TECH**BRIEF**

Long-Term Pavement Performance Program—Pavement Performance Measures and Forecasting and the Effects of Maintenance and Rehabilitation Strategy on Treatment Effectiveness

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.

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This document is a technical summary of the Federal Highway Administration Long-Term Pavement Performance Program report, *Pavement Performance Measures and Forecasting and the Effects of Maintenance and Rehabilitation Strategy on Treatment Effectiveness* (FHWA-HRT-16-047).

Introduction and Objective

This TechBrief presents the methodologies and procedures used by the research team in the analyses of the Long-Term Pavement Performance (LTPP) data to develop and implement pavement performance measures and to analyze treatment effectiveness. The LTPP study focused on using data from the various LTPP experiments to define pavement performance in a way that supports the selection of cost-effective pavement treatment strategy and to better estimate pavement treatment effectiveness and the role of pavement treatments in the pavement's lifecycle. This TechBrief includes a description and examples of the dual pavement condition rating systems, LTPP data analyses results, and application of the analyses to datasets from three State transportation departments.

Dual Pavement Condition Rating Systems

To address the objectives of this study, comprehensive dual pavement condition rating systems were developed based on pavement conditions and rates of deterioration. An accurate pavement condition rating system best represents pavement behavior when it is based on both current and future pavement conditions. The main benefit of including the estimation of future conditions is the ability of pavement managers to plan, budget, and create cost-effective long-term pavement treatment strategies to preserve the pavement network. Pavement condition ratings based on current conditions alone only allow decisions to be made for the given data collection cycle and do not support lifecycle cost analyses (LCCA).

Balanced and comprehensive dual pavement condition rating systems were developed based on two types of pavement conditions: functional and structural. The functional rating is based on ride quality (International Roughness Index (IRI)) and safety (rut depth) and is expressed by the remaining functional period (RFP). (See the section entitled Definitions of RFP and RSP.) The structural rating is based on cracking and rut depth or faulting and is expressed by the remaining structural period (RSP). The RFP and RSP could be expanded by the road authority to include other pavement conditions and distress types such as skid resistance for the RFP, block cracking (for the RSP of flexible pavements), or corner breaks (for the RSP of rigid pavements). In this study, two pavement condition measures (IRI and rut depth) were used to calculate the RFP and four pavement distress types (alligator, longitudinal, and transverse cracking and rut depth or faulting) to calculate the RSP.

Definitions of RFP and RSP

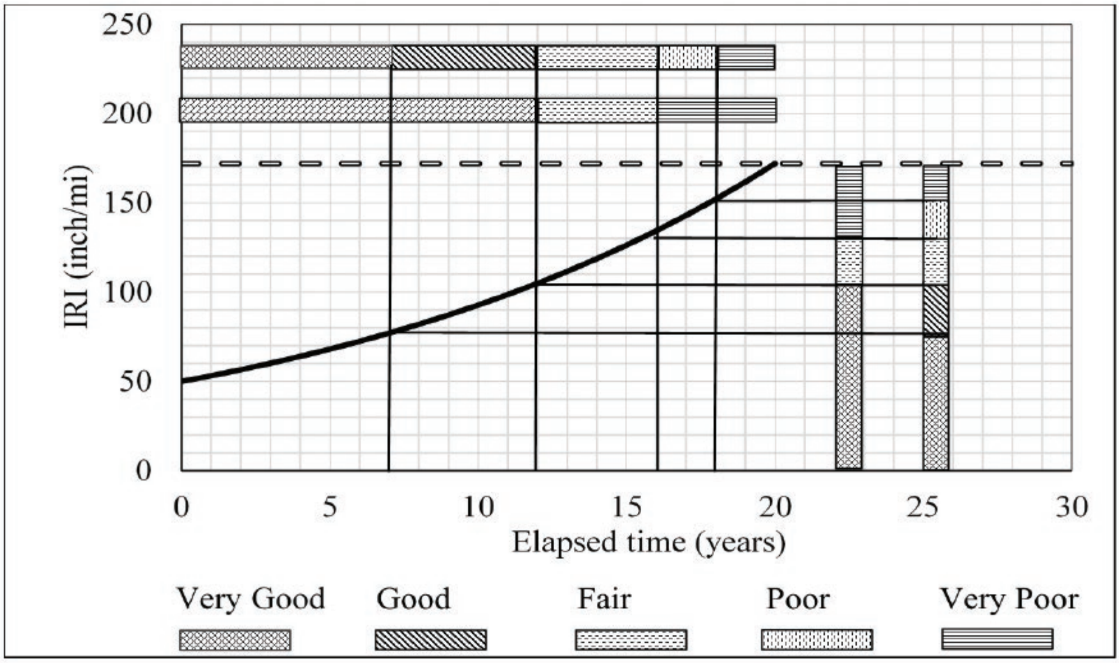
The RFP is defined as the shortest time period measured in years from the time of the last data collection cycle to the time when a functional condition (e.g., IRI, rut depth, or other) reaches its corresponding prespecified threshold value. For a given pavement section and when supported by the available data, two or more RFP values can be calculated: one based on IRI, one on rut depth, one on skid resistance, and so forth. The shortest of the RFP values is assigned to the pavement section in question to flag the section for potential treatment actions. It should be noted that the measured pavement condition and distress data must be retained in the database and used to facilitate the selection of treatment types. The RFP is depicted in figure 1.

The RSP is defined as the shortest time period measured in years from the time of the last data collection to the time when a structural distress reaches its corresponding prespecified threshold value. For a given pavement section and when supported by the available data, two or more RSP values should be calculated: one for transverse, longitudinal, alligator, edge, and block cracking and one for either rut depth (for flexible pavements) or faulting (for rigid pavements). The shortest of the RSP values is assigned to the pavement section in question to flag the section for potential treatment actions. Once again, the measured distress data must be retained in the database to facilitate the selection of treatment types. The RSP is depicted in figure 2.

Rating Scale

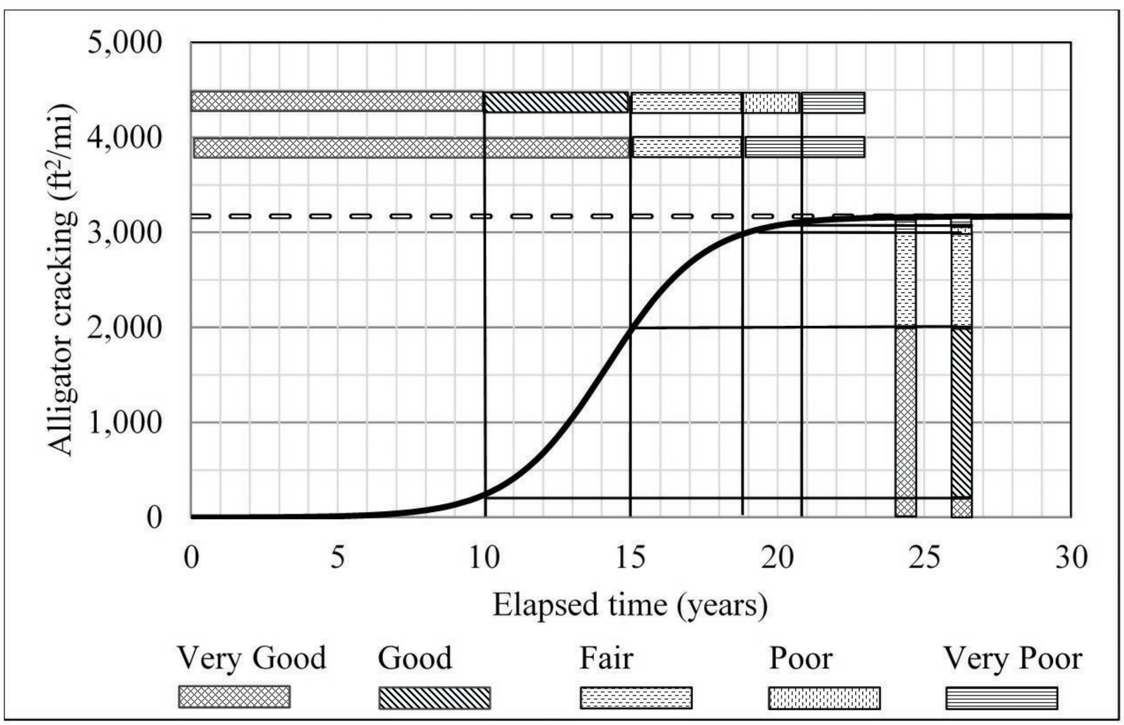
Two rating scales could be used for each of the RFP and RSP. One scale is based on three levels, and the other scale is based on five levels. For each scale, the pavement condition states (CSs) can be expressed either in descriptive terms or in numeric terms that represent the RFP and the RSP. For example, for the three-level scale, the CS of a given pavement section may be expressed in one

Figure 1. RFP condition states (CSs) for three- and five-level scales.



1 inch/mi = 0.01588 m/km.

Figure 2. RSP CSs for three- and five-level scales.



1 ft^2/mi = 0.05806 m^2/km.

of the following categories as illustrated in this list and in table 1:

- CS-1, or red, or poor and RFP or RSP of shorter than 4 years.
- CS-2, or yellow, or fair, and RFP or RSP between 4 and 8 years.
- CS-3, or green, or good, and RFP or RSP longer than or equal to 8 years.

The dual rating systems could be used to select treatment categories at the network level. For example, preservation treatments should generally be applied to pavement sections with fair or better CSs. Heavy preservation treatment, or more likely rehabilitation, should generally be applied to pavement sections having poor RSP CSs. The treatment selection should be verified at the project level.

The five-category rating scale included in table 2 provides finer and additional data analyses.

The three- and five-category rating scales are also depicted in figure 1 and figure 2 for RFP

Table 1. Pavement condition rating based on three CSs.

CS			RFP Range (Year)	RSP Range (Year)	Cost per Lane-Mile (Lane-Km) \$ times 10^5	
Code	Pattern or Color	Descriptor			RFP	RSP
1	Horizontal solid line or red	Poor	< 4	< 4	5 (3.1)	10 (6.2)
2	Horizontal dashed line or yellow	Fair	4 to < 8	4 to < 8	2.2 (1.4)	5.5 (3.4)
3	Diagonal crisscross line or green	Good	> 8	> 8	0.3 (0.2)	1.0 (0.6)

Table 2. Pavement condition rating based on five CSs.

CS			RFP Range (Year)	RSP Range (Year)	Cost per Lane-Mile (Lane-Km) \$ times 10^5	
Code	Pattern or Color	Descriptor			RFP	RSP
1a	Horizontal solid line or red	Very poor	< 2	< 2	5 (3.1)	10 (6.2)
1b	Vertical dashed line or pink	Poor	2 to < 4	2 to < 4	3 (1.9)	7 (4.4)
2	Horizontal dashed line or yellow	Fair	4 to < 8	4 to < 8	1.5 (0.9)	4 (2.5)
3a	Diagonal line or light green	Good	8 to < 13	8 to < 13	0.5 (0.3)	1.5 (0.9)
3b	Diagonal crisscross line or green	Very good	> 13	> 13	0.1 (0.1)	0.5 (0.3)

and RSP, respectively. Note that for both pavement rating scales, the main reason for using the same ranges in years for RFP and RSP for each rating category is for ease of communication. The CS numbers could be used for programming purposes, the color code for mapping, the descriptive (poor, fair, and good) for communication with the public and legislators, and the RFP and RSP scales for planning and for LCCA. The latter could be better accomplished if the road agencies used their own cost data to assign an average pavement preservation cost per lane mile for each RFP range and for each RSP range (similar to the conceptual cost included in table 1 and table 2). In general, the cost of preserving pavement sections based on short RFP is much lower than the cost of preservation based on short RSP.

The main advantage of the RFP and RSP is that the value of each should decrease 1 year for every calendar year. Although the RFP and RSP are calculated using nonlinear functions to model the pavement condition and distress as a function of time (i.e., exponential function for IRI, power function for rut depth, and logistic (S-shaped curve) for cracking), the resulting RFP and RSP are linear functions of time. Each should decrease by 1 year for every calendar year. Nevertheless, the RFP and RSP can be considered forecasting tools that can be used to establish cost-effective strategies that address planning, budgeting, and contracting pavement preservation activities at the proper time.

One Record Condition State Estimate (ORCSE)

As stated earlier, for a given pavement section, the RFP and/or the RSP values can be considered the forecasting tool to flag pavement sections that require attention. The two values are based on the measured time-dependent pavement condition and distress data. The data are fitted to the proper mathematical function, which is used to forecast the time at which the pavement section in question will reach the threshold value. However, for many pavement sections, the pavement management database does not contain the required minimum three data points to model the pavement condition and distress as a function of time. This scenario is especially true for newly constructed or rehabilitated pavement sections. To address the problem, the LTPP database was used to develop a forecasting system called ORCSE based on a single measured data point.[1] In the development, the LTPP data from Specific Pavement Study (SPS)-1 were analyzed, and the RFP an RSP for each test section were calculated. The calculated RFP and RSP values and one individual measured data point were modeled using the Epanechnikov Kernel probability density function model. The model provided the closest fit to the observed data while generating secondary benefits of the identification of possible sub-probability groups or divergent behaviors within the larger SPS-1 generalized sample. Table 3 lists CS probabilities based on ranges of measured IRI for SPS-1 test sections before treatment (BT). For older SPS-1 sections, the ORCSE results were within 5 percent of those using three or more data points. Therefore, the ORCSE is a reliable method for estimating RFP and RSP while time series data are under collection.

Table 3. ORCSE model table example from LTPP SPS-1 BT evaluation.

IRI Range (inches/mi)	Probability of a CS or RFP Level for Selected IRI Ranges (percent)				
	CS 1 or RFP < 2 years	CS 2 or RFP 2 to < 4 years	CS 3 or RFP 4 to < 8 years	CS 4 or RFP 8 to < 13 years	CS 5 or RFP ≥ 13 years
.25–.50	0	0	0	3	97
.50–.75	0	0	3	14	83
.75–1.00	0	0	4	19	77
1.00–1.25	0	0	9	39	52
1.25–1.50	0	3	19	66	11
1.50–1.75	0	12	49	37	1
1.75–2.00	3	28	59	10	0
2.00–2.25	13	61	22	3	0
2.25–2.50	55	36	6	3	0
2.50–2.70	88	8	1	2	0

1 inch/mi = 0.02 m/km.

LTPP Data Analyses

Pavement condition and distress data as well as inventory and treatment data were obtained from the LTPP Standard Data Release 28. The available data for test sections from SPS-1 through SPS-7, General Pavement Studies (GPS)-6, GPS-7, and GPS-9 experiments were modeled both before and after the application of treatments. For the total of 1,555 test sections (see table 4), sufficient data were available and were analyzed before treatment (BT) and after treatment (AT) in 1,182 instances; sufficient data were available and were analyzed BT in only 1,544 instances, and sufficient data were available and were analyzed AT in only 2,691 instances.

For each treatment application, the IRI data were modeled using an exponential function, rut depth data using a power function, and cracking data using a logistic (S-shaped) function.

The conclusions and recommendations drawn from these analyses are presented in the last section of this TechBrief. For each treatment application, the RFP and RSP values were calculated based on the threshold values. The following should be noted:

- The following threshold values are flexible and can be adjusted based on the road authority goals, constraints, and needs:
    - IRI—172 inch/mi (2.7 m/km).

Table 4. Summary of treatments applied to SPS-1 through SPS-7 and GPS-6, -7, and -9.

Number of Test Sections	Number of Treated Sections	Number of Treatment Applications	Pavement Distress/ Condition	Number of Treatment Applications Analyzed		
				BT and AT	BT Only	AT Only
1,555	1,301	2,674	Cracking	278	463	925
			IRI	468	558	911
			Rut depth	394	453	747
			Faulting	42	70	108
Total				1,182	1,544	2,691

- Rut depth—0.5 inch (12.7 mm).
- Alligator cracking—1,267 ft^2/0.1 mi (73 m^2/0.1 km).
- Longitudinal cracking—1,056 ft/0.1 mi (201 m/0.1 km).
- Transverse cracking (hot-mix asphalt (HMA))—350 ft/0.1 mi (67 m/0.1 km).
- Transverse cracking (jointed concrete pavement (JCP))—264 ft/0.1 mi (50 m/0.1 km).
- Faulting-average—0.25 inch over 0.1 mi (3.97 mm over 0.1 km).

- These threshold values cannot and should not be used to select certain pavement preservation actions such as thin or thick overlay or mill-and-fill treatments. The threshold values indicate the minimum acceptable level of service or pavement condition. The resulting RFP and RSP are mainly used to flag pavement sections in need of preservation. The flagging level could be set at RFP and/or RSP values of 4 or 7 years or whatever value is perceived by the road owners based on their needs and constraints.
- The selection of cost-effective pavement preservation treatments should be based on the measured pavement condition and distress data and on the causes of pavement deterioration.

Application of Methodology to State Data

Similar analyses to those performed on the LTPP data were performed on pavement condition and distress data measured by three State transportation departments (Colorado, Louisiana, and Washington) along various pavement projects of their respective pavement networks. The data collected and stored by the State transportation departments are similar to the LTPP data with few exceptions. These data include the pavement segment length, definition of some pavement distresses and units of measurement, pavement structure or cross-section, and other inventory data. The three State transportation departments collect and store data for each 0.1-mi (0.16-km)-long pavement segment along their respective networks. For each pavement project and for each data collection cycle, the number of data points available in the database is the same as the number of consecutive 0.1-mi (0.16-km)-long pavement segments along the project. The analyzed pavement projects were subjected to various treatments, including single chip seal, thin and thick HMA overlays, and thin and thick mill-and-fill treatments.

Nevertheless, results of the analyses indicate the following:

- The newly developed dual pavement performance rating systems are applicable to the State and the LTPP data.
- The treatment benefits calculated using the LTPP data are almost equal to the treatment benefits calculated using the State data.
- The variability of the measured IRI, rut depth, and cracking data along a given pavement project is similar to the variability in the same data of comparable LTPP test sections.

The important implication of the findings is that the analysis methodologies described in this study can be used by the various State transportation departments. Furthermore, the RFP and RSP concept and the CSs apply equally to the State and the LTPP data.

Finally, the research team strongly recommends that treatment benefit benchmarks obtained from the analyses of the LTPP data be adopted and used by the American Association of State

Highway and Transportation Officials (AASHTO) and the State transportation departments. This would standardize the designations of the treatment benefits prior to the LCCA.

Deflection Data Analyses

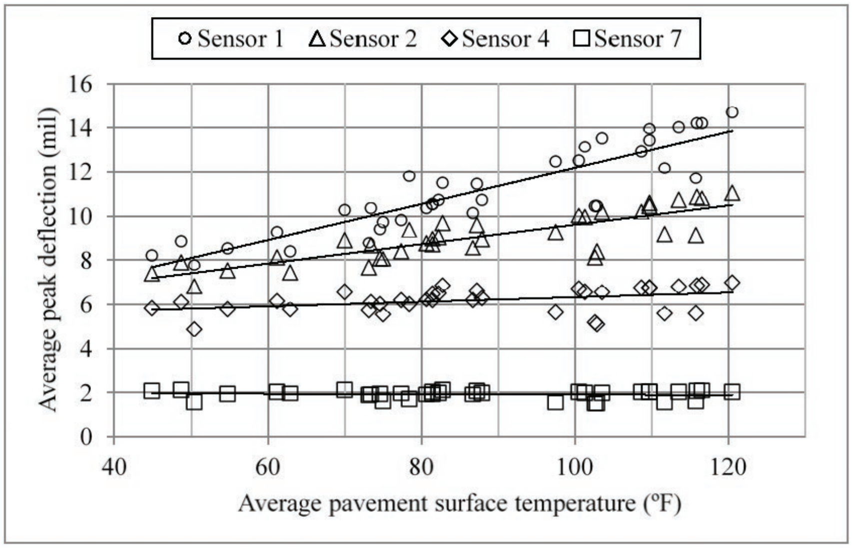
The RFP and RSP algorithms are primarily based on the measured time-series pavement surface condition and distress data and their corresponding threshold values. Hence, the distress (such as cracking) must be visible from the pavement surface to be counted. During the development of the RFP and RSP concepts, it was envisioned that the pavement deflection data could be used to indicate impending surface distress and be a part of the RSP algorithm. Such algorithms would empower State transportation departments to take corrective actions prior to the manifestation of surface defects. To incorporate deflection into the RSP algorithm, a deflection threshold value must be developed for each pavement section. To investigate the potential for the development of deflection threshold values, the measured falling weight deflectometer (FWD) deflection data of various LTPP seasonal monitoring program (SMP) and other test sections were analyzed.

The main purpose of the analyses of the deflection data is to identify relationships, if any, between the measured pavement deflection and the measured pavement condition data to determine whether the deflection data can be used to estimate the optimum time for pavement preservation. To conduct the analyses, the measured pavement surface deflections of some flexible pavement test sections were examined. Figure 3 shows the impacts of the measured pavement surface temperature on the pavement surface deflection measured at deflection sensors 1, 2, 4, and 7 (0, 8, 18, and 60 inches (0, 203, 457, and 1,524 mm) from the load) of the FWD. As was expected, the data indicate that the effects of temperature decrease with increasing distance from the center of the FWD load plate. The measured deflections were then adjusted to the standard temperature of 70 °F (21 °C) using existing temperature adjustment models, such as the Asphalt Institute (AI) and BELLS models.[2,3] None of the SMP site results agreed with the measured deflection data at the standard temperature of 70 °F (21 °C). Therefore, a global temperature adjustment procedure was developed using the LTPP measured deflection data along with various SMP test sections. The new procedure is applicable to all deflection sensors and in all climatic regions.

The AI method and the new procedure were then used to adjust the measured deflection data over time to the standard temperature of 70 °F (21 °C). Figure 4 depicts the percent error between the temperature-adjusted deflection data and the measured deflection data at 70 °F (21 °C) at the same SMP test site. It can be seen that the new procedure has much smaller errors than the AI procedure.

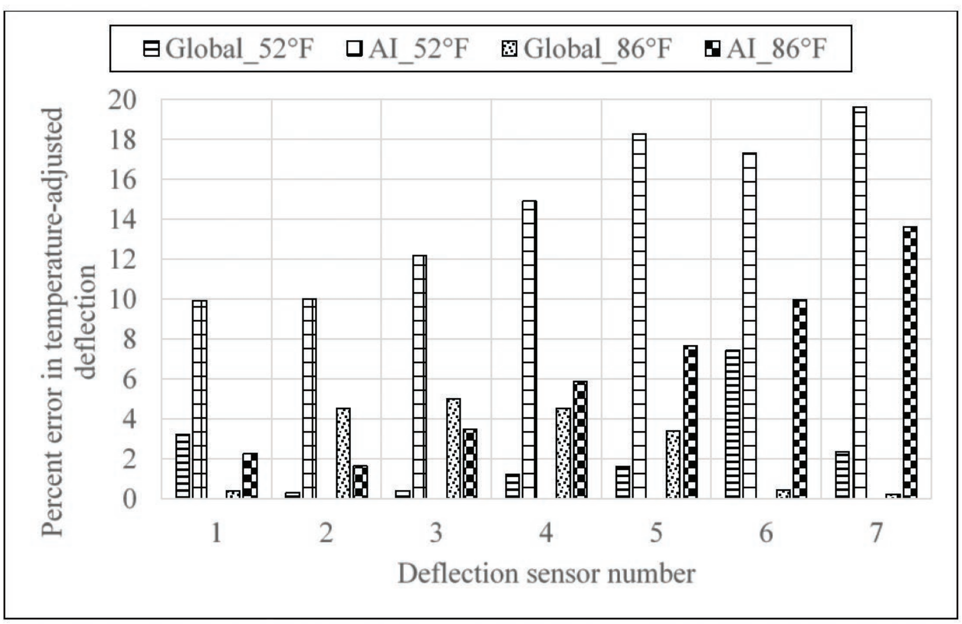
After adjusting the measured deflection data to 70 °F (21 °C), the adjusted data of one test section were then plotted against the pavement distress data that were measured at the same SMP test section. It was found that the measured and temperature-adjusted deflection did not correlate with the measured cracking data. In fact, the deflection data did not show any consistent pattern against time. Therefore, the data cannot be used to develop a deflection threshold value and cannot be included in the RSP algorithm. However, the deflection data can be used to estimate the moduli of the pavement layers and to design pavement treatments.

Figure 3. Peak measured pavement deflection at sensors 1, 2, 4, and 7 versus pavement surface temperature for LTPP test section 010101, F3.



°C = (5/9)(°F–32°).
1 mil = 25.4 micron.

Figure 4. Percent errors of the temperature-adjusted deflection data using the new procedure and the AI procedure.



°C = (5/9)(°F–32°).

Conclusions

Based on the results of the analyses, conclusions and recommendations were drawn that cover a range of study-related topics.

Pavement Performance Measures

The researchers drew the following conclusions related to pavement performance measures:

- The pavement cracking data are typically collected and stored based on low, medium, and high severity levels. Excessive variability from one year to the next creates a problem in analyzing per severity level, but analyses of the cracking data based on the sum of all severity levels has been proven to overcome the problem.
- For pavement projects that used the same treatment type, treatment transition matrices (T^2Ms) can be developed to display the distribution of the pavement conditions along the project BT and AT. The data in the T^2Ms can be and were used to estimate the benefits of the various treatments.
- Pavement condition rating should be based on current conditions and distresses as well as the pavement's rates of deterioration.
- The three- and five-level dual pavement condition rating systems developed in this study are useful and were equally applied to both State and LTPP data. The systems are flexible and can be easily tailored to fit the needs and constraints of any road agency.
- The estimated average cost of pavement preservation for each level of the dual pavement rating system can be used in the LCCAs and in strategy optimization.
- Threshold values were provided for calculation of the RFP and RSP. The values are based on minimum level of service to the user (functional) and loss of structural integrity (structural).

Flexible Pavements

Concerning flexible pavements, the researchers drew the following conclusions:

- Conditions in wet-freeze (WF) regions have significant adverse impacts on pavement performance in terms of IRI, rut depth, and cracking.
- Drainable bases decrease the impacts of the conditions in WF regions on pavement performance. The improvement in the pavement performance from use of drainable bases is slightly better than that from increasing the asphalt concrete (AC) layer thickness from 4 to 7 inches (102 to 178 mm). Therefore, the use of drainable bases in the WF region is cost effective.
- The inclusion of drainable bases in the dry freeze (DF) and dry-no-freeze (DNF) regions does not affect pavement performance in terms of RFP or RSP. This was expected because the volume and frequency of available water are low. Furthermore, most rainfall takes place over short periods of time where most water runs off the surface and does not penetrate the pavement layers.
- Increasing the thickness of the AC layer from 4 to 7 inches (102 to 178 mm) increases the frost protection of the lower layers and decreases the impact of the conditions in the WF region on pavement performance. However, this option is not cost effective.
- The conditions in the wet-no-freeze (WNF), DF, and DNF regions do not affect the

pavement performance relative to rutting potential and IRI.

- The conditions in the DF region have more adverse effects on cracking potential than those in the DNF region mainly because of higher oxidation (aging) potential of the AC layer in the DF region.
- The thin overlay treatment improves the pavement performance of the SPS-3 test sections in terms of IRI and rut depth in all climatic regions except the DNF region. This could be related to construction issues and, perhaps, to relatively high solar radiation (accelerated oxidation/aging) in the DNF region.
- In general, the thin overlay treatment does not improve the pavement performance of the SPS-3 test sections in terms of alligator, longitudinal, and transverse cracking. This is mainly because of the high rate of reflective cracking. Immediately after treatment, all cracks are hidden by the thin overlay. However, within a few years, most cracks are reflected through the overlay, which implies relatively high rate of deterioration and therefore short RSP. The exception is in the DNF region where the two test sections showed an increase of 12 years in the average RSP relative to the one control section. This oddity is mainly related to the limited number of test sections (i.e., the conclusion is not reliable because of the limited number of test sections and control sections).
- The slurry seal treatment improves the pavement performance of the SPS-3 test sections in terms of IRI and rut depth but does not have much impact on alligator, longitudinal, and transverse cracking.
- Crack sealing appears to improve the pavement performance of the SPS-3 test sections in terms of rutting. However, it did not improve the pavement performance relative to cracking.
- Aggregate seal coats appear to improve the pavement performance of the SPS-3 test sections in all climatic regions in terms of IRI, rut depth, and cracking.
- In general, the worse the pavement conditions are BT, the shorter the benefits of treatments in terms of the RFP and/or RSP values.
- On average, the impact of 2- and 4-inch (50.8- and 101.6-mm) virgin or recycled AC overlays on pavement performance of the SPS-5 test sections is almost the same.
- The 2-inch (50.8-mm)-thick AC overlay (virgin or recycled mix) does not provide a long-term remediation of transverse cracking. The cracks in the lower pavement structure typically reflect through the overlay in a few years.
- On average, the change in the structural period of a flexible pavement structure as a result of 2-inch (50.8-mm) AC overlay in terms of alligator cracking is slightly less than the 4-inch (101.6-mm) overlay.
- In each climatic region, the impacts of the thin and thick overlay or thin and thick mill-and-fill treatments on IRI and rut depths are almost the same. This was expected because good quality construction can decrease the pavement surface roughness substantially and remove ruts regardless of the overlay thickness.

ORCSE Method

The researchers concluded the following:

- The ORCSE method was successful in predicting the CSs of the test sections based on RFP and RSP. For older test sections, the average estimation error for the most critical CSs is less than 1 percent.

- The ORCSE method provides significant potential benefits to local roadway owners as well as to State transportation department managers when only two or fewer data points are available.

Rigid and Composite Pavements

Concerning rigid and composite pavements, the researchers concluded the following:

- On average, the majority of the SPS-2 test sections located in the WNF region performed worse in terms of longitudinal cracking than those in the DNF region. This is mainly owing to the impact of excessive moisture on pavement performance.
- The conditions in the WF region have a more damaging impact on the performance of the SPS-4 test sections in terms of transverse cracking than test sections located in the WNF, DF, and DNF regions. This was expected owing to the combined effects of subfreezing temperatures and moisture.
- On average, in terms of IRI, joint and crack sealing treatment has positive impact on the performance of the SPS-4 test sections located in the WNF region, no impact in the WF region, and negative impact in the DF and DNF regions.
- Joint and crack sealing is effective in the WF region and not effective in the other three climatic regions. Joint undersealing is not effective in any region.
- The performance of treated SPS-6 test sections in terms of IRI is independent of the climatic region and pavement type. It is also independent of treatment type in terms of rut depth.
- It is highly likely that the alligator cracking data in the SPS-6 database represent an advanced form of top-down fatigue cracking: (i.e., the top-down cracks are fatigue cracks that initiate at the pavement surface and propagate downward over time). The short transverse and longitudinal cracks resemble the traditional bottom-up alligator cracking pattern.
- The performance of the test sections in terms of longitudinal cracking was worse after subjecting the section to any of the seven analyzed treatment types.
- Minimum and maximum pavement restoration with no AC overlay treatments do not improve the performance of the jointed reinforced concrete pavement test sections.
- The IRI-based performance of the treated continuously reinforced concrete pavements (CRCP) (SPS-7) test sections is independent of the eight treatment types and their presence in the WF and WNF climatic regions.
- The performance of the jointed plane concrete pavement (JPCP) test sections subjected to 3-inch (76.2-mm) concrete overlay with milling (703) or with shot blasting (704) treatments is lower than the performance of the other JPCP test sections subjected to the other six treatments. None

of the eight applied treatments are effective in treating transverse cracking problems of the CRCP test sections.

Deflection

In the area of deflection, the researchers drew the following conclusions:

- The LTPP deflection data collected for the SMP test sections do not support the use of the AI temperature adjustment procedure of the measured deflection data.
- The newly developed global flexible pavement deflection temperature adjustment algorithm is applicable to all deflection sensors and all climatic regions.
- The LTPP deflection data collected for the SMP test sections do not correlate to the measured pavement condition and distress data. Therefore, the data do not support their inclusion in the RFP and RSP algorithms.
- The LTPP deflection and load transfer efficiency data collected for the SPS-2 test sections within Arizona, Colorado, Delaware, and Michigan do not support the modeling of the data as a function of time.

State Data

The State data indicate the following:

- The weighted average benefits of each of five treatment types (thin overlay (≤ 2.5 inch (63.5 mm)), thick overlay (> 2.5 inch (63.5 mm)), thin mill and fill (≤ 2.5 inch (63.5 mm)), thick mill and fill (> 2.5 inch (63.5 mm)), and single chip seal) relative to each pavement condition and distress type obtained from the analyses of the LTPP data are similar to the benefits obtained from the three State transportation departments' data.
- The treatment benefits provided in this report using the LTPP data can be used as benchmark values for the national practice. This data may be used by State transportation departments to do the following:
    - Gauge the effectiveness of their current practices using similar analyses.
    - Conduct LCCA of various treatment alternatives to optimize the pavement rehabilitation and treatment strategy at the network level.
- The methodologies described in this report for the analyses of the LTPP pavement condition and distress data also apply to the State data.
- The three- (poor, fair, and good) and five-level (very poor, poor, fair, good, and very good) pavement rating systems developed in this study, based on the time series pavement condition and distress, are equally applicable to the LTPP and the State data.
- The average variability in the pavement condition and distress data of the LTPP test sections is almost the same as the average variability of the State measured data.
- The percent of the LTPP test sections that were excluded from the analyses because of inadequate numbers of data points or improving pavement condition and/or

distress over time without the application of treatments is similar to the percent of the 0.1-mi (0.16-km)-long pavement segments of a given pavement project that was excluded from the analyses for the same reasons.

Recommendations

Performance Measures

Based on the results of the LTPP and State data analyses and the conclusions listed above, the following actions are strongly recommended:

- Use the sum of crack lengths or crack areas of all severity levels to model the pavement condition and distress data as a function of time.
- Base accurate pavement planning and management decisions on the pavement conditions and rates of deterioration.
- Have FHWA adopt the three- and/or five-level rating systems and have them submitted to AASHTO for approval.
- Adopt either the threshold values used in this study to estimate the RFP and RSP of the various pavement sections or similar ones developed by the road agencies.
- Have each road agency develop the average cost of pavement preservation for each RFP and RSP range of the dual pavement rating systems using their own cost record.
- Perform LCCA at the project level and strategy optimization at the network level to improve the overall cost effectiveness of the pavement management application.
- Have highway agencies adopt and use the T^2M procedure to assess treatment effectiveness and to select the optimum treatment time.
- Use the dual pavement rating systems in future analyses and assessment of the benefits of pavement rehabilitation and/or maintenance treatments.

Flexible Pavements

Concerning flexible pavements, the following actions are strongly recommended:

- Drainable bases should be constructed to enhance the performance of pavement sections located in the WF region.
- For future studies, the control or linked test sections should be selected to border the regular test sections in question, and their history should be included in the database. This would eliminate unnecessary variability.
- The pavement condition and distress data should be measured BT and AT. The quality control data for project acceptance should be included in the pavement management system database.
- The frequency of pavement condition and distress data collection should be considered a function of treatment type. Treatments having short treatment life should be surveyed more often than long-life treatments.

ORCSE Method

The researchers recommend that the ORCSE method be expanded to other pavement conditions and distresses and applied to a wider range of LTPP and State transportation department data to further verify its successful prediction of pavement CSs.

Deflection

In the area of deflection, the researchers recommend the following:

- The new global flexible pavement deflection temperature adjustment algorithm should be adopted and used to adjust the measured pavement deflection to a standard temperature.
- The estimation of the AC modulus at the standard temperature of 70 °F (21 °C) could be accomplished using one of the following two procedures:
    - Adjust the measured deflection data to 70 °F (21 °C) using the newly developed global model and then backcalculate the modulus.
    - Conduct a minimum of three FWD tests and measure the pavement deflection at three temperatures. Backcalculate the AC modulus value for each of the three FWD tests. Plot the modulus as a function of the measured pavement temperature and estimate the AC modulus at 70 °F (21 °C) from the graph.
- For new LTPP experiments or road tests, FWD tests should be conducted BT and AT.

State Data

Concerning the State data, the following are recommended:

- FHWA, AASHTO, and the State transportation departments should adopt the dual pavement condition rating systems to unify the analyses of pavement performance nationwide.
- The benchmark benefit values of the five treatment types included in this study should be expanded to include additional pavement treatments.

Future Studies

Future studies should address the following recommendations:

- Initiate studies to produce a national catalog of the service life of various treatment types as a function of pretreatment pavement conditions and distress. The studies should be based mainly on the LTPP data and applied to some State data.
- Initiate studies to establish automated data collection processes, quality control procedures, and data storage to minimize the impact of subjective factors and human error on pavement conditions and distress.
- Initiate studies to scrutinize the newly developed self-powered wireless Pico sensors (3.9^{-13} inches (9.9^{-12} mm)) that can be embedded in pavement and transportation infrastructures to measure their performance in terms of cracking and induced stresses and strains.
- Eliminate the need for traditional data collection by exploring the accuracy of the newly developed chemical sensors that can be included in concrete and asphalt mixes to measure future pavement conditions and distresses.
- Develop short course materials that include examples to train engineers and staff of various State transportation departments to use the MATLAB® computer program for the analyses of pavement condition and distress and to emphasize the benefits of the LTPP Program.

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