TECH**BRIEF**

Investigation of Increase in Roughness Due to Environmental Factors in Flexible Pavements Using Profile Data From Long-Term Pavement Performance Specific Pavement Studies 1 Experiment

The Long-Term Pavement Performance (LTPP) Program is a large research project for the study of in-service pavements across North America. Its goal is to extend the life of highway pavements through various designs of new and rehabilitated pavement structures, using different materials and under different loads, environments, subgrade soil, and maintenance practices. LTPP was established under the Strategic Highway Research Program and is now managed by the Federal Highway Administration.

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology

Turner-Fairbank Highway Research Center

6300 Georgetown Pike

McLean, VA 22101-2296

www.fhwa.dot.gov/research

FHWA Publication No.: FHWA-HRT-17-120

FHWA Contact: Larry Wiser, HRDI-30, 202-493-3079, larry.wiser@dot.gov

This document is a technical summary of the Federal Highway Administration Long-Term Pavement Performance Program report *Investigation of Increase in Roughness Due to Environmental Factors in Flexible Pavements Using Profile Data From Long-Term Pavement Performance Specific Pavement Studies 1 Experiment* (FHWA-HRT-17-049).

Introduction and Objective

From the start of the Long-Term Pavement Performance (LTPP) Program, the longitudinal profiles along the two wheelpaths at LTPP sections have been collected using an inertial profiler. Since December 1996, profilers used to collect data at LTPP sections have collected profile data along the center of the lane in addition to collecting profile data along the two wheelpaths.

On a flexible pavement, the change in roughness along the wheelpaths can be attributed to the change in the profile along the wheelpaths caused by traffic loadings and environmental effects.

Environmental effects can cause changes in the moisture content of the subgrade from the as-constructed value, which can cause the subgrade to shrink or swell. This can affect the profile of the pavement and cause a change in roughness. Freezing temperatures can cause frost heave, which can also affect the pavement profile and cause an increase in roughness. Therefore, the interaction between environmental effects and subsurface layers can cause a change in the profile of a pavement, thereby increasing the roughness of a pavement.

When evaluating the changes in roughness that have occurred along the wheelpaths, environmental effects could not be separated from traffic effects because the collected profile showed the consequences of both factors. On a flexible pavement, the change in roughness along the center of the lane was expected to be mainly affected by the change in the profile that was due to environmental effects. The only traffic the center of the lane experienced was when vehicles changed lanes, and such maneuvers were expected to apply only minimal traffic to the center of the lane. In flexible pavements, transverse cracking can occur because of thermal movements induced on the asphalt concrete (AC) surface, and this cracking can also increase the roughness along the center of the lane. Hence, along the center of the lane, transverse cracking and the interaction between environmental effects and subsurface layers that cause a change in the profile can cause an increase in roughness.

The International Roughness Index (IRI) is an index that is commonly used to characterize the roughness of a pavement. State transportation departments use the mean IRI (MIRI), which is the average of the left and the right wheelpath IRI, to monitor the roughness of their pavement network.

The MIRI values computed from the profile data collected at the LTPP Specific Pavement Studies 1 (SPS-1) experiment, which was developed to investigate the effect of selected structural factors on the long-term performance of flexible pavements that were constructed on different subgrade types and different environmental regions, were used in this research.

The objectives of this study included analyzing the center of the lane IRI (CLIRI) and MIRI at the test sections to evaluate changes over time, comparing the change in CLIRI and MIRI at the test sections, and investigating the effect of subgrade and environmental parameters on the increase in CLIRI.

LTPP SPS-1 Experiment

New pavements were constructed for the SPS-1 experiment. In the SPS-1 experiment, 12 test sections were constructed at a project location. Each test section was 500 ft long with a transition area between the test sections. The pavement structure of the test sections in the SPS-1 experiment is shown in table 1. The 12 test sections in an SPS-1 project were either section numbers 1 through 12 or section numbers 13 through 24.

The structural factors considered in the SPS-1 experiment are asphalt thickness, base type, base thickness, and drainability (presence or lack of as provided by an open-graded permeable asphalt-treated layer and edge drains). Five different base types were used in this experiment: dense-graded aggregate base (DGAB), asphalt-treated base (ATB), ATB over DGAB, permeable ATB (PATB) over DGAB, and ATB over PATB. The subgrade types considered in this experiment were classified as fine-grained and coarse-grained, and the environmental regions considered are the four LTPP environmental regions, which are wet-freeze (WF), wet-no freeze (WNF), dry-freeze (DF), and dry-no freeze (DNF).

In the LTPP Program, the boundary between a wet and a dry region is an annual precipitation

Table 1. SPS-1 test sections.

Test Section Number	AC Thickness (Inches)	Layer 2		Layer 3	
		Material	Thickness (Inches)	Material	Thickness (Inches)
1	7	DGAB	8	—	—
2	4	DGAB	12	—	—
3	4	ATB	8	—	—
4	7	ATB	12	—	—
5	4	ATB	4	DGAB	4
6	7	ATB	8	DGAB	4
7	4	PATB	4	DGAB	4
8	7	PATB	4	DGAB	8
9	7	PATB	4	DGAB	12
10	7	ATB	4	PATB	4
11	4	ATB	8	PATB	4
12	4	ATB	12	PATB	4
13	4	DGAB	8	—	—
14	7	DGAB	12	—	—
15	7	ATB	8	—	—
16	4	ATB	12	—	—
17	7	ATB	4	DGAB	4
18	4	ATB	8	DGAB	4
19	7	PATB	4	DGAB	4
20	4	PATB	4	DGAB	8
21	4	PATB	4	DGAB	12
22	4	ATB	4	PATB	4
23	7	ATB	8	PATB	4
24	7	ATB	12	PATB	4

—Not applicable. DGAB = dense-graded aggregate base; ATB = asphalt-treated base; PATB = permeable asphalt-treated base.

of 20 inches. An area receiving an annual precipitation less than or equal to 20 inches is considered a dry region, while an area receiving an annual precipitation greater than 20 inches is considered a wet region. In the LTPP Program, the boundary between a freezing region and a nonfreezing region is a Freezing Index (FI) of 190 °F d/yr. A region having an FI of less than or equal to 190 °F d/yr is considered a nonfreezing region, while a region having an FI greater than 190 °F d/yr is considered a freezing region.

Climatic and Subgrade Information for SPS-1 Projects

Climatic information at SPS-1 project locations, computed from virtual weather stations data, is available for each year in the Pavement Performance Database (PPDB).[1] The annual precipitation and FI values for each SPS-1 project location were extracted from the PPDB and averaged over the years when center of the lane profile data were collected at the site to obtain a single value for each SPS-1 project.

The subgrade type (i.e., fine-grained or coarse-grained) at each SPS-1 project was obtained from information contained in the PPDB. Also, the Plasticity Index (PI) values for the test sections located on fine-grained subgrade were obtained from the PPDB. As all test sections in a project did not have PI values, the available PI values were averaged to obtain an average PI value for a project.

Eighteen SPS-1 projects were constructed for the LTPP Program. Table 2 shows the States in which the SPS-1 projects were constructed, classified according to the environmental region and subgrade type. The test section numbers constructed for each project are shown within parentheses for each State in this table.

This table shows the SPS-1 projects are not balanced over the environmental regions and the subgrade types. Eleven SPS-1 projects are located on coarse-grained subgrade compared to seven projects that are located on fine-grained subgrade. The distribution of the projects according to the environmental regions was DNF, two projects; DF, two projects; WNF, eight projects; and WF, six projects. A third of the SPS-1 projects are located in the WNF region on a coarse-grained subgrade. Data from 201 SPS-1 test sections that had CLIRI data were analyzed for this research. Of these test sections, 125 were located on coarse-grained subgrade, and the other 76 sections were located on fine-grained subgrade. Because this was not a balanced experiment, some biases could be present when comparisons are performed between environmental regions and subgrade types.

The median ages of the test sections that were analyzed were 11.8 and 9.3 yr for the sections on coarse- and fine-grained subgrade, respectively. The third quartile values for the age of the test sections were 13.7 and 12.2 yr for the sections on coarse- and fine-grained subgrade, respectively.

Table 2. SPS-1 projects classified according to environmental region and subgrade type.

Environmental Region	Subgrade Type	
	Fine-Grained	Coarse-Grained
DNF	New Mexico (1–12)	Arizona (13–24)
DF	None	Montana (13–24) Nevada (1–12)
WNF	Alabama (1–12) Louisiana (13–24)	Arkansas (13–24) Delaware (1–12) Florida (1–12) Oklahoma (13–24) Texas (13–24) Virginia (13–24)
WF	Iowa (1–12) Michigan (13–24) Nebraska (13–24) Ohio (1–12)	Kansas (1–12) Wisconsin (13–24)

IRI Data for Analysis

Profile data files that contain the left wheelpath, right wheelpath, and center of the lane data at 0.98-inch intervals are stored in the LTPP Ancillary Information Management System. These data files conform to the University of Michigan Transportation Research Institute Engineering Research Division (ERD) file format. These ERD files were requested for this study through the LTPP Customer Support Service.[2]

The profile data in the ERD files were used to compute the left wheelpath, right wheelpath, and CLIRI values. During a site visit, the profiler collecting data typically performs seven to nine repeat runs at a test section. For each site visit, the IRI values for the repeat runs were averaged to obtain an average IRI for each profiled path (i.e., left wheelpath, right wheelpath, and center of the lane).

A construction number of 1 is assigned to an SPS-1 section initially after construction. Whenever any maintenance or rehabilitation activity is performed at an SPS-1 section, the construction number is incremented, and the date that the maintenance or rehabilitation was performed, including the type of maintenance or rehabilitation activity, is recorded in a table in the PPDB.

Maintenance activities at a section can include crack sealing, slurry sealing, applying an aggregate seal coat, or patching. Such an activity can cause a decrease in IRI, an increase in IRI, or have no impact on the IRI. Rehabilitation performed at a section typically involves the placement of an overlay, which will usually cause a sharp reduction in the IRI of the pavement.

IRI versus pavement age plots were developed for each test section to evaluate how the IRI of the left wheelpath, right wheelpath, and center of the lane changed over time. Figure 1 shows an example of such a plot for section 010106. The horizontal axis of this plot represents the pavement age, with the pavement age being assigned a value of 0 for the traffic open date. The first IRI value shown in this plot corresponds to the date when center of the lane profile data were first collected at this section. The time series IRI values at each test section were visually examined to evaluate the changes in IRI over time. The IRI values before and after a change in construction number were reviewed to evaluate if the activity impacted the IRI. If the activity had an impact on IRI, a sharp change in IRI would be noticed between the IRI before and after the activity. If a sharp increase or decrease in IRI occurred between visits and there was no maintenance or rehabilitation activity indicated in the PPDB table, such data points were closely evaluated to determine the cause for the sharp increase or decrease in IRI. When investigating the cause for the change in IRI, in addition to evaluating the profile data, distress data, cracks maps, photographs, and videos obtained during the distress surveys were used as appropriate to determine the cause for the sudden change in IRI.

After evaluating the time-sequence IRI values, an IRI dataset that was suitable for analysis was assembled. For sections where maintenance or rehabilitation affected the IRI, only the IRI data before the maintenance or rehabilitation were considered for analysis.

An LTPP section is said to be deassigned when that section goes out of the LTPP Program. In an SPS-1 project, all test sections are not necessarily deassigned on the same date. Individual sections can be deassigned at different times when they are rehabilitated. In such projects, the period over which profile data have been collected at test sections in the project can vary, with test sections that were deassigned earlier being monitored over a shorter time period when compared to sections that were deassigned later.

Table 3 shows the SPS-1 projects classified according to the average timespan over which center of the lane data were available for the project. The average timespan was computed by averaging the timespan over which IRI data were available at each section in the SPS-1 project. As shown in table 3, the average timespan over which center of the lane data were collected was fewer than 6 yr for five SPS-1 projects, between 6 and 10 yr for six SPS-1 projects, and over 10 yr for seven SPS-1 projects.

Evaluation of the IRI versus time plots for the SPS-1 sections showed a linear trend in IRI progression for a majority of the sections, except for a few of the structurally weak sections that showed an exponential trend for increase in IRI at the latter years. As a majority of the sections showed a linear trend for IRI increase, a linear regression analysis between IRI and pavement age was performed on all sections to estimate the rate of increase of MIRI and CLIRI of each section.

Figure 1. Graph. IRI progression at section 010106.[3]

Source: FHWA.

Table 3. SPS-1 projects classified based on average timespan over which center of the lane data were available.

Average Period Over Which Center of the Lane Data Were Collected (Years)	SPS-1 Project
2–4	Iowa, Nebraska, Texas
4–6	Kansas, Michigan
6–8	Alabama, Arizona, Ohio
8–10	Arkansas, Delaware, New Mexico
10–12	Montana, Nevada, Virginia, Wisconsin
12–14	Oklahoma
14–16	Florida, Louisiana

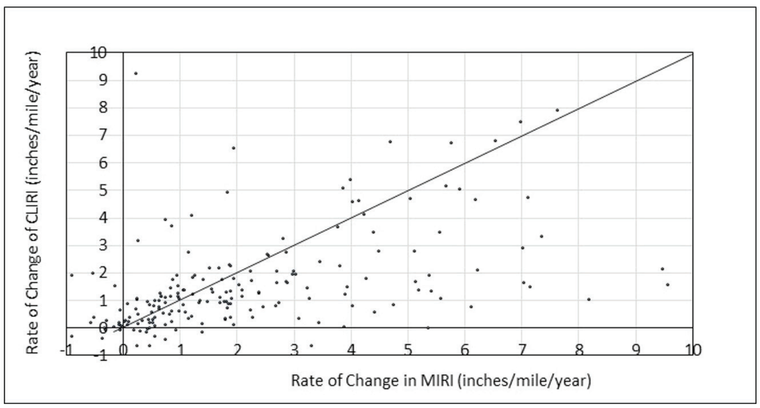
Findings From Research

Rate of Change of MIRI and CLIRI

Figure 2 shows the relationship between the rate of change of MIRI and CLIRI at the SPS-1 test sections. When all SPS-1 test sections were considered, the median value of the rate of change of MIRI and CLIRI was 1.56 and 1.05 inches/mi/yr, respectively, while the third quartile values for these parameters were 3.22 and 1.19 inches/mi/yr, respectively. The rate of change of MIRI was greater than the rate of change of CLIRI at 62 percent of the test sections.

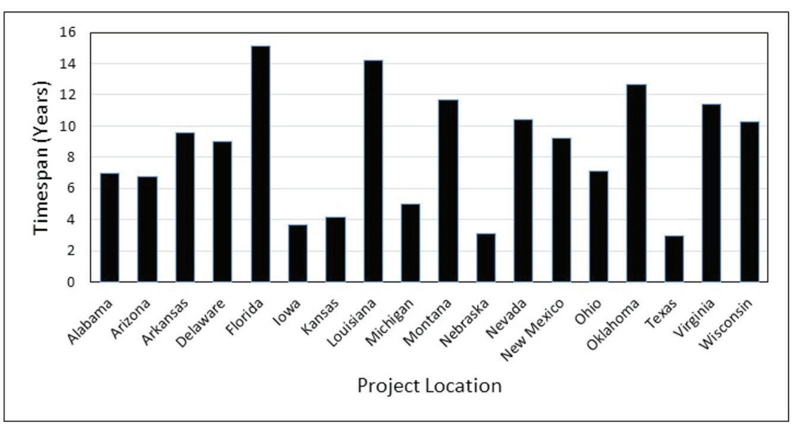
Figure 3 shows the average timespan over which IRI data were collected at the test sections in each SPS-1 project. The average timespan was computed by averaging the timespan over which data were collected at each test section in the SPS-1 project. Figure 4 and figure 5 show box plots of the rate of change of MIRI and CLIRI at the sections in each SPS-1 project, respectively. A box plot is a simple graphical representation that shows the distribution of data. For each SPS-1 project, the box plot shows the distribution of the change in IRI values for the test sections located in the SPS-1 project. The horizontal line located within the box shows the median of the data. The bottom of the box shows the value of the first quartile of the data (i.e., 25th-percentile value), while the top of the

Figure 2. Graph. Relationship between the rate of change of CLIRI and MIRI.[3]



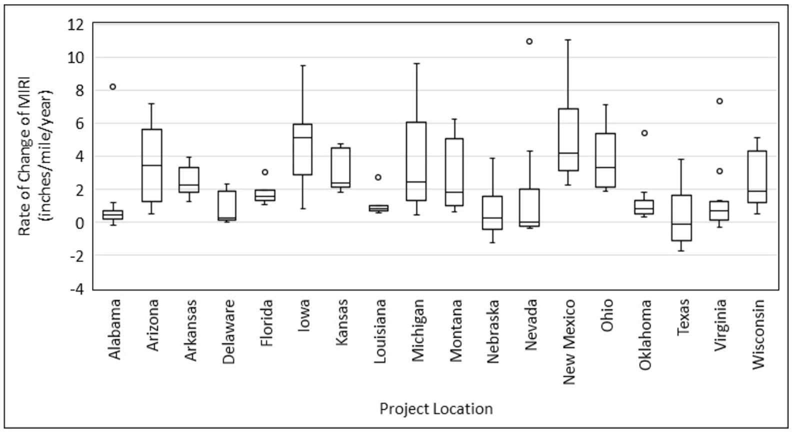
Source: FHWA.

Figure 3. Bar graph. Average timespan over which CLIRI data were available for test sections in SPS-1 projects.[3]



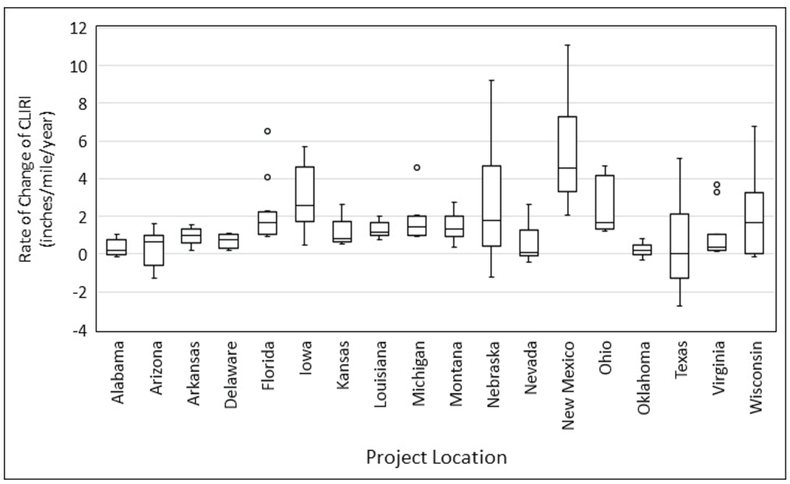
Source: FHWA.

Figure 4. Box plots. Rate of change of MIRI at test sections in each SPS 1 project.[3]



Source: FHWA.

Figure 5. Box plots. Rate of change of CLIRI at test sections in each SPS-1 project.[3]



Source: FHWA.

box shows the value of the third quartile of the data (i.e., 75th-percentile value). The whiskers (i.e., the horizontal lines) in the plot at the top and the bottom show the range of the data. An outlier is shown as a circle above or below the whiskers. The magnitude of the rate of change of MIRI as well as CLIRI at test sections in a project varied from project to project. In some projects, the rate of change of CLIRI fell within a narrow range, while in others, the range was wider.

Effect of Subgrade Type

Overall, sections on fine-grained subgrade showed a higher rate of change of MIRI and CLIRI compared to sections on coarse-grained subgrade. The median, first quartile, and third quartile values for the rate of change of MIRI and CLIRI for sections located on fine-grained and coarse-grained subgrade are shown in table 4. A t-test at a significance level of 0.05 indicated that the mean value for the rate of change of

MIRI as well as CLIRI for sections on fine-grained subgrade was greater than the corresponding values for sections on coarse-grained subgrade.

Sufficient projects were available to compare the performance of the sections on fine- and coarse-grained subgrade in the WF and WNF environmental regions. The median, first quartile, and third quartile values for the rate of change of MIRI and CLIRI for sections in the WF and WNF regions are shown in table 5. As seen in table 5, in both environmental regions, the sections on fine-grained subgrade showed higher rate of change of MIRI as well as CLIRI compared to the sections on coarse-grained subgrade.

Effect of Drainage

A PATB layer was present in the pavement structure to provide drainage at test sections 7 through 12 and 19 through 24. At sections 7 through 9 and 19 through 21, the PATB layer was located between the AC surface and the DGAB layer. In sections 10 through 12 and 22 through 24, the PATB layer was located between the ATB layer and the subgrade.

Table 6 shows the median, first quartile, and third quartile values for the rate of change of MIRI and CLIRI classified according to subgrade type and provision of drainage. Data in table 6 show the provision of drainage reduced the rate of change of MIRI as well as CLIRI. The reduction in the rate of change of MIRI as well as CLIRI with

Table 4. Median, first quartile, and third quartile values for rate of change of IRI for sections on fine- and coarse-grained subgrade.

Parameter	Number of Test Sections	Rate of Change of IRI (Inches/mi/yr)		
		Median	First Quartile	Third Quartile
MIRI, fine	76	1.87	0.65	4.45
MIRI, coarse	125	1.43	0.48	2.69
CLIRI, fine	76	1.65	0.95	3.49
CLIRI, coarse	125	0.78	0.18	1.45

Table 5. Median, first quartile, and third quartile values for rate of change of IRI for sections on fine- and coarse-grained subgrade classified according to WF and WNF environmental regions.

IRI	Environmental Region	Subgrade	Number of Test Sections	Rate of Change of IRI (Inches/mi/yr)		
				Median	First Quartile	Third Quartile
MIRI	WF	Coarse	19	2.26	1.59	4.42
		Fine	40	2.80	0.81	5.47
	WNF	Coarse	70	1.09	0.29	1.90
		Fine	24	0.67	0.48	0.96
CLIRI	WF	Coarse	19	1.36	0.59	2.18
		Fine	40	1.86	1.29	3.56
	WNF	Coarse	70	0.67	0.20	1.26
		Fine	24	0.92	0.25	1.15

the provision of drainage was greater for the sections on fine-grained subgrade compared to the sections on coarse-grained subgrade.

As seen in table 6, the provision of drainage for the sections on coarse-grained subgrade also reduced the rate of change of IRI, though not as much as for fine-grained subgrade. A coarse-grained subgrade can have a fines content of up to 50 percent, and the effect of drainage for sections on coarse-grained subgrade could vary depending on the amount of fines content in the subgrade.

Sufficient projects were available to compare the performance of the sections on fine-grained subgrade in the WF and WNF environmental regions with and without drainage. Table 7 shows the median, first quartile, and third quartile values for the rate of change of MIRI and CLIRI classified according to subgrade type and provision of drainage in these environmental regions. The information presented in table 7 shows the provision of drainage for pavements on fine-grained subgrade located in the WF region can reduce the rate of change of IRI significantly.

Table 6. Median, first quartile, and third quartile values for rate of change of IRI for sections on fine- and coarse-grained subgrade classified according to presence of drainage.

IRI	Parameter	Number of Test Sections	Rate of Change of IRI (Inches/mi/yr)		
			Median	First Quartile	Third Quartile
MIRI	Fine, no drainage	37	2.72	0.89	5.92
	Fine, drainage	39	1.24	0.53	3.43
	Coarse, no drainage	62	1.55	0.50	3.31
	Coarse, drainage	63	1.40	0.50	2.34
CLIRI	Fine, no drainage	37	2.40	1.23	4.58
	Fine, drainage	39	1.23	0.61	1.97
	Coarse, no drainage	62	0.85	0.18	1.46
	Coarse, drainage	63	0.66	0.19	1.36

Table 7. Median, first quartile, and third quartile values for rate of change of IRI for sections on fine-grained subgrade classified according to WF and WNF environmental regions and presence of drainage.

IRI	Environmental Region	Provision of Drainage	Number of Test Sections	Rate of Change of IRI (Inches/mi/yr)		
				Median	First Quartile	Third Quartile
MIRI	WF	No drainage	19	3.01	1.83	6.07
		Drainage	21	1.90	0.65	3.91
	WNF	No drainage	12	0.93	0.56	1.03
		Drainage	12	0.59	0.36	0.67
CLIRI	WF	No drainage	19	2.88	2.00	4.66
		Drainage	21	1.33	0.93	1.82
	WNF	No drainage	12	0.99	0.72	1.30
		Drainage	12	0.66	0.01	1.12

For sections on fine-grained subgrade, the sections where the PATB layer was below the ATB layer (i.e., ATB/PATB) had an overall lower rate of change of MRI and CLIRI when compared to sections where the PATB layer was placed above the DGAB layer (i.e., PATB/DGAB). The median values for the rate of change of MIRI where drainage was provided by ATB/PATB and PATB/DGAB were 1.12 and 1.24 inches/mi/yr, respectively, while the rate of change of CLIRI for these two cases was 1.16 and 1.32 inches/mi/yr, respectively. The third quartile value for the rate of change of MIRI where drainage was provided by ATB/PATB and PATB/DGAB was 2.88 and 4.55 inches/mi/yr, respectively, while the corresponding values for the rate of change of CLIRI were 1.81 and 2.67 inches/mi/yr, respectively.

Effect of PI

For sections on fine-grained subgrade, the rate of increase of CLIRI and MIRI showed an increasing trend with the increase in PI values of the subgrade. Figure 6 shows the rate of change of CLIRI of test sections plotted with the PI of the subgrade for the SPS-1 projects located on fine-grained subgrade. The rate of change of CLIRI values shown vertically for a specific value of PI are those for the various test sections in that SPS-1 project.

Other Observations

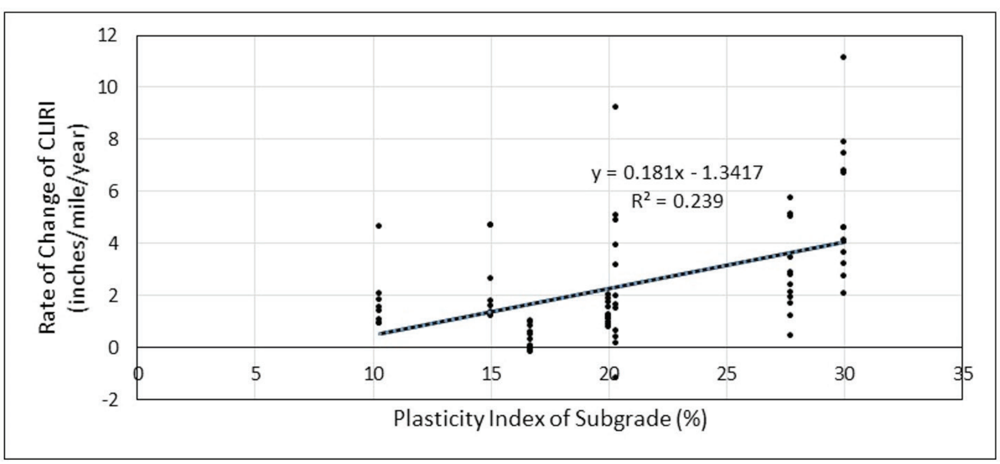
Raveling of the pavement surface contributed to the increase in MIRI as well as the CLIRI at all test sections in the New Mexico SPS-1 project.

In many cases, construction of patches increased the IRI of the pavement significantly. This implies more care should be taken when constructing patches to ensure they are adequately compacted and their surfaces are smooth.

Benefits of Collecting Profile Data Along the Center of the Lane

State transportation departments obtain network-level profile data along the two wheelpaths of the travel lane and use the MIRI computed from the collected data to track the roughness of their highway network. Collecting profile data along the center of the lane could provide information on how the CLIRI along the center of the lane, which is mainly influenced

Figure 6. Graph. Rate of change of CLIRI of test sections located on fine-grained subgrade versus the PI of the subgrade.[3]



Source: FHWA.

by environmental effects, would change over time. This information could be used to modify or improve the agency's pavement design procedure to minimize large increases in IRI in areas where the combination of environmental and subgrade conditions caused such increases in the center of the lane. This information can also be used by the agency to build better models for predicting the change in IRI due to environmental conditions.

References

1. Federal Highway Administration. (2016). "LTPP InfoPave™." (website) Washington, DC. Available online: https://infopave.fhwa.dot.gov/, last accessed March 15, 2016.
2. Federal Highway Administration. (2016). "LTPP InfoPave™." (website) Washington, DC. Available online: https://infopave.fhwa.dot.gov/Help/CustomerSupport, last accessed March 15, 2016.
3. Perera, R.W. and Al-Rawashdeh, A. (2017). *Investigation of Increase in Roughness Due to Environmental Factors in Flexible Pavements Using Profile Data From Long-Term Pavement Performance Specific Pavements Studies 1 Experiment*, Report No. HRT-17-049, Federal Highway Administration, McLean, VA. Available online: https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/17049/17049.pdf, last accessed March 15, 2018.

Researchers—R.W. Perera and A. Al-Rawashdeh, SME, Plymouth, Michigan.

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Key Words—IRI, LTPP, long-term pavement performance, pavement smoothness, pavement roughness, environmental factors.

JUNE 2018

FHWA-HRT-17-120
HRDI-30/06-18(WEB)E