TECH**BRIEF**

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Acceptance Testing of High-Speed Transverse Profile Measuring Systems Purchased for the Long-Term Pavement Performance Program

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INTRODUCTION

The Federal Highway Administration purchased four Ames Engineering transverse profile measuring systems (ATPMSs) late in 2017. This technical brief (TechBrief) describes the procedures used to perform acceptance testing of ATPMSs. The test sections used to collect data, collection of reference data, transverse profile data collection by the AHSVs, procedures for analysis of the transverse profile data, and results from the analysis are described in this TechBrief.

An ATPMS has been installed on each of the four Ames Engineering high-speed survey vehicles (AHSVs) that currently collect longitudinal profile and macrotexture data for the Long-Term Pavement Performance program. An ATPMS consists of a single camera mounted on the rear of the vehicle at an approximate height of 84 inches from the ground's surface. Figure 1 shows the AHSVs with an ATPMS installed on the back of each vehicle. Figure 2 shows a close-up view of an ATPMS.

The ATPMSs collect transverse profile elevation data over a distance of approximately 13 ft. A single transverse profile consists of 2,048 data points with 0.076-inch spacing between the data points. The transverse profiles are obtained at a longitudinal interval of 0.98 inches based on the signal obtained from the distance measuring instrument in the AHSV. An ATPMS is capable of collecting transverse profile data at this interval up to a speed of 70 mph. According to the manufacturer, the specified vertical resolution of the ATPMS is 0.0256 inch, while the vertical range is ±4 inches.(1) ATPMSs are not equipped with an inertial-measurement system for measuring a vehicle's roll, which is needed to obtain the cross slope of the pavement. After the transverse profile elevation data are collected, the data are normalized to the end points of the measurements by a computer program since the cross slope of the pavement cannot be determined from the collected data.

Intensity images obtained by an ATPMS are used to detect the outer and inner lane edges from the striping on the pavement, and the range data from an ATPMS show the transverse profile. Figure 3 shows an example of an intensity image obtained from an ATPMS. The solid white stripe at the bottom is the stripe on the edge of the right lane

Figure 1. Photograph. ATPMSs mounted on the backs of AHSVs.

Source: FHWA.

Figure 2. Photograph. Close-up view of an ATPMS.

Source: FHWA.

demarcating the shoulder, and the intermittent lane marking at the top is the striping on the left side of the right lane.

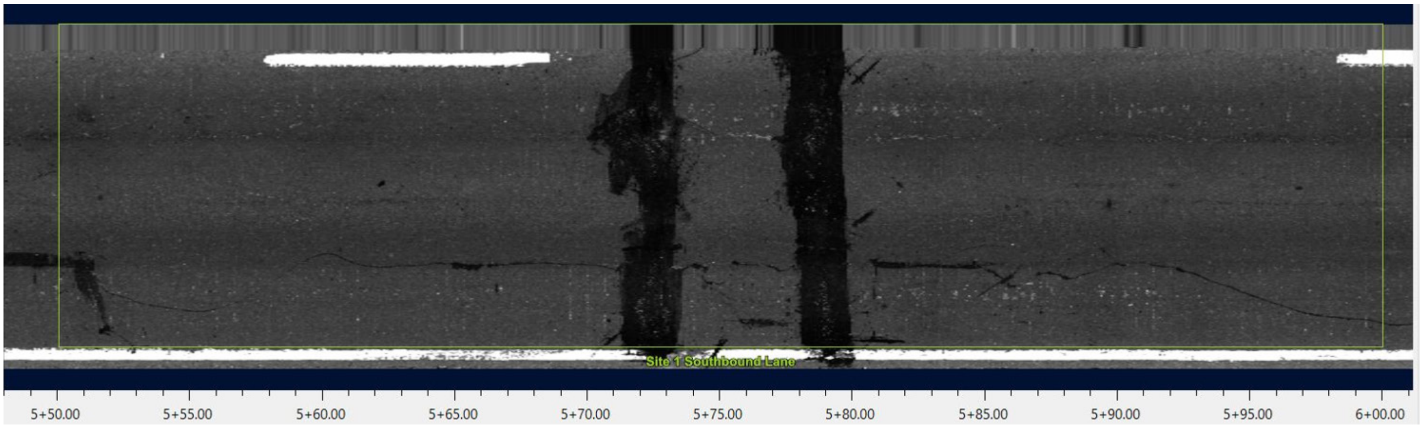
EQUIPMENT CRITERIA SPECIFIED IN AASHTO R 88

Table 1 shows the requirements for the following items specified in AASHTO R 88, "Standard Practice for Collecting the Transverse Pavement Profile": maximum distance between collected transverse profiles, minimum width of transverse profile, maximum interval between data points in a transverse profile, vertical-measurement resolution, and maximum deviation of transverse profile from a path perpendicular to the lane centerline.[2] ATPMS values for these items are also shown in table 1, which shows that ATPMSs satisfy the equipment requirements specified in AASHTO R 88.[2]

TEST SECTIONS AND REFERENCE DATA COLLECTION

Six test sections, each 50 ft long, were established for evaluating the ATPMSs. The test sections were established on a portion of southbound I-35 near Ames, IA, that was abandoned because of a highway realignment. Reference transverse profile data were collected on each test section at a location 1 ft in front of the reflective tape placed at the start of each test section to initiate data collection with the AHSVs. The reference data were collected using a device that had a laser mounted on a beam, which was developed by the ATPMS manufacturer. Figure 4 is a photograph of this reference device, which consists of an aluminum beam that is placed on the pavement and holds a single point–laser height sensor and a distance encoder. The laser height sensor is pushed forward manually, and the encoder records the traveled distance. This device

Figure 3. Photograph. Example intensity image.



Source: FHWA.

Table 1. Requirements in AASHTO R 88 and associated values for ATPMSs.

Parameter	AASHTO R 88 Requirement[2]	ATPMS Value
Maximum distance between collected transverse profiles	1.5 ft for project level and 10 ft for network level	0.98 inch
Minimum width of transverse profile	13 ft	13 ft
Maximum interval between data points in a transverse profile	0.4 inch	0.076 inch
Vertical measurement resolution	≤0.04 inch	0.0256 inch
Maximum deviation of transverse profile from path perpendicular to lane centerline	15 degrees	0 degrees

records transverse profile data at 0.077-inch intervals. Three measurements were taken with the reference device at each test location.

Transverse profile data collected within the lane starting 4 inches from the inside edge of the lane stripe at the right edge of the lane and ending 4 inches before the stripe at the left edge that demarcated the travel lanes were used for analysis. The collected data were normalized to remove the cross slope. Figure 5 shows an example of data collected by the reference device at a test section. Data for three runs are shown in this plot. In the plot, a distance of 0 ft represents the left edge of the lane (i.e., 4 inches from the stripe). As this plot shows, the data collected by the reference device demonstrate good repeatability.

DATA COLLECTED BY AHSVS

Each AHSV performed six runs at each test section at a speed of 50 mph to collect transverse profile data. Transverse profile data, which were collected at the same locations as the reference data at each test section, were used to evaluate the repeatability and accuracy of the transverse profile data collected by the AHSVs. The following procedure was used to obtain the data at these locations:

1. Average transverse profiles were computed over a 1-ft distance centered at the location where reference data were collected. As transverse profile data were collected at 0.98-inch intervals, typically 13 transverse profiles were averaged.
2. A 2-inch moving average was applied to the averaged transverse profile elevations.
3. The data at the right and left edges were trimmed to obtain elevation data between 4 inches from the inside edge of the lane stripe at the right edge of the lane and 4 inches before the edge of the lane stripe that demarcated the travel lanes.
4. Slope in the transverse profile was removed by normalizing the data to the transverse profile end points. This step was done by adjusting each elevation value to a datum through the two end points, whose elevations were set to 0 inches.

Figure 6 shows the transverse profile data for six runs collected by an AHSV on a test section at the location where reference measurements were taken. In the plot, a distance of 0 ft represents the left edge of the lane (i.e., 4 inches from the stripe).

Figure 4. Photograph. Reference device that collected reference transverse profile data.

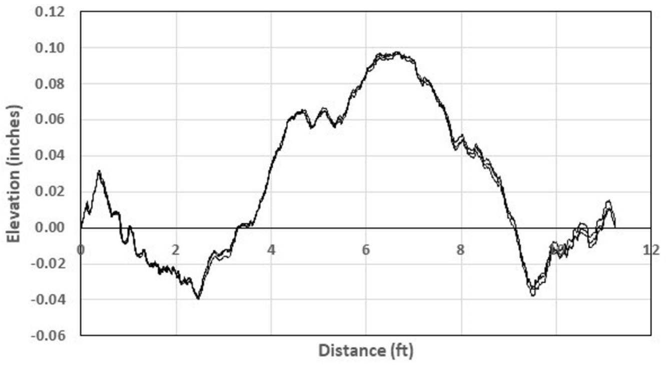
Source: FHWA.

CROSS-CORRELATION METHOD

The cross-correlation method can be used to rate the agreement between two profiles.[3] In AASHTO R 56, “Standard Practice for Certification of Inertial Profiling Systems,” the repeatability and accuracy of longitudinal profile data collected by an inertial profiler are assessed using the cross-correlation method that is applied to profiles filtered via the International Roughness Index algorithm.[4] ProVAL, a free software available on the Web, can be used to perform this analysis.[5]

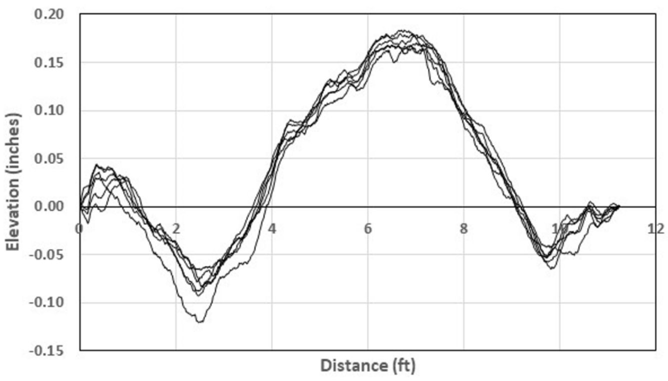
The repeatability and accuracy of transverse profiles collected by the AHSVs were evaluated using the cross-correlation method. ProVAL was used to perform

Figure 5. Graph. Transverse profile data collected by the reference device.



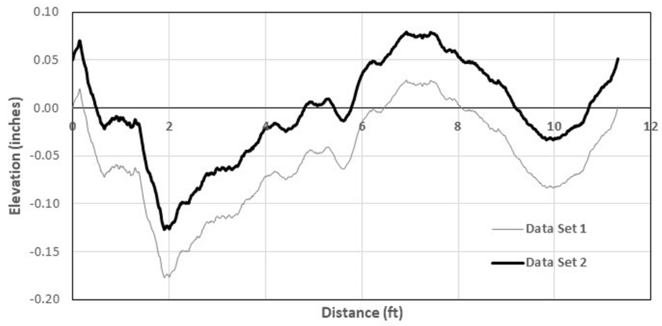
Source: FHWA.

Figure 6. Graph. Transverse profile measured for six repeat runs by an AHSV at a test location.



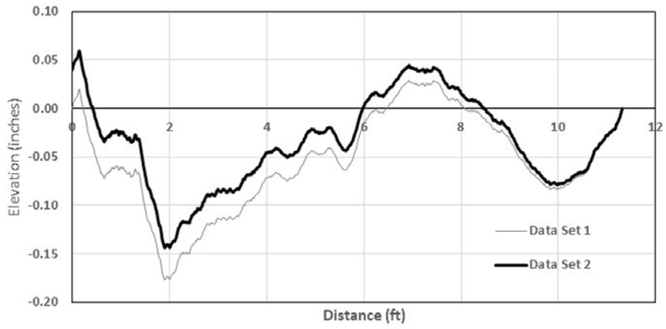
Source: FHWA.

Figure 7. Graph. Two identical profiles with one profile having a constant vertical offset from the other.



Source: FHWA.

Figure 8. Graph. Two identical profiles, where one profile has a varying vertical offset from other.



Source: FHWA.

this analysis. Files in ERD format that contained the transverse profile data were loaded into ProVAL for the analyses.(6) No additional filters were applied to the transverse profile data through ProVAL when performing the cross-correlation analysis. Therefore, all analyses were performed on the actual transverse profile data.

ProVAL computes the cross-correlation between two data sets by fixing one profile and horizontally shifting the other profile to obtain the maximum cross-correlation for the two data sets. A cross-correlation value of 100 percent indicates the two profiles are identical, while a value of 0 percent indicates there is no relationship between the two profiles.

A constant vertical offset between two profiles does not affect the computed cross-correlation value. Figure 7 shows transverse profile plots for two data sets. The second data set was obtained by adding a constant vertical offset of 0.05 inch to the first data set. The cross-correlation between these two data sets computed by ProVAL was 100 percent as the two data sets were identical except for a constant vertical offset between them.

Figure 8 shows transverse profile plots for two data sets, where the second data set was obtained by adding a varying vertical offset to the first profile. The vertical offset of the second profile is 0.04 inch from the first profile at the left edge, and the vertical offset decreases at a constant rate such that the offset is 0 inches at the right edge of the profile. The cross-correlation between these two data sets computed by ProVAL was 95 percent. Although the two profiles had the same shape, the varying vertical offset between the two profiles caused the cross-correlation to be reduced by 5 percent. ProVAL does not have the ability to rotate one profile while fixing the other profile to obtain the maximum cross-correlation between two profiles. In this example, if the second profile were rotated with respect to the first profile to obtain the maximum cross-correlation, the cross-correlation between the two profiles would have been 100 percent.

Therefore, when performing cross-correlation between two profiles using ProVAL, a profile that has a similar shape but is rotated with respect to the other profile, will decrease the cross-correlation between the two profiles.

REPEATABILITY OF TRANSVERSE PROFILE DATA COLLECTED BY AHSVS

The repeatability of transverse profile data collected by the AHSVs was evaluated through the cross-correlation technique by using ProVAL. The Profiler Certification module in ProVAL was used with no filters applied to the data being analyzed. ProVAL computes cross-correlation values for all possible pairs of data, and then, the computed values are averaged to obtain an average cross-correlation value. As 6 repeat runs were performed on each test section by each AHSV, cross-correlation values were computed for 15 pairs of data and averaged to obtain the average cross-correlation value for the AHSV at a test section. The average cross-correlation values for the transverse profile data collected by each AHSV at each test section are shown in table 2.

For AHSV1, at test section northbound (NB)-1, the highest cross-correlation between two runs occurred for run 2 and run 3, with a value of 95 percent. For the same device at this test section, the lowest cross-correlation between two runs occurred for run 1 and run 4, with a value of 70 percent. The transverse profile plots for the two runs with the highest cross-correlation (i.e., 2 and 3) are shown in figure 9, while the transverse profile plots for the two runs with the lowest cross-correlation (i.e., 1 and 4) are shown in figure 10. A visual review of figure 10 showed the cross-correlation between the profiles could be improved by rotating one profile with respect to the other; however, ProVAL does not have the ability to perform this function.

ACCURACY OF TRANSVERSE PROFILE DATA COLLECTED BY THE AHSVS

As described in the section Test Sections and Reference Data Collection, three data sets were collected with the reference device at each test section. Table 3 shows the cross-correlation values between the reference data sets at all test sections. As table 3 shows, the reference data collected at each test section were extremely repeatable. As the reference data showed good repeatability, the data collected during the first data-collection run were used as reference data in the analysis at all test sections.

The accuracy of transverse profile data collected by the AHSVs was also evaluated through the cross-correlation technique. Using ProVAL, the reference data were compared to the data collected by the AHSVs. The Profiler Certification module in ProVAL was used to compute the accuracy cross-correlation with no filters applied to the data. The cross-correlation between the reference data and the data collected by each AHSV was computed at each test section. During computation, the data from the reference device were fixed, and the data from the AHSV were shifted horizontally to obtain the maximum cross-correlation for the two data sets. As six repeat runs were obtained by each AHSV at a test section, cross-correlation values were computed between the data from each run and the reference data, and the computed values were averaged to obtain the average accuracy cross-correlation for each AHSV at that test section. Table 4 shows the accuracy cross-correlation values that were computed at test section NB-1 for the data collected by the four AHSVs for all runs.

The computed average accuracy cross-correlation values for the AHSVs at all test sections are shown in table 5. A visual review of the data in table 5 shows that none of the AHSVs is collecting data that are vastly different from the data collected by another AHSV.

Table 2. Average repeatability cross-correlation values.

Test Section	AHSV1 (%)	AHSV2 (%)	AHSV3 (%)	AHSV4 (%)
NB-1	85	94	93	96
NB-2	95	97	92	92
NB-3	96	96	91	89
SB-1	92	97	94	94
SB-2	98	99	97	98
SB-3	92	97	91	90
Average	93	97	93	93

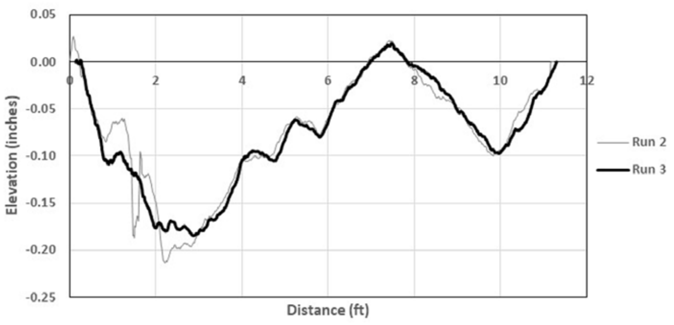
NB = northbound; SB = southbound.

The overall average accuracy cross-correlation value, computed by averaging the accuracy cross-correlation values computed at the six test sections, for the AHSVs ranged from 79 to 88 percent.

When examining the accuracy cross-correlation values for all AHSV runs at all test sections, the worst cross-correlation value was noted for run 1 of AHSV2 at section NB-1, where the accuracy cross-correlation was 62 percent. Figure 11 shows AHSV2's run 1 and the reference device's transverse profile at NB-1 after ProVAL shifted the profile for AHSV2 horizontally to obtain the maximum cross-correlation, which was 62 percent. A review of the two plots in figure 11 shows the vertical offset between the two profiles is not constant; the offset decreases from left to right. A review of the plots indicated the cross-correlation between the two profiles can be improved by rotating the profile from AHSV2 downward from the left end so it will better match the profile of the reference device.

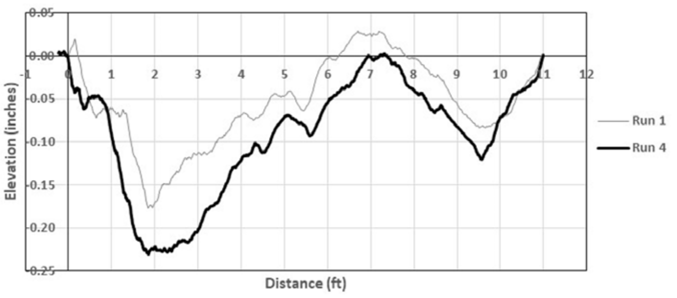
As described in the section Cross-Correlation Method, a constant vertical offset between two profiles does not affect the cross-correlation value, but a varying

Figure 9. Graph. Two runs with the highest cross-correlation for AHSV1 at test section NB-1 (run 2 and run 3, cross-correlation = 95 percent).



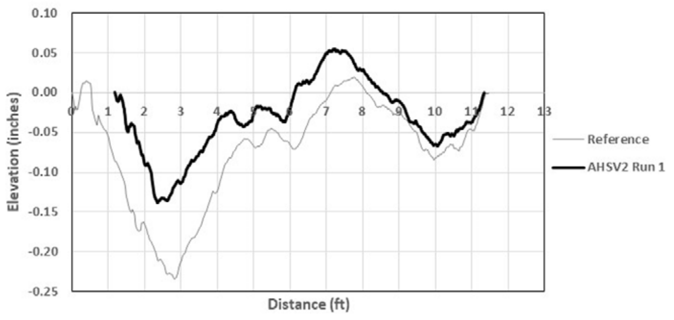
Source: FHWA.

Figure 10. Graph. Two runs with the lowest cross-correlation for AHSV1 at test section NB-1 (run 1 and run 4, cross-correlation = 70 percent).



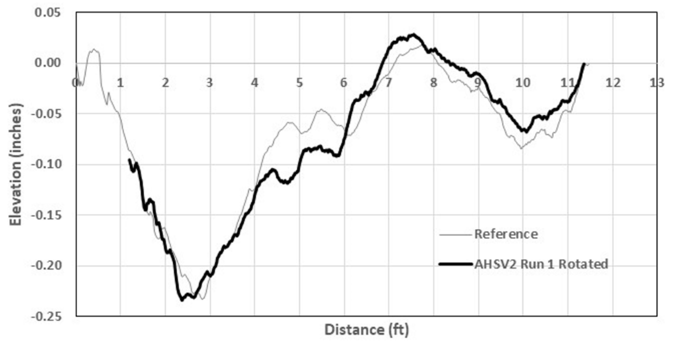
Source: FHWA.

Figure 11. Graph. Transverse profiles from run 1 of AHSV2 and the reference device at section NB-1.



Source: FHWA.

Figure 12. Graph. Reference-device data and rotated profile of AHSV2's run 1 at section NB-1.



Source: FHWA.

Table 3. Cross-correlation values between runs for reference data collected at the test sections.

Compared Runs	NB-1 (%)	NB-2 (%)	NB-3 (%)	SB-1 (%)	SB-2 (%)	SB-3 (%)
1 and 2	99.3	98.8	99.8	99.4	100.0	99.4
1 and 3	99.5	98.7	99.6	100.0	99.2	99.4
2 and 3	98.8	99.7	99.8	99.4	99.2	100.0
Average	99.2	99.1	99.7	99.6	99.5	99.6

SB = southbound.

Table 4. Accuracy cross-correlation values at test section NB-1 for the four AHSVs.

Run	AHSV1 (%)	AHSV2 (%)	AHSV3 (%)	AHSV4 (%)
1	71	62	90	79
2	85	73	89	84
3	83	68	88	80
4	94	71	86	77
5	71	68	85	78
6	76	70	87	80
Average	80	69	87	80
Minimum	71	62	85	77
Maximum	94	73	90	84

Table 5. Average accuracy cross-correlation values for the AHSVs.

Test Section	AHSV1 (%)	AHSV2 (%)	AHSV3 (%)	AHSV4 (%)
NB-1	80	69	87	80
NB-2	82	90	68	71
NB-3	81	94	83	83
SB-1	92	94	75	88
SB-2	92	98	84	91
SB-3	83	82	77	91
Average	85	88	79	84

SB = southbound.

vertical offset between two profiles will. The profile from AHSV2 was rotated manually to match with the reference profile, and figure 12 shows a plot of the rotated profile as well as the profile from the reference device. The cross-correlation between the two profiles shown in figure 12 is 88 percent. Hence, by rotating the profile from AHSV2, it was possible to increase the accuracy cross-correlation of the two profiles from 62 to 88 percent.

A review of plots that had low accuracy cross-correlation values indicated the accuracy of cross-correlation values for some profiles could be increased by rotating the profile collected by the AHSV with respect to the profile collected by the reference device. Therefore, some of the average accuracy cross-correlation values presented in table 5 could be improved by using a technique that will rotate the profile from the AHSV after horizontally offsetting the profiles to obtain the maximum accuracy cross-correlation value.

However, developing a computer program that can do this type of analysis was beyond the scope of this project. Evaluation of transverse profile data collected by the reference device and AHSVs showed that, overall, the AHSVs were able to capture the transverse profile measured by the reference device.

COMPARISON OF RUT DEPTHS COMPUTED FROM REFERENCE DATA AND DATA COLLECTED BY AHSVS

The wireline method option in the Ames Engineering profiler system software was used to compute the rut depths from the data collected for the first pass of the reference device at each test section.(1) In the wireline method, an imaginary wire is fixed at the right edge of the lane and stretched across the lane, connecting the high points on the pavement surface ending at the left edge of the lane. The maximum distance between this wire and the pavement surface in each half of the lane is computed and treated as the rut depth in each lane half. Rut depths were also computed from the transverse profile data collected by the AHSVs at the same locations where reference data were collected for each run at each test section and then averaged to obtain an average rut depth for each test section. Table 6 shows

Table 6. Rut depths from the reference device and AHSVs at the location where reference data were obtained.

Test Section	Reference (Inches)	AHSV1 (Inches)	AHSV2 (Inches)	AHSV3 (Inches)	AHSV4 (Inches)
NB-1, inside lane half	0.25	0.18	0.14	0.20	0.21
NB-2, inside lane half	0.18	0.10	0.07	0.09	0.13
NB-3, inside lane half	0.22	0.17	0.13	0.17	0.16
NB-1, outside lane half	0.09	0.10	0.09	0.14	0.11
NB-2, outside lane half	0.08	0.11	0.10	0.08	0.11
NB-3, outside lane half	0.09	0.12	0.10	0.08	0.08
SB-1, inside lane half	0.19	0.19	0.18	0.19	0.18
SB-2, inside lane half	0.21	0.21	0.20	0.23	0.20
SB-3, inside lane half	0.12	0.10	0.15	0.13	0.12
SB-1, outside lane half	0.12	0.09	0.09	0.13	0.11
SB-2, outside lane half	0.15	0.17	0.15	0.17	0.16
SB-3, outside lane half	0.08	0.07	0.09	0.07	0.10

SB = southbound.

Table 7. Average rut depths for the entire test section.

Section	Lane Half	AHSV1 Rut Depth (Inches)	AHSV2 Rut Depth (Inches)	AHSV3 Rut Depth (Inches)	AHSV4 Rut Depth (Inches)	Range For Four AHSVs (Inches)
NB-1	Inside	0.18	0.16	0.21	0.21	0.16–0.21
NB-2	Inside	0.12	0.09	0.14	0.14	0.09–0.14
NB-3	Inside	0.18	0.14	0.20	0.17	0.14–0.20
SB-1	Inside	0.23	0.22	0.24	0.20	0.20–0.24
SB-2	Inside	0.19	0.19	0.22	0.18	0.18–0.22
SB-3	Inside	0.11	0.18	0.13	0.13	0.11–0.18
NB-1	Outside	0.11	0.09	0.09	0.10	0.09–0.11
NB-2	Outside	0.12	0.10	0.07	0.11	0.07–0.12
NB-3	Outside	0.13	0.10	0.07	0.06	0.06–0.13
SB-1	Outside	0.12	0.10	0.13	0.12	0.10–0.13
SB-2	Outside	0.12	0.11	0.13	0.13	0.11–0.13
SB-3	Outside	0.10	0.12	0.10	0.11	0.10–0.12

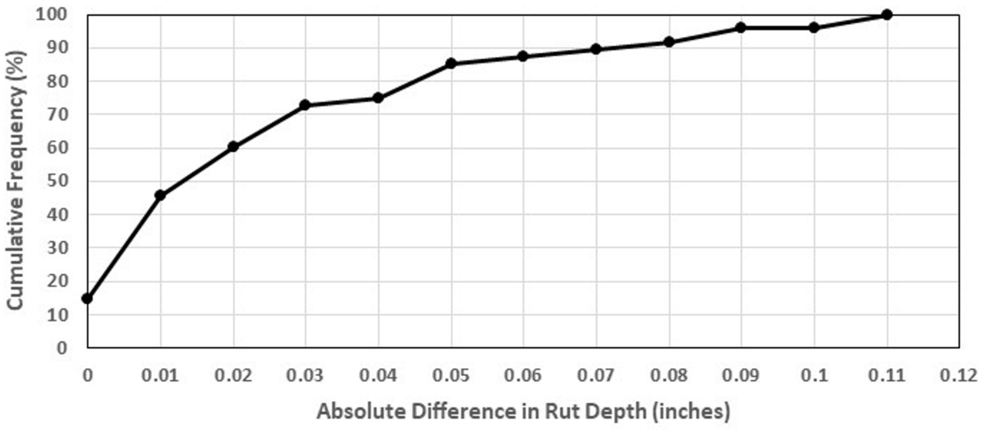
SB = southbound.

the computed average rut depths for the inside and outside lane halves for the test sections.

Since there were six test sections, four AHSVs, and two locations for rut depths (i.e., inside and outside lane halves), there are 48 cases in which reference and AHSV-computed rut depths can be compared. Figure 13 shows the cumulative frequency distribution of the absolute difference in rut depth computed from the reference-device data and corresponding data collected by an AHSV. The following results are seen in figure 13:

- Rut depths from the AHSVs were within 0.01 inch of the reference rut depths for 46 percent of cases.
- Rut depths from the AHSVs were within 0.01 to 0.03 inch of the reference rut depths for 27 percent of cases.
- Rut depths from the AHSVs were within 0.03 to 0.05 inch of the reference rut depths for 13 percent of cases.
- Rut depths from the AHSVs were within 0.05 to 0.11 inch of the reference rut depths for 14 percent of cases.

Figure 13. Graph. Cumulative frequency distribution of absolute difference in rut depths from reference device and AHSVs.



Source: FHWA.

RUT DEPTH FOR ENTIRE SECTION

The data collected by the AHSVs were used to compute rut depths at 1-ft intervals at all six test sections, which were each 50 ft long. The rut depths were computed using the wireline method in Ames Engineering profiler system software. Thereafter, an average rut depth was calculated at the test section for each lane half for each run by averaging the rut depths computed at 1-ft intervals. The average rut depth for the six runs were then averaged, and the computed values are shown in table 7. The rut depths computed from the data collected by all four AHSVs were within 0.05 inch of each other for 9 of the 12 cases shown in table 7. For the other three cases, the rut depths were within 0.06 to 0.07 inch.

CONCLUSIONS

The transverse profiles collected by all four AHSVs showed good repeatability and, when compared to reference profiles, good accuracy.

It was demonstrated that the cross-correlation method could be used to evaluate the repeatability and the accuracy of data collected by transverse profile measuring systems.

In this analysis, ProVAL, which is used to evaluate longitudinal profile data, was used to evaluate the repeatability and accuracy of transverse profile data. In the accuracy evaluation, the data collected by a reference device were used to evaluate the data collected by the AHSVs. The transverse profile data collected by the AHSVs were analyzed using the Profiler Certification module in ProVAL with no filters applied to the data. When comparing two transverse profiles in this module, one profile is fixed, and the other profile is shifted horizontally to obtain the maximum cross-correlation between the two profiles. However, these maximum cross-correlation values could be improved by using a technique that rotates one transverse profile with respect to the other after horizontally offsetting the profiles. Therefore, the cross-correlation value computed by ProVAL will underestimate the actual cross-correlation between two transverse profiles if a profile being evaluated has a rotational shift.

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