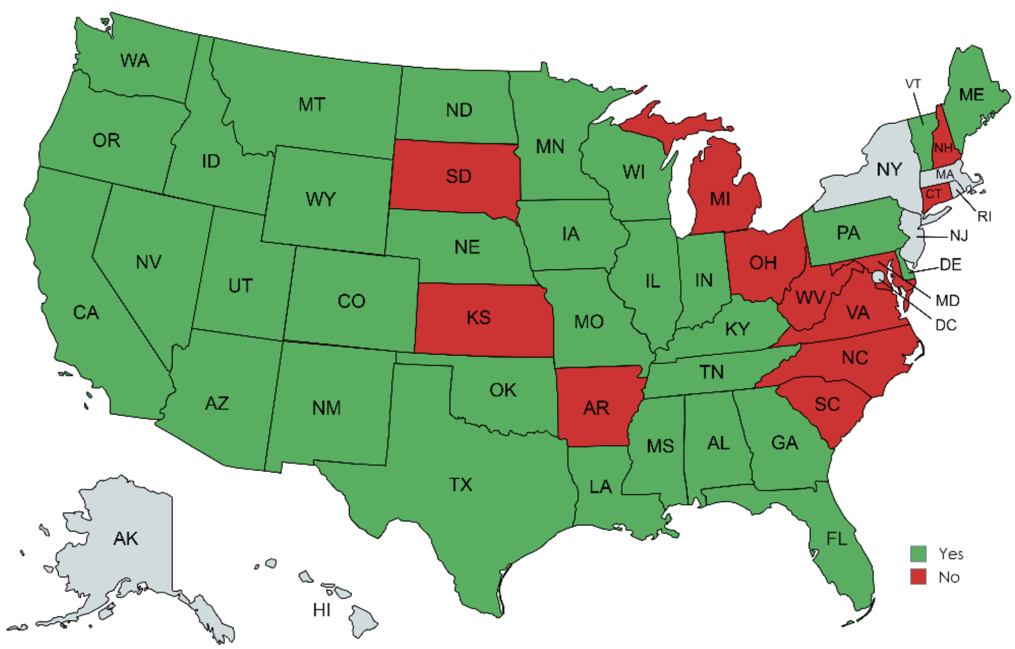


Figure 1. U.S. SHAs using HWTT for Evaluating Asphalt Mixtures (total number of survey respondents: 43)

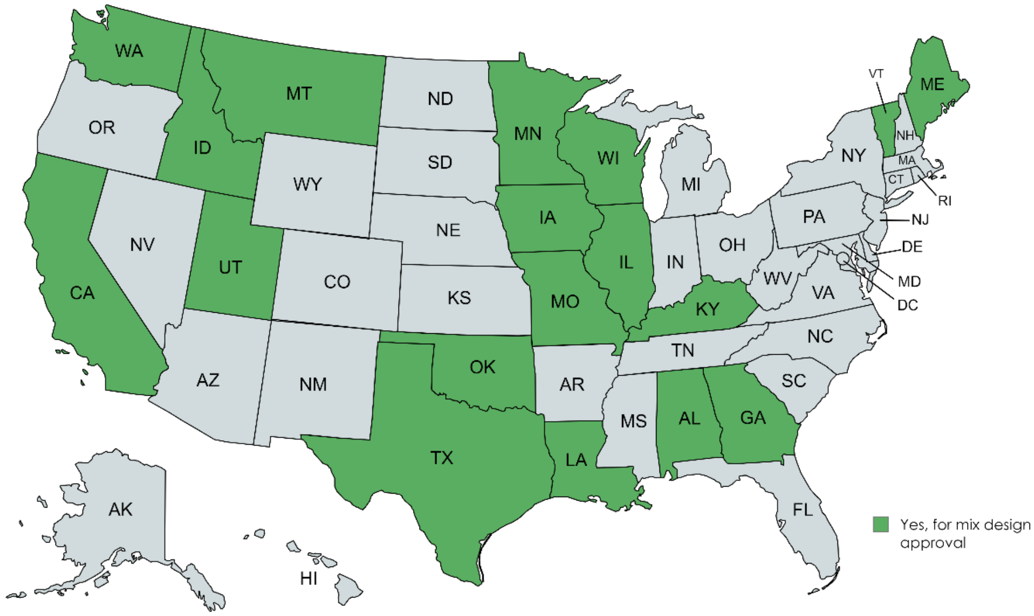


Figure 2. U.S. SHAs using HWTT for Mix Design Approval (answered by 18 out of 43 survey respondents)

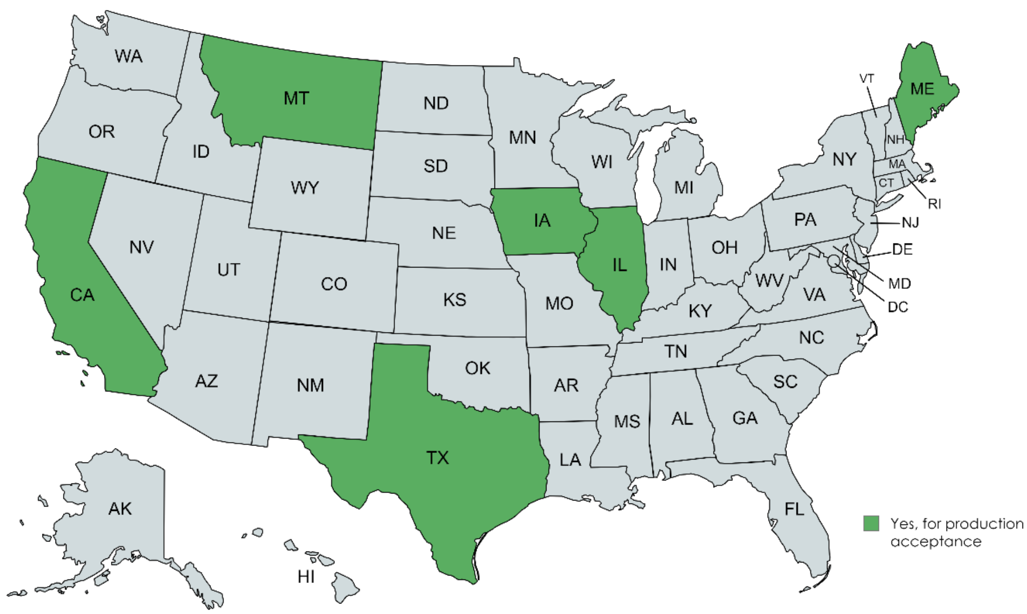


Figure 3. U.S. SHAs using HWTT for Production Acceptance (answered by 6 out of 43 survey respondents)

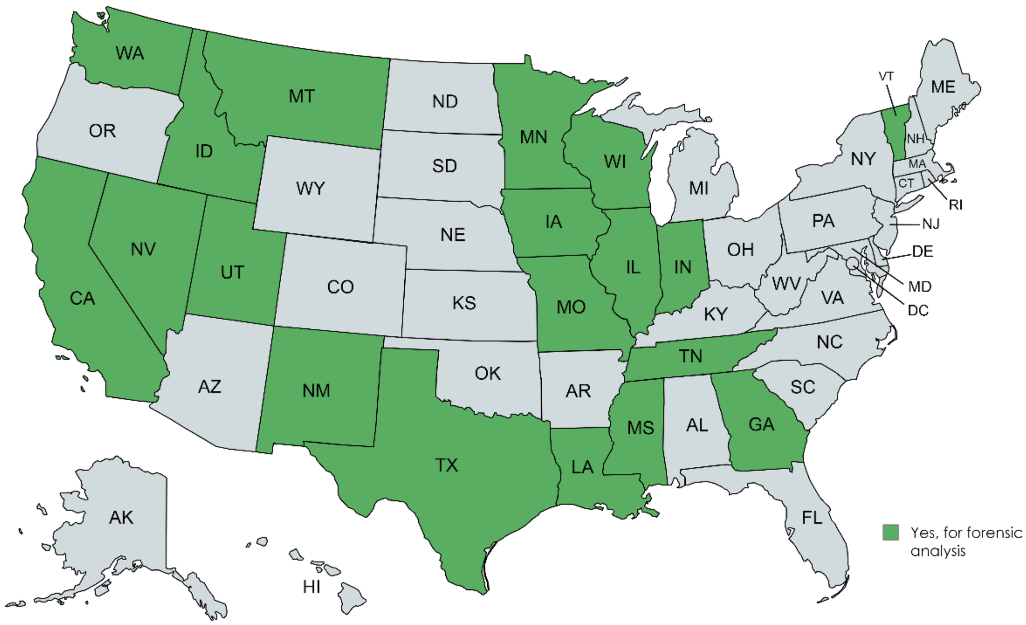


Figure 4. U.S. SHAs using HWTT for Forensic Analysis (answered by 19 out of 43 survey respondents)

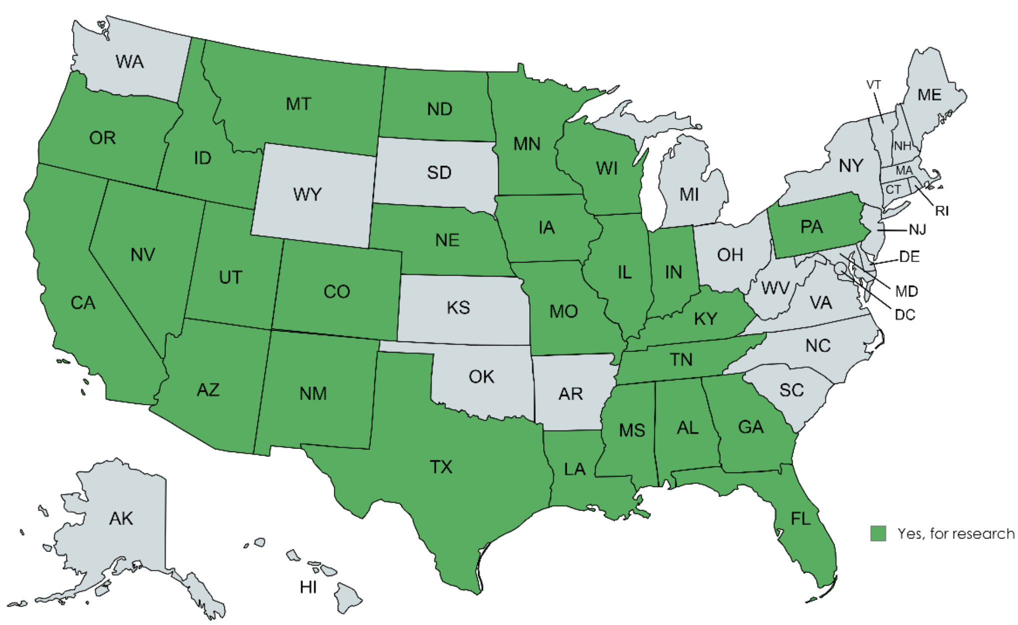


Figure 5. U.S. SHAs using HWTT for Research Evaluation (answered by 26 out of 43 survey respondents)

Among the 32 SHAs utilizing the HWTT, 13 employ it to evaluate the rutting resistance of asphalt mixtures, one evaluates moisture resistance, and 18 evaluate both rutting and moisture resistance, as shown in Figure 6. All 32 SHAs test the HWTT on lab-compacted gyratory cylindrical specimens, three allow lab-compacted slab specimens, and 16 allow field cores. No agency currently requires moisture conditioning of the HWTT specimens before testing. However, the Louisiana Department of Transportation and Development (LaDOTD) is considering its inclusion as a potential step for mix design approval in the future.

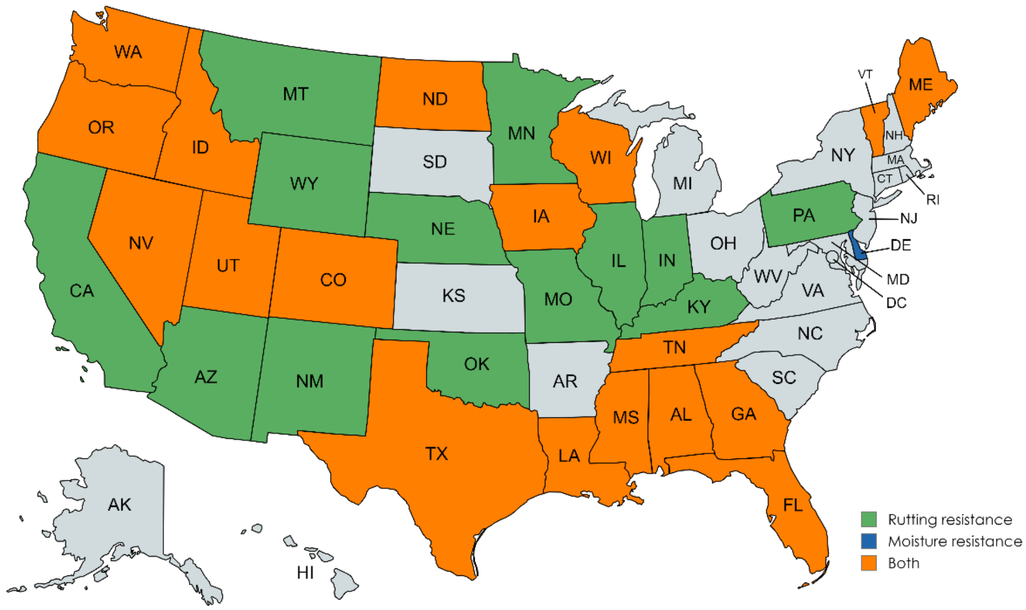


Figure 6. U.S. SHAs using HWTT for Evaluating Rutting and/or Moisture Resistance of Asphalt Mixtures (answered by 32 out of 43 survey respondents)

Figure 7 provides an overview of the various HWTT parameters utilized by the 32 SHAs. The three most used parameters are rut depth at a specific number of passes, SIP, and number of passes to reach a 12.5 mm rut depth, respectively. Other parameters include creep slope, stripping slope, corrected rut depth, stripping number (SN), and stripping/creep slope ratio. Among the 17 SHAs using SIP (Figure 8), only the Iowa and Maine DOTs specify the calculation method for SIP. The remaining 15 agencies utilize SIP values provided by the HWTT manufacturer, although most recognize that different manufacturers use different methods to calculate SIP.

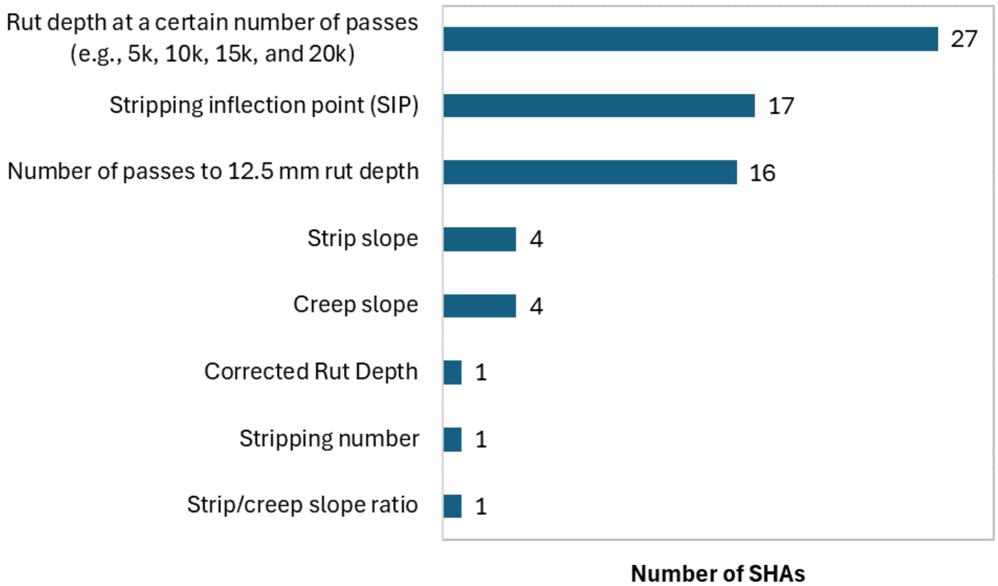


Figure 7. HWTT Test Parameters Used by U.S. SHAs (answered by 32 out of 43 survey respondents)

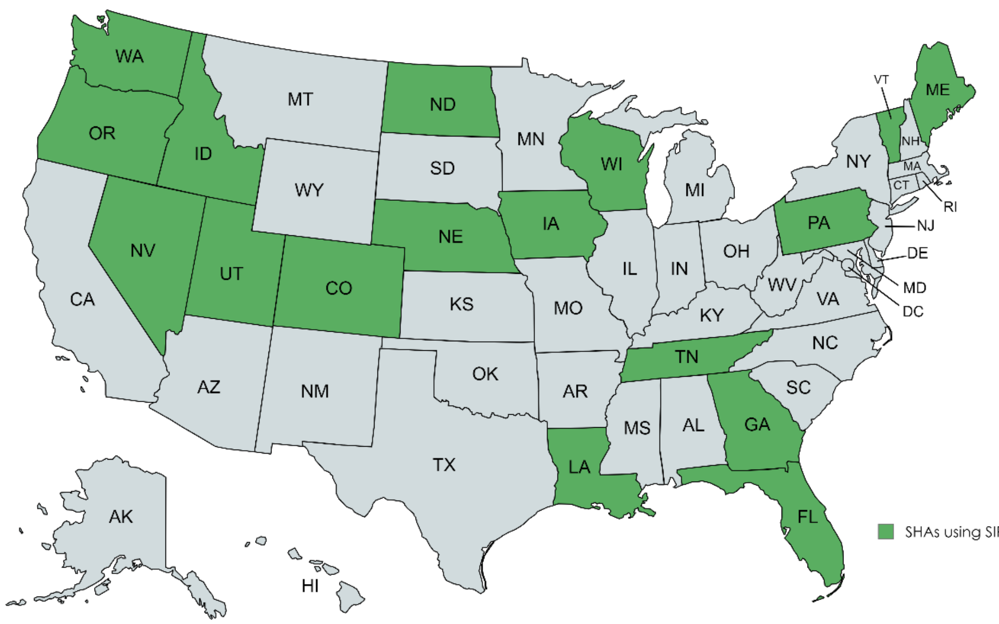


Figure 8. U.S. SHAs using HWTT SIP as a Test Parameter (answered by 17 out of 43 survey respondents)

In addition to the SIP calculation method, a discrepancy exists among the 32 SHAs regarding the number of deformation (sensor) locations used to report the HWTT rut depth. As shown in Figure 9, 19 agencies use the average of five middle locations (i.e., located at -46mm, -23mm, 0mm, +23mm, and +46mm) per AASHTO T 324-23, four agencies use the average of all locations, two use the average of seven middle locations, one uses the average of three middle locations, and one uses the maximum (absolute value) of all locations. Additionally, three SHAs use alternative locations, including the average of the maximum location and two adjacent locations for the Illinois DOT; the average of locations three through nine out of 11 for the Iowa DOT; and the maximum of all locations, excluding two inches on each end of the wheel path for the Utah DOT.

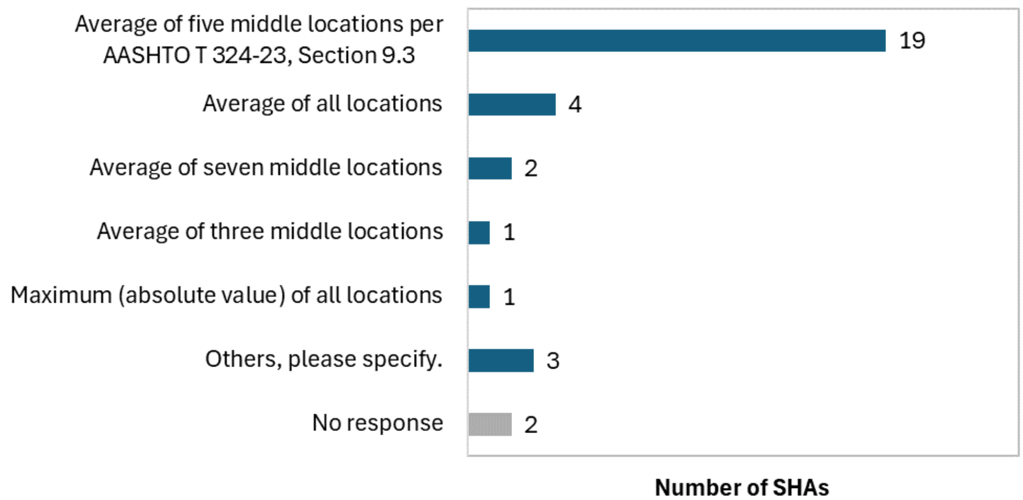


Figure 9. Deformation Locations for Reporting HWTT Rut Depth Used by U.S. SHAs (answered by 32 out of 43 survey respondents)

Figure 10 provides an overview of the different HWTT devices utilized by the 32 SHAs, with the three most popular ones being the InstroTek SmarTracker™, Cox & Sons Hamburg Wheel Tracker, and Troxler Hamburg Wheel Tracker, respectively. Other devices include the PTI Asphalt Pavement Analyzer Junior (APA Jr.) and PMW (now Troxler) Hamburg Wheel Tracker.

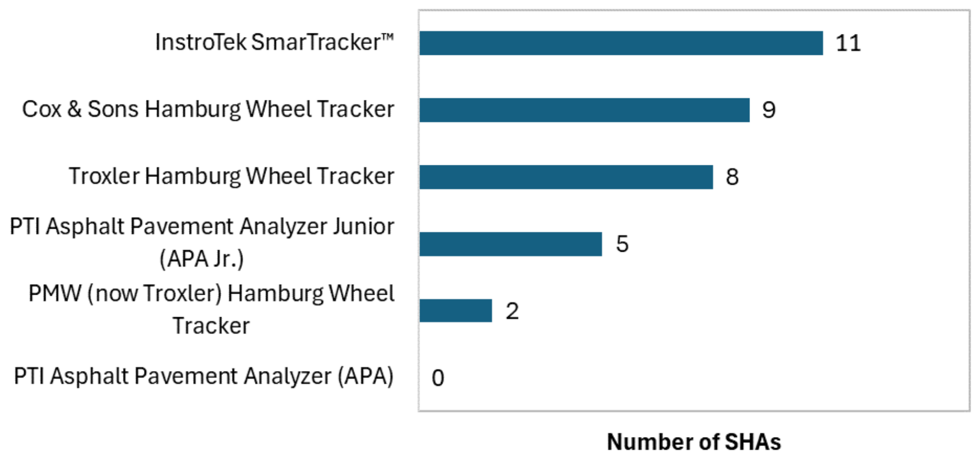


Figure 10. HWTT Devices Used by U.S. SHAs (answered by 32 out of 43 survey respondents)

Finally, among the 32 SHAs utilizing the HWTT, 29 are willing to provide raw data files for the National Center for Asphalt Technology (NCAT)'s use as templates for developing the HWTT analysis software, and 25 express interest in participating in the software's beta testing phase.

SIP Calculation Methods

According to the SHA survey and discussions with the HWTT equipment manufacturers, there are seven methods to calculate SIP for the HWTT results. Each method is detailed below.

Method A

This method, employed by one of the HWTT equipment manufacturers, requires the user to determine if the stripping phase exists by visually assessing the shape of the HWTT curve. If the stripping phase is identified, users are asked to manually select the start and end points on the curve to define the creep and stripping phases, as depicted 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 for the intersection point of the creep and stripping lines following AASHTO T 324. If the user determines that the stripping phase does not exist, SIP will not be calculated.

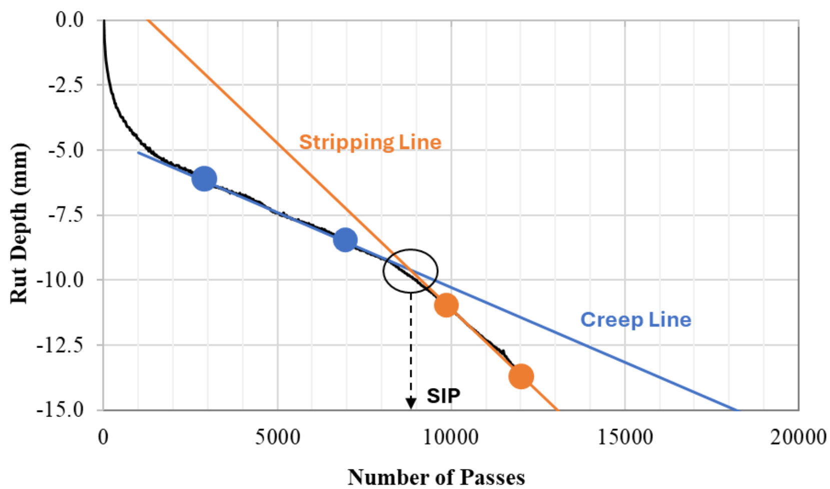


Figure 11. Graphic Illustration of Method A

Method B

This method is used by one of the HWTT equipment manufacturers. Like Method A, it also requires the user to determine if the stripping phase exists by visually assessing the shape of the HWTT curve. If the stripping phase is identified, users are asked to define a "criterion of change" (i.e., slope) for rut depth change over a specific 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 based on the rut depth at 1,000 passes (marking the end of the post-compaction phase and the start of the creep phase) and the defined slope for the creep phase, as shown in Figure 12. For example, 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 determined 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 pre-defined slope for the stripping phase (also shown in Figure 12). Finally, SIP is calculated as the number of passes for the intersection point of the creep and stripping lines following AASHTO T 324. If the stripping phase does not exist, SIP will not be calculated.

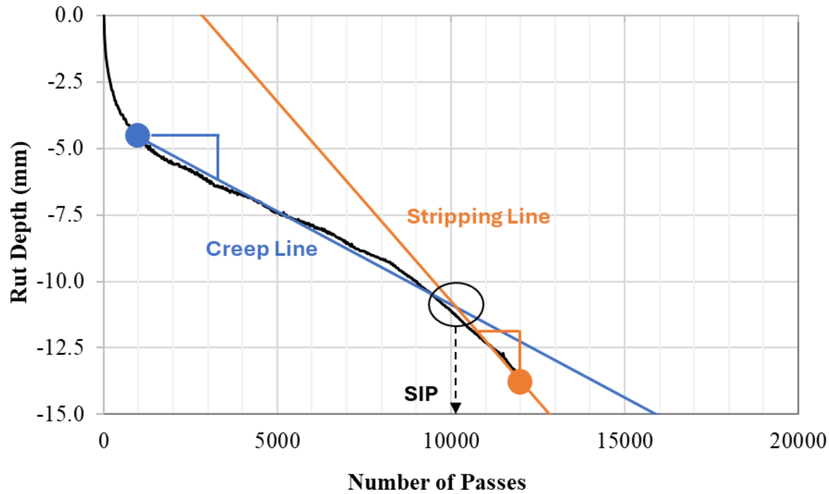


Figure 12. Graphic Illustration of Method B

Method C

This method, employed by one of the HWTT equipment manufacturers,utilizes the simple derivative filtering technique to determine the steady-state tangent approximations of the HWTT curve without relying on a model choice for deformation during the test (Macon, 2023). First, the HWTT curve is processed through a monotonic filter to eliminate spurious bumps on the HWTT curve caused by the loss of aggregate from the specimen during testing. Subsequently, the steady-state tangent D_i is calculated with a half-spacing (n) chosen according to Table 1 using Equation 1. The resulting D_i values are shown in Figure 13 (a). The minimum smoothed derivative D_i is determined 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. Note that the number of passes corresponding to the minimum Di is comparable to SN defined in Method G, discussed later in this report.

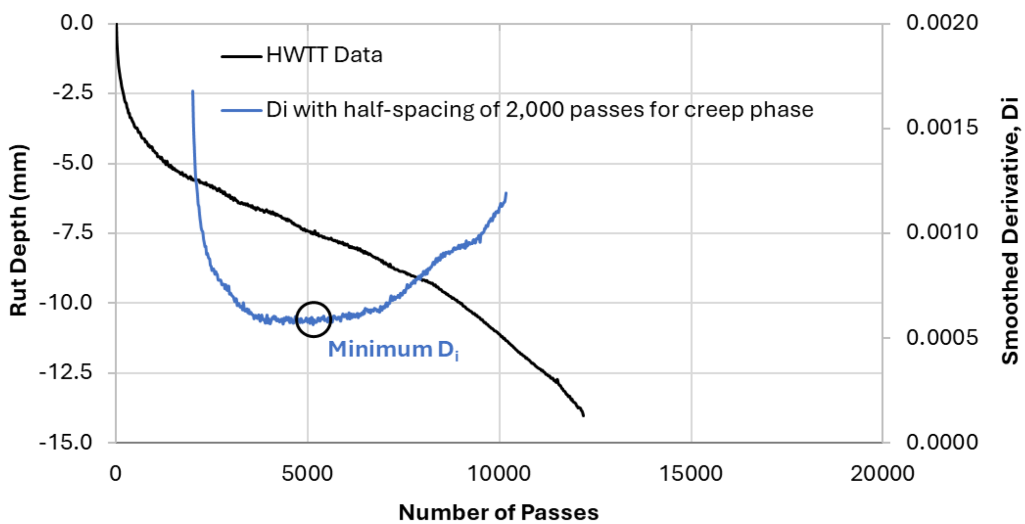
$$D_i^{(n)} = \frac{R_{i+n} - R_{i-n}}{2n} (n < i < N - n) \quad \text{Equation 1}$$

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.

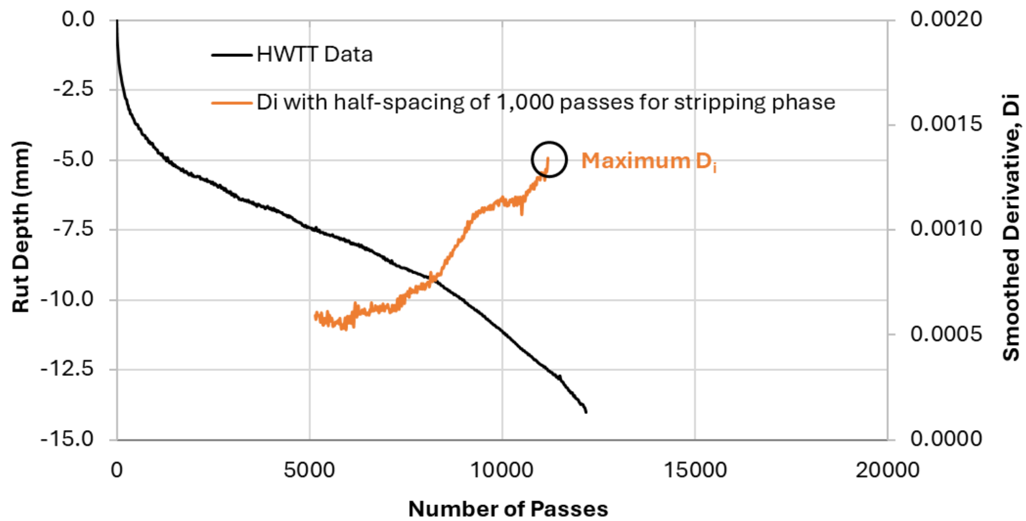
Table 1. Spacing Filter Parameter Adjustment for Non-standard Length Tests using Method C

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 indentifying 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 determined using the stripping slope (i.e., maximum D_i) and the corresponding point on the HWTT curve. Finally, SIP is calculated as the number of passes for the intersection point of the creep and stripping lines following AASHTO T 324. For this method, SIP is valid only if the difference between the stripping slope and creep slope exceeds 2 mm per 10,000 passes.



(a)



(b)

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

Method D

This method, employed by one of the HWTT equipment manufacturers, begins by fitting a straight line to the HWTT curve starting at 100 or 200 passes, excluding data from the post-compaction (initial densification) phase. The difference between the measured and fitted rut depth is then determined, as shown by the red curve in Figure 14. The number of passes at the “Min” difference and the “Max” difference are then defined as the start and end points of the creep phase, which are hereinafter referred to as the “Min” and “Max” difference points, respectively. 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 for the intersection point of the creep and stripping lines following AASHTO T 324.

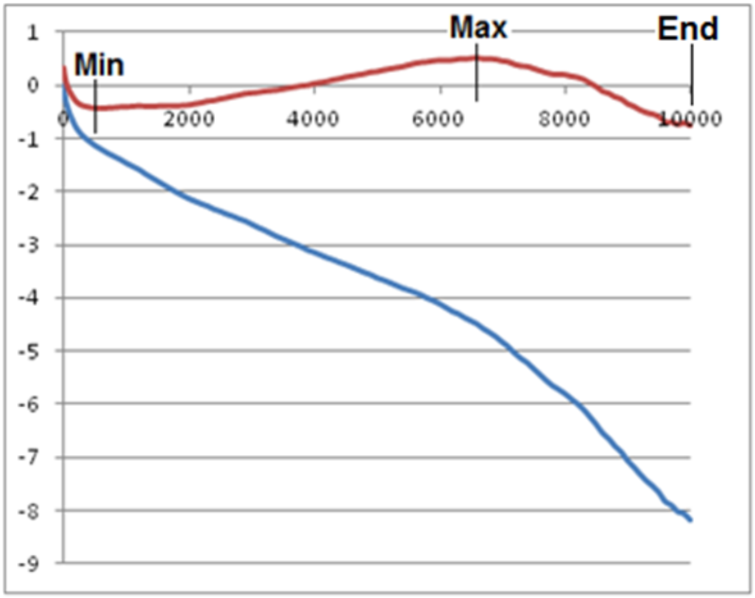


Figure 14. Determining “Min” and “Max” Difference Points for Method D (Cooper, 2023)

Method E

This method, implemented by the Iowa DOT (Iowa DOT, 2024), begins by fitting the HWTT curve with a 6th-degree polynomial determined through least-squares multiple regression. If the curve has an R^2 greater than or equal to 90%, it undergoes further processing to determine the creep slope, stripping slope, and SIP. Otherwise, the HWTT data is considered invalid and will be discarded. Afterward, 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 determined as the maximum absolute derivative value nearest the end of the fitted polynomial curve, which corresponds to the point having the most negative first derivative of the curve (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 determined above. Following this, the creep slope is determined 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 slopeabove. Finally, SIP is calculated as the number of passes for the intersection point of the creep and stripping lines following AASHTO T 324. For this method, SIP is considered invalid when the ratio of the stripping slope to the creep slope is less than 2.0.

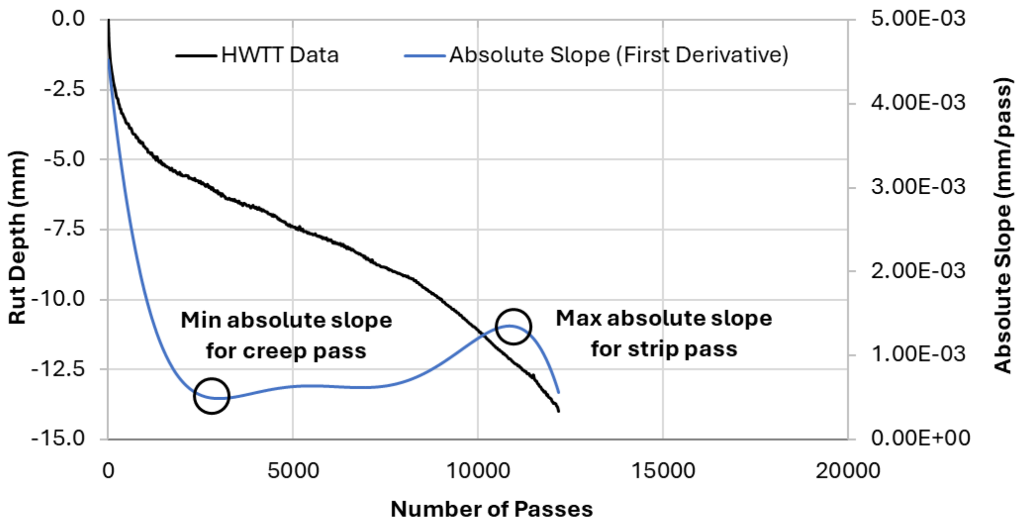


Figure 15. Determining Strip Pass with Maximum Absolute Slope and Creep Pass with Minimum Absolute Slope for Method E

Method F

This method, utilized by the Maine DOT (Maine DOT, 2023), begins with fitting the HWTT curve with a 6^{th}-degree polynomial determined through least-squares multiple regression, similarily 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 of the curve within that range, efined as the strip pass, as shown in Figure 16. The stripping line is then determined based on the strip pass and the stripping slope determined above. Following this, the creep slope is determined by identifying the minimum absolute slope of the fitted polynomial curve between 1,500 passes and the strip pass, as shown in Figure 16. The corresponding point on the HWTT curve denotes the creep point. 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 for the intersection point of the creep and stripping lines following AASHTO T 324. 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.

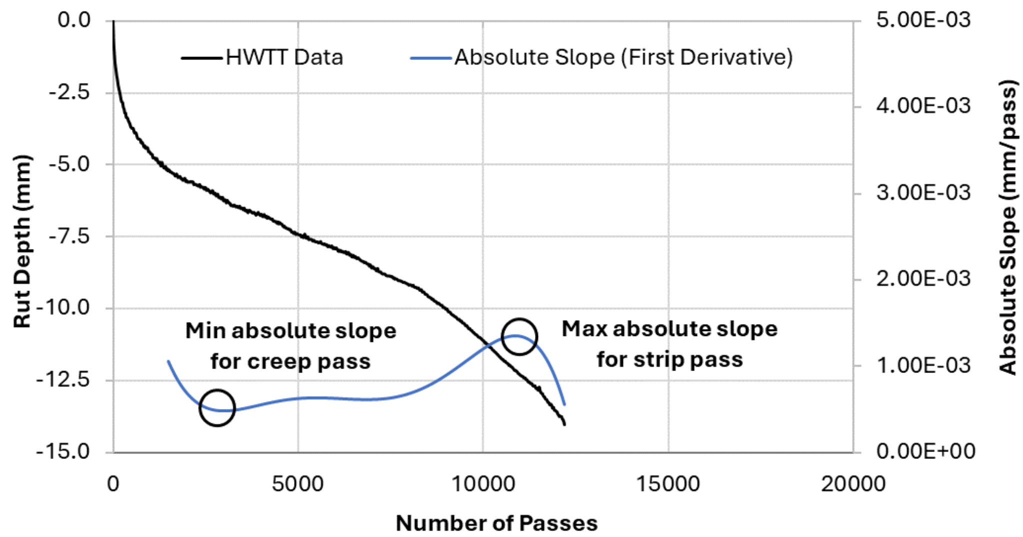


Figure 16. Determining Strip Pass with Maximum Absolute Slope and Creep Pass with Minimum Absolute Slope for Method F

Method G

This method, used by NCAT, begins with fitting the HWTT curve with the Francken model following Equation 2. This model aligns with the one employed to fit the permanent strain versus load cycle curve from the Flow Number test per AASHTO T 378. Then, 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 then determined by identifying the minimum absolute slope. The 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 determined as the tangent of the fitted HWTT curve at the endpoint of the curve, which has 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 for the intersection point of the creep and stripping lines following AASHTO T 324. For this method, SN and SIP are two different parameters, with SN significantly lower than SIP (Yin et al., 2020).

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

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

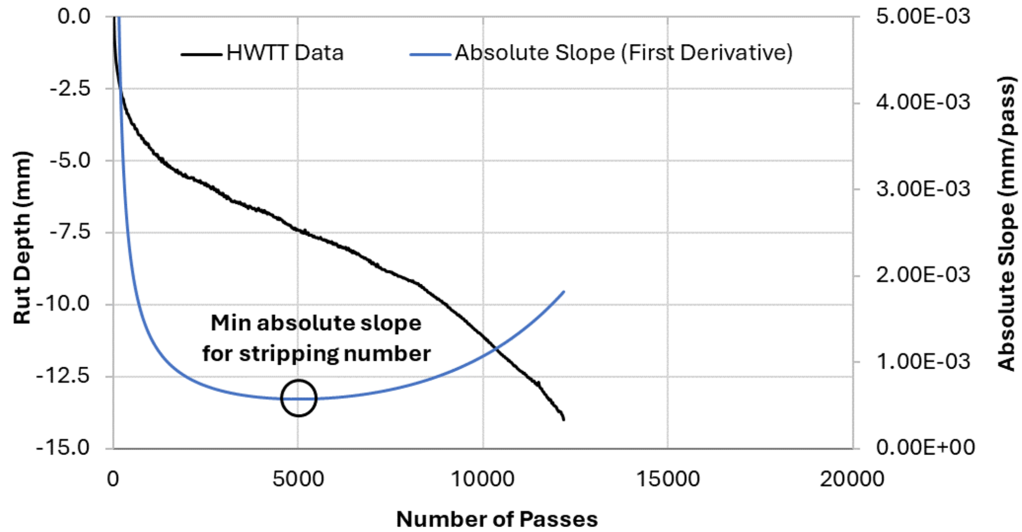


Figure 17. Determining Stripping Number (SN) for Method G

Critical Review of SIP Calculation Methods

Each SIP method discussed previously underwent critical review to identify potential limitations for standardization in AASHTO T 324. A review summary is provided below:

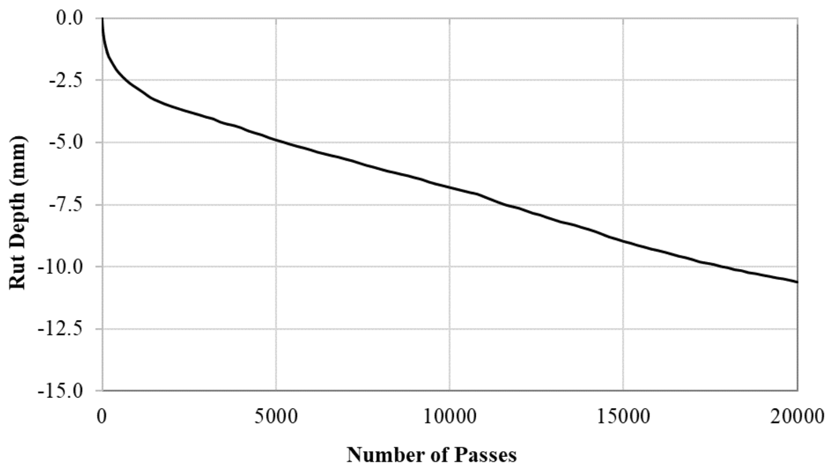
- Method A requires the user to determine the presence of the stripping phase by visually assessing the shape of the HWTT curve and manually defining the creep and stripping regions for calculating SIP, posing subjectivity concerns and making it not ideal for standardization in AASHTO T 324.
- Method B requires the user to determine the presence of the stripping phase by visually assessing the shape of the HWTT curve and then define a “criterion of change” for the rut depth change over a specific number of passes for calculating SIP, also subject to interpretation and not ideal for standardization in AASHTO T 324. This method assumes the first 1,000 passes represent the post-compaction phase and that the creep phase begins following, which may not apply to certain asphalt mixtures.
- Method C determines the presence of the stripping phase by comparing the difference between the stripping slope and the creep slope against a threshold of 2.0 mm rut depth over 10,000 passes. This threshold was selected based on experience and may not apply to certain asphalt mixtures, especially those with marginal stripping failure or those with 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 apply to asphalt mixtures with late stripping failure in the HWTT.
- Method E requires fitting the HWTT curve with a 6^{th}-degree polynomial and determining the stripping slope by identifying the maximum absolute slope of the fitted curve nearest the end of the test. However, “nearest the end of the test” lacks

clarity and necessitates further explanation for standardization in AASHTO T 324. Furthermore, the 6th-degree polynomial is an empirical trendline fitting the HWTT data but fails to 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 and may not universally apply to certain asphalt mixtures, especially those with marginal stripping failure or those with high susceptibility to both rutting and stripping in the HWTT.

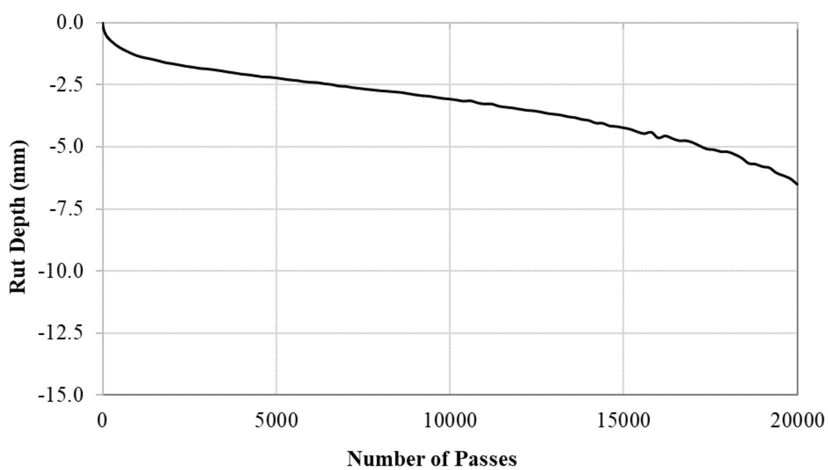
- Method F resembles Method E but clarifies the determination of the stripping slope by using the HWTT curve from the midpoint to the endpoint of the test. Nevertheless, this method inherits the same limitations discussed above for Method E. The 6th-degree polynomial is an empirical trendline that fits the HWTT data but fails to accurately characterize the rutting and stripping behaviors of the mixture in the HWTT. Furthermore, the method considers SIP invalid if the stripping-over-creep slope ratio falls below 3.0 or the stripping slope is less than 0.63 mm per 1,000 passes. However, these criteria are derived from experience and may not universally apply to certain asphalt mixtures, especially those with marginal stripping failure or those with high susceptibility to both rutting and stripping in the HWTT.
- Method G utilizes an existing asphalt mixture permanent deformation model (i.e., the Francken model) to fit the HWTT curve. The presence of the stripping phase is determined solely based on 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 and neither SN or SIP will be calculated.

Comparison of SIP Calculation Methods

To further illustrate different SIP calculation methods, three HWTT results were analyzed using each method, including cases with with no, marginal, and severe stripping failure, as shown in Figure 18(a-c). The analysis results are summarized in Tables 2 through 4 and graphically represented in Figures 19 through 21.



(a)



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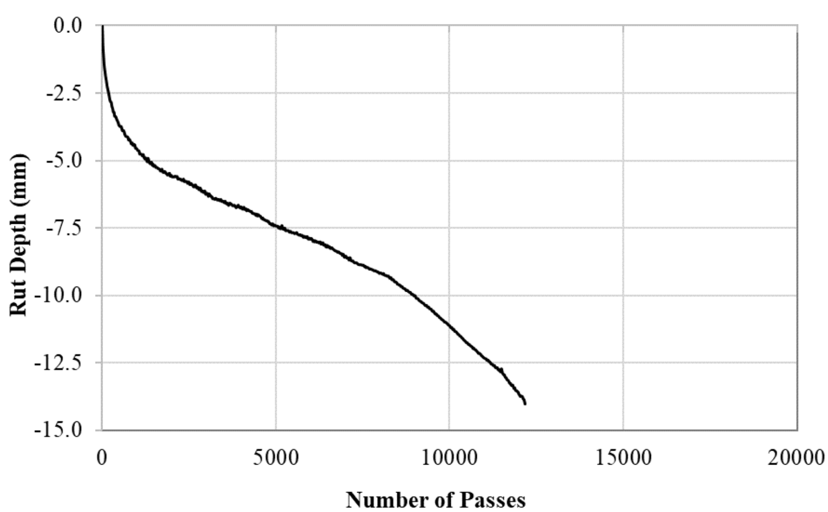


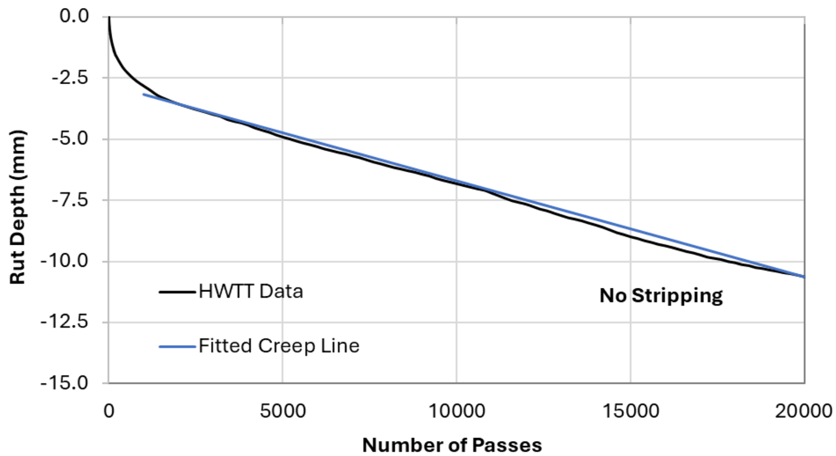
(c)

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

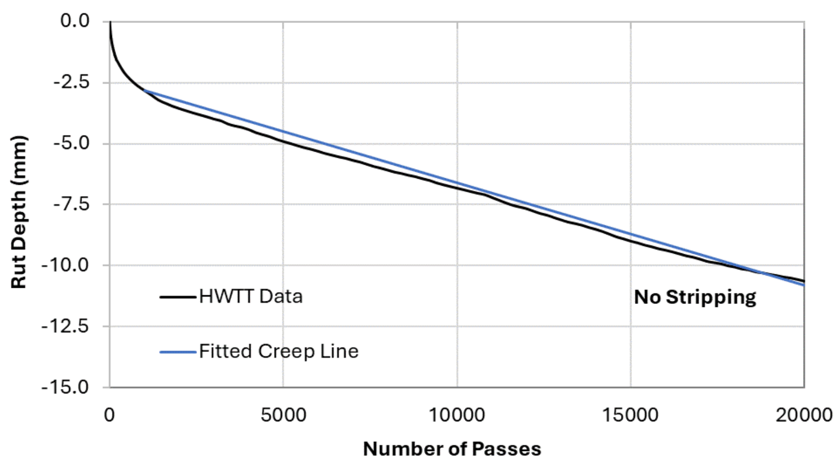
Table 2. Comparison of SIP Results for HWTT Result with No Stripping Failure

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

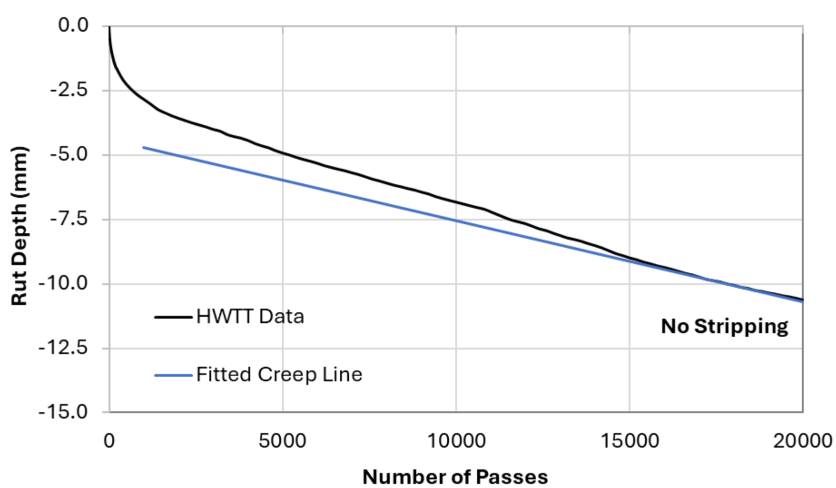
As shown in Table 2, all methods determine that the HWTT result in Figure 18(a) exhibits no stripping failure. Despite SIP calculation for Methods E and F, the results were deemed invalid due to stripping-over-creep slope ratios falling below the 2.0 and 3.0 thresholds. As a result, "no stripping" is reported for the stripping slope, slope ratio, and SIP results in Table 2. Among the methods, calculated creep slope varies from 0.27 mm to 0.42 mm per 1,000 passes, with Method E yielding the lowest value and Method B yielding the highest.


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

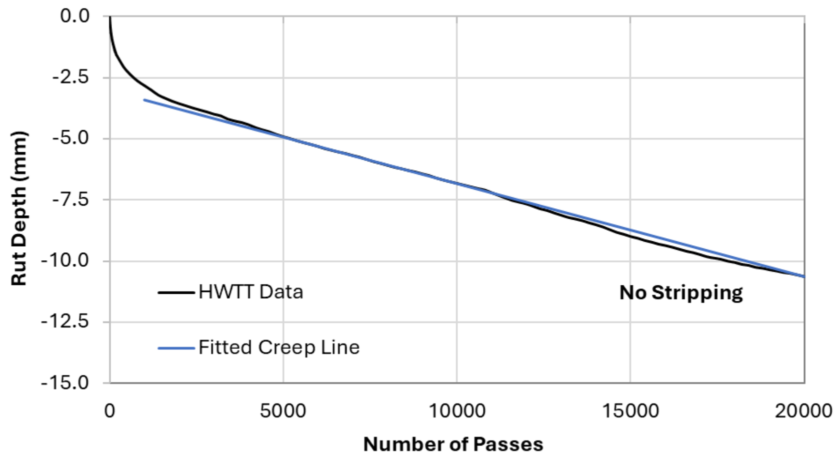
(a)


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

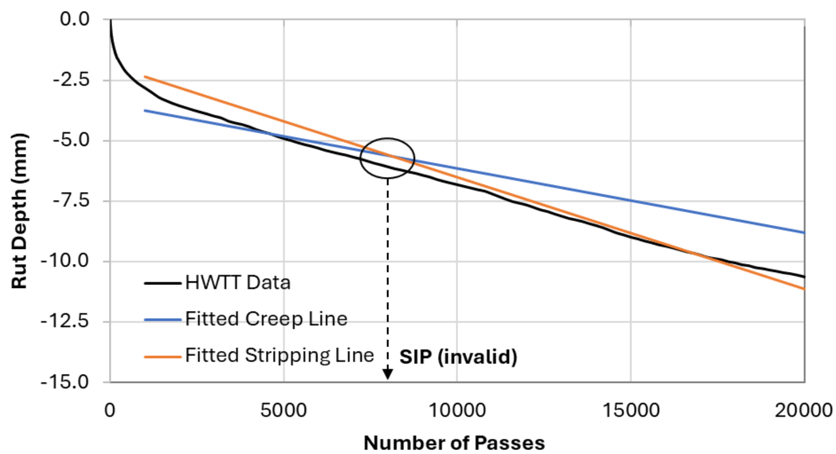
(b)


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

(c)


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

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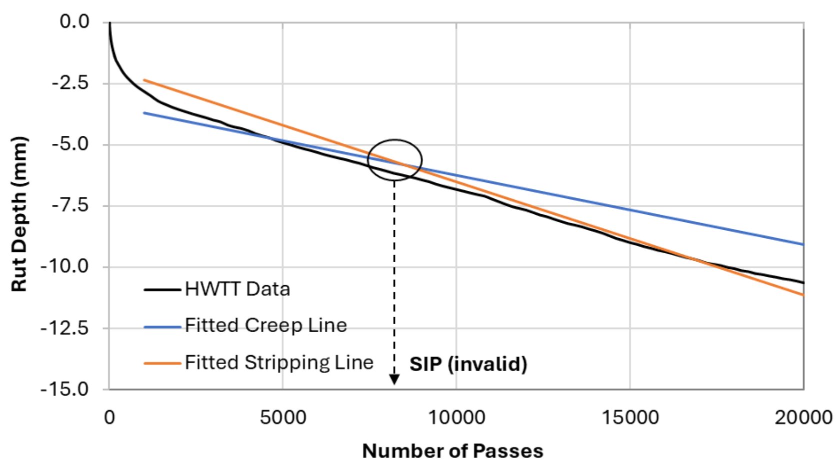
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
0
5000
10000
15000
20000
Number of Passes
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP (invalid)

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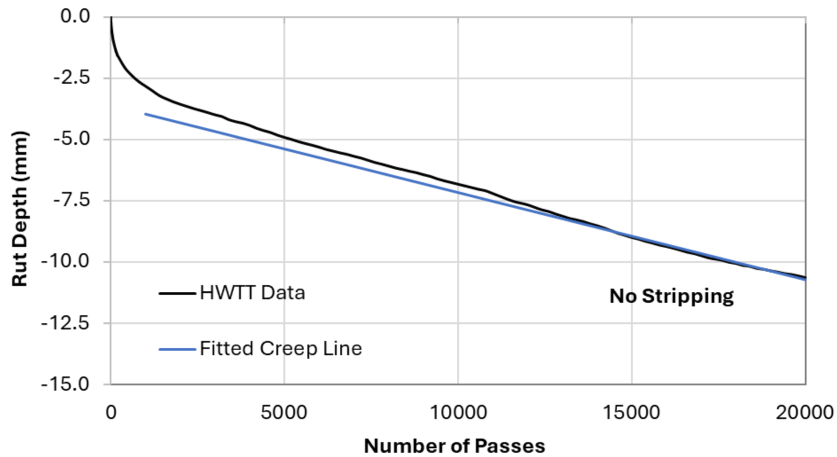
-15.0
Rut Depth (mm)
0
5000
10000
15000
20000
Number of Passes
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP (invalid)

(f)



(g)

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

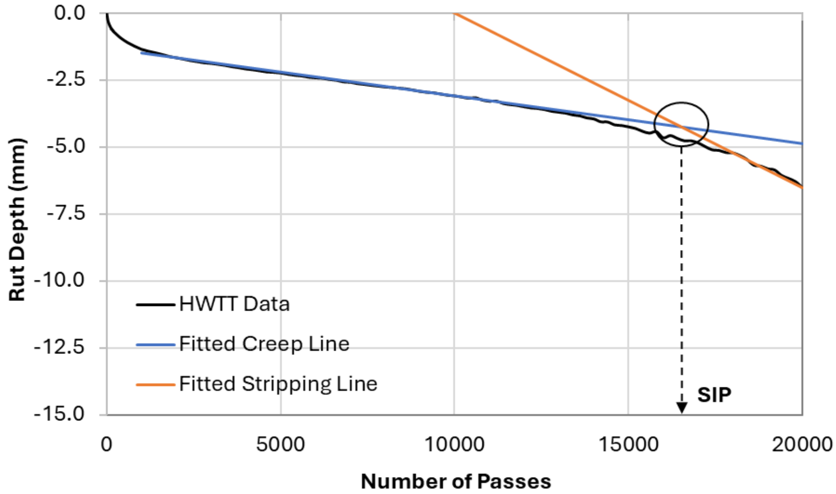
Table 3. Comparison of SIP Results for HWTT Result with Marginal Stripping Failure

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

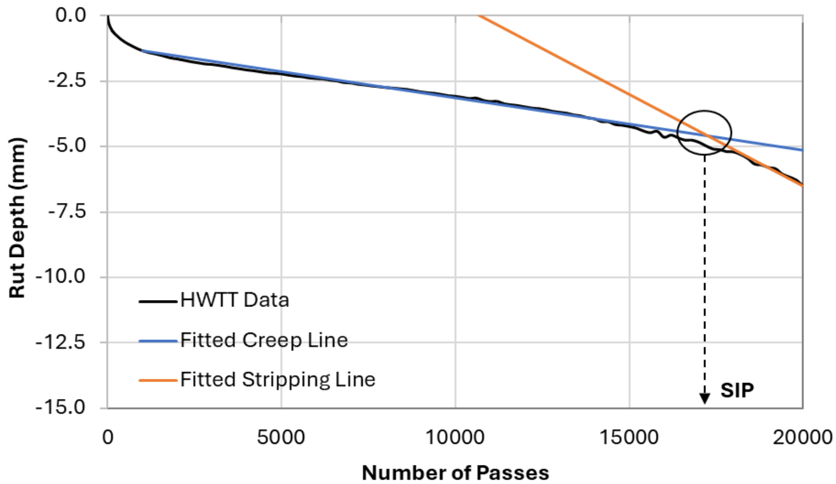
Notes:
* Based on the HWTT curve, the “criterion of change” was selected as 0.2 mm at 1,000 passes for the creep phase and 0.7 mm at 1,000 passes for the stripping phase.

As shown in Table 3, all methods determine that the HWTT result in Figure 18(b) exhibits late marginal stripping failure. Method B yields the highest SIP at 17,260 passes, while Method D yields the lowest SIP at 13,200 passes, with other methods falling in the middle.

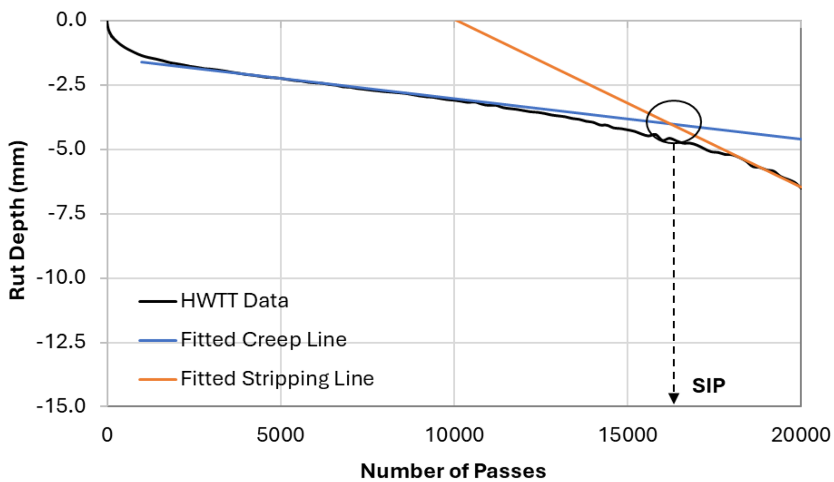
Method D, despite exhibiting considerably lower creep and stripping slopes, yields a SIP comparable to other methods.



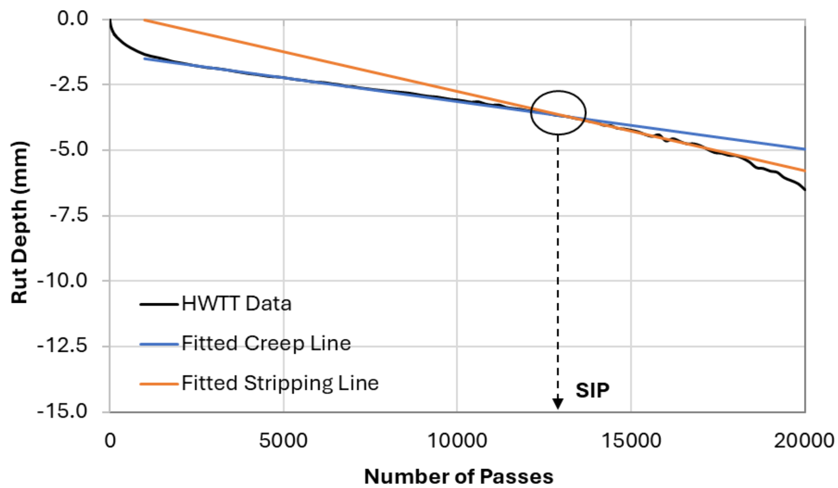
(a)



(b)

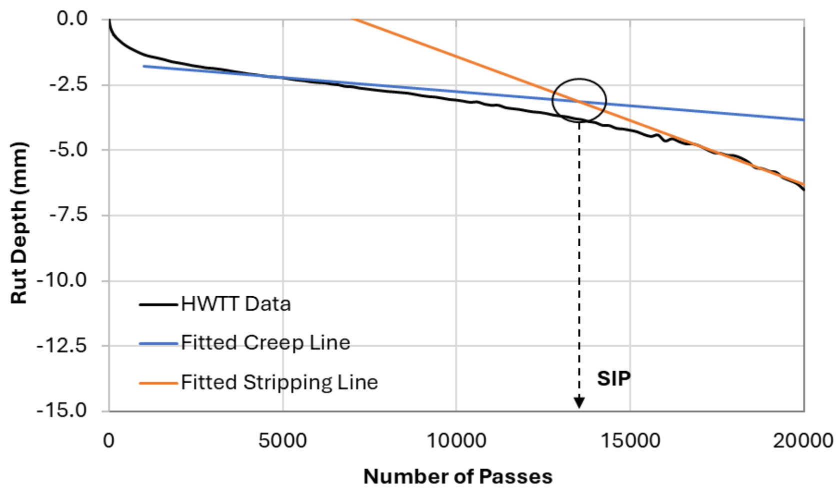


(c)



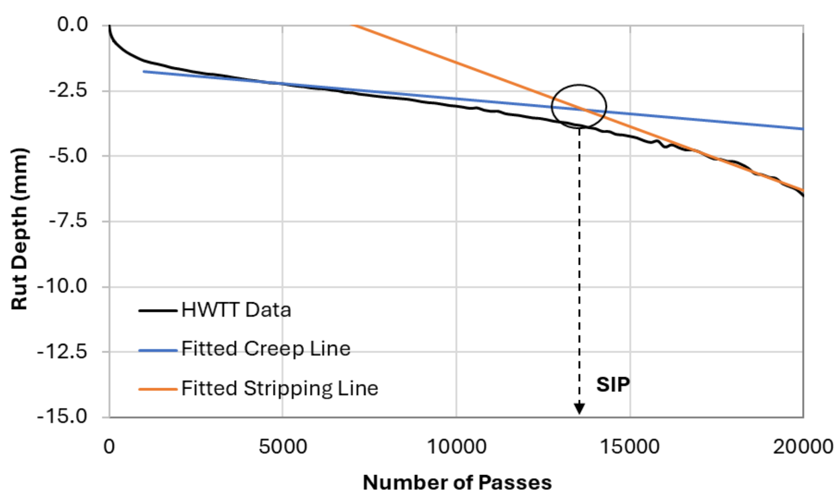
0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
0
5000
10000
15000
20000
Number of Passes
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP

(d)



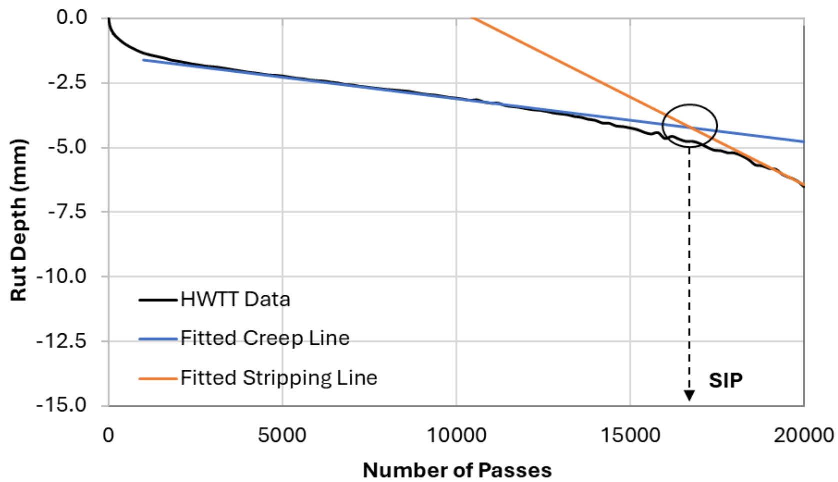
0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
0
5000
10000
15000
20000
Number of Passes
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP

(e)



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
Fitted Stripping Line
SIP

(f)



(g)

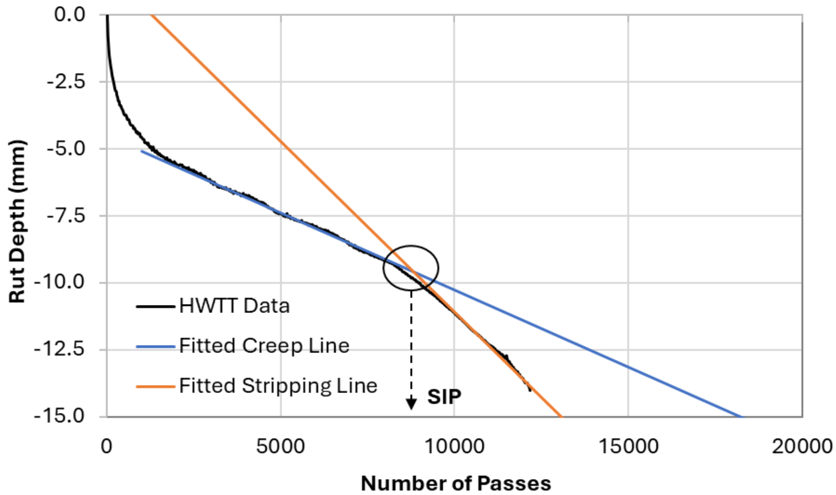
Figure 20. Comparison of SIP Results for HWTT Result with Marginal Stripping Failure: (a) Method A, (b) Method B, (c) Method C, (d) Method D, (e) Method E, (f) Method F, (g) Method G

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

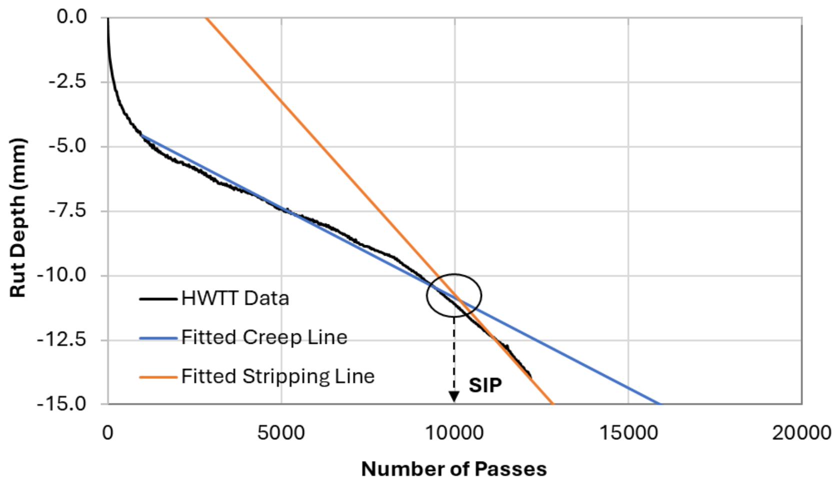
Method	Curve Fitting R^2	Curve Fitting RMSE	Creep Slope (mm/1k passes)	Stripping Slope (mm/1k passes)	Slope Ratio	SIP	SN
A	n/a	n/a	0.58	1.27	2.21	8,817	n/a
B*	n/a	n/a	0.70	1.50	2.14	10,159	n/a
C	n/a	n/a	0.56	1.34	2.38	9,192	n/a
D	n/a	n/a	0.59	1.08	1.82	8,320	n/a
E	0.998	0.124	0.49	1.35	2.78	8,389	n/a
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

Notes:
* 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.

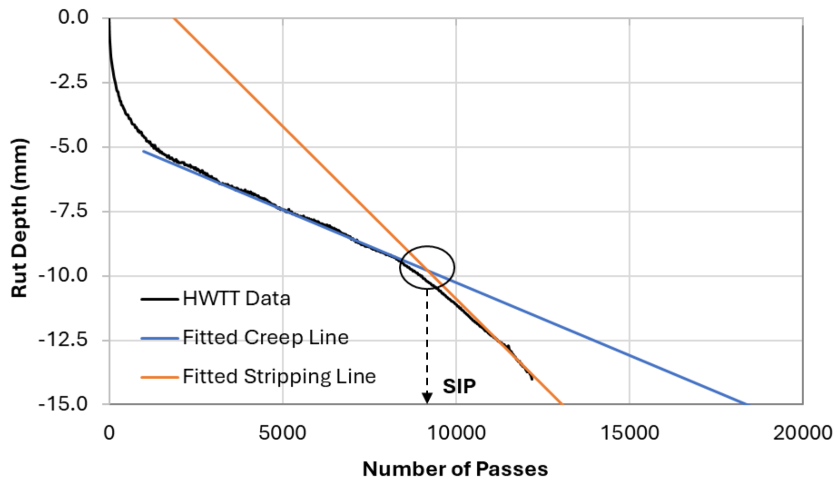
As shown in Table 4, all methods, except Method F, determine that the HWTT result in Figure 18(c) displays severe stripping failure. Method B yields the highest SIP at 10,159 passes, while Method D yields the lowest SIP at 8,320 passes, with other methods falling in the middle. Similar to the results in Table 3, Method D, despite presenting notably lower creep and stripping slopes, yields a SIP comparable to other methods. Method F calculates SIP at 8,663 passes, but the result was considered invalid due to the stripping-over-creep slope ratio falling below the 3.0 limit. As a result, "no stripping" is reported for the stripping slope, slope ratio, and SIP results in Table 4.



(a)

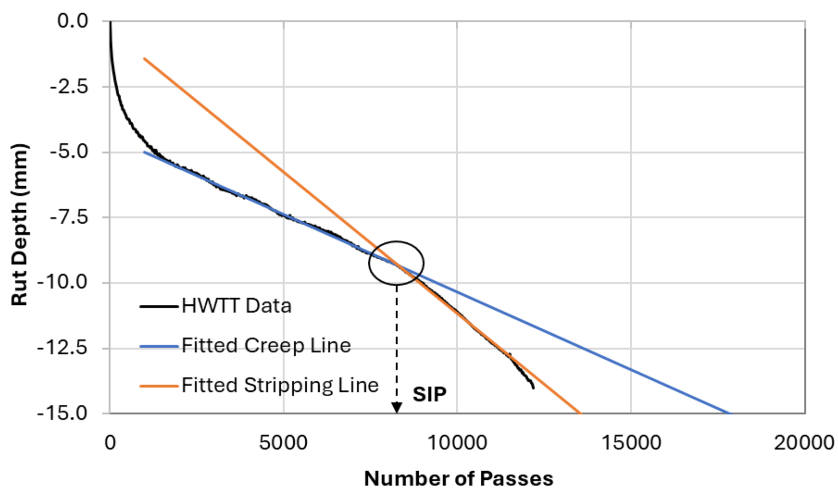


(b)



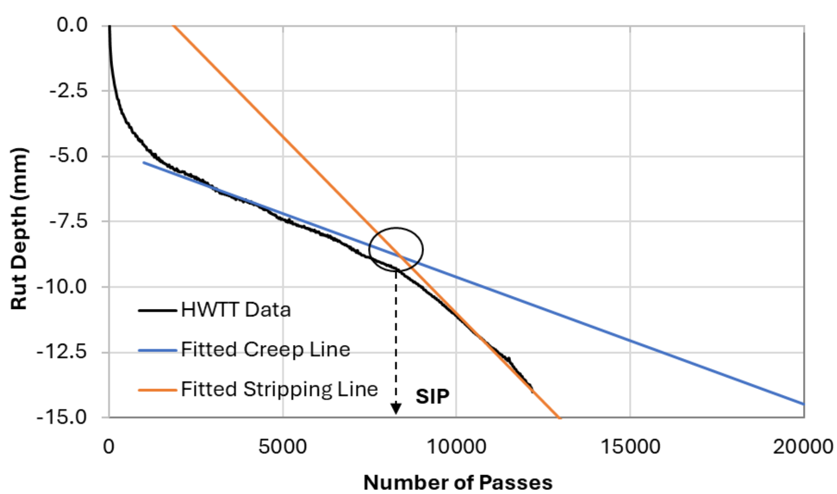
0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP
0
5000
10000
15000
20000
Number of Passes

(c)



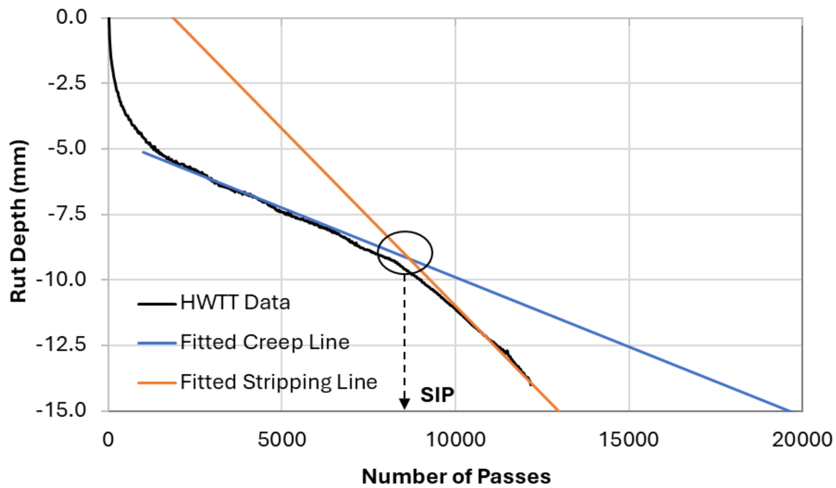
0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP
0
5000
10000
15000
20000
Number of Passes

(d)

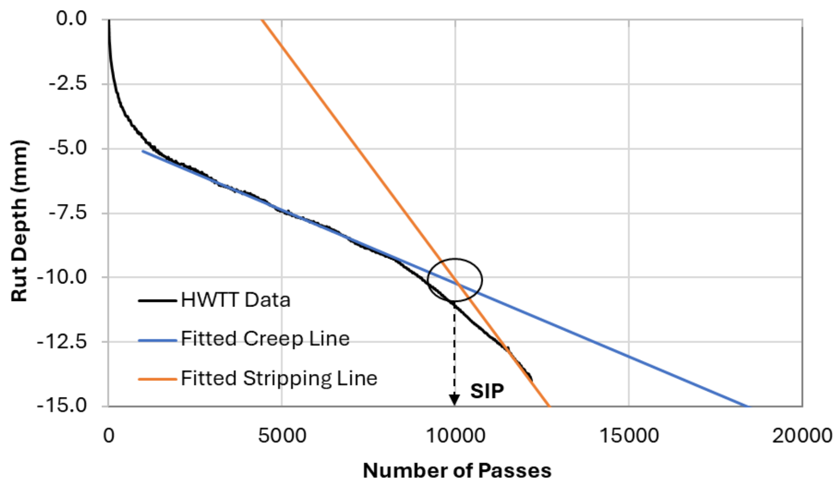


0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Rut Depth (mm)
HWTT Data
Fitted Creep Line
Fitted Stripping Line
SIP
0
5000
10000
15000
20000
Number of Passes

(e)



(f)



(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

Recommended SIP Calculation Method for HWTT Software Development

Based on the critical review and comparison of SIP methods presented previously, it is recommended that Method G be utilized for developing HWTT software in this project. This method utilizes an existing asphalt mixture permanent deformation model (i.e., the Francken model) and determines the presence of the stripping phase solely based on the shape and curvature of the fitted HWTT curve. By doing so, it avoids subjective data interpretation of creep and stripping slope results against empirical thresholds that may not universally apply to certain asphalt mixtures. Furthermore, as shown in Tables 2 through 4, the SIP results for Method G are reasonably consistent with the other methods currently used by the HWTT equipment manufacturers, Iowa DOT, and Maine DOT.

References

Cooper, A. (2023). Email Communication with Fan Yin.

Iowa Department of Transportation (2024). Moisture Sensitivity Testing of Asphalt Mixtures. https://www.iowadot.gov/erl/current/im/content/319.htm, accessed on March 3, 2024.

Macon, K.T. (2023). InstroTek SIP Calculation. A document prepared for use by the National Center of Asphalt Technology (NCAT) for the National Road Research Alliance (NRRA) research project, titled "*Standardization of SIP Calculation for Hamburg Wheel Tracking Test*."

Maine Department of Transportation (2023). HMA Hamburg Wheel Tracker Testing. *MaineDOT Policies and Procedures for HMA Sampling and Testing* (January 17, 2023).

Yin, F., Chen, C., West, R., Martin, A. E., and Arambula-Mercado, E. (2020). Determining the relationship among hamburg wheel-tracking test parameters and correlation to field performance of asphalt pavements. *Transportation Research Record*, 2674(4), 281-291.

Appendix. State Highway Agency Survey Questionnaire

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.