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TPF-5(291) FINAL REPORT:

IMPACT OF CHANGES IN CLIMATE, TRAFFIC, DISTRESS, AND MAINTENANCE ON DETERIORATION RATE

Prepared On Behalf Of	Date	Project Number
State Pooled Fund Study TPF-5(291)	October 2021	56A0418-008 (TPF-5(291)) 219.03.10 (NCE)

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1.0 BACKGROUND

The NCE team was awarded the Transportation Pooled Fund (TPF) Study 5(291) to investigate data from the Long-Term Pavement Performance (LTPP) Specific Pavement Study (SPS)-2 experiment for concrete pavement design factors, with the Washington State Department of Transportation as the Lead State. This pooled fund study included the investigation and proposal of a pavement preservation experiment utilizing existing test site conditions. Upon completion of the initial phase of the study, several SPS-2 Tech Days were conducted to broaden the pavement community's knowledge of the SPS-2 experiment and to garner input on analyses the community would find useful. The Pooled Fund Technical Advisory Committee (TAC) also provided recommendations for additional analyses.

As a result, five additional tasks were focused on SPS-2 test sections:

- Conducting a deterioration rate analysis
- Analyzing performance data
- Investigating sources of non-LTPP data
- Analyzing joint score and area of localized roughness (ALR) impacts on performance
- Updating previous SPS-2 analyses

Upon completion of these tasks, an additional 11 tasks were proposed. The purpose of this supplementary extension of TPF-5(291) was to conduct further analyses of existing data from the LTPP SPS-2 concrete pavement experiment. The focus of this set of tasks was to investigate the impact of non-experimental factors on pavement performance. The following tasks were completed:

- Identifying agency-specific trends
- Analyzing the impact of construction and materials issues
- Reviewing early SPS-2 failures
- Identifying lessons learned from state supplemental sections
- Analyzing the impacts of climate, traffic, and overall condition on deterioration rate
- Comparing SPS-8 and SPS-2 performance
- Assessing diurnal changes in roughness
- Evaluating service life
- Comparing mix-design performance
- Conducting Mechanistic Empirical Pavement Design Guide (MEPDG) sensitivity analysis of portland cement concrete/lean concrete base (PCC/LCB) bond
- Evaluating transverse joint opening width

This report presents the results of an assessment of the impact of project-specific factors on project-wide performance.

2.0 OVERVIEW

The SPS-2 experiment was designed to be a study on the impact of different levels of design factors on rigid pavements. Fourteen SPS-2 projects were constructed in different states consisting of 12 core test sections and a varying number of supplemental sections. The 12 core test sections were a half-factorial of the combination of four distinct design factors:

- Pavement thickness
  - 8-inch thin pavement
  - 11-inch thick pavement
- Base type
  - Dense graded aggregate base (DGAB)
  - Lean concrete base (LCB)
  - Permeable asphalt treated base (PATB)
- PCC design strength
  - 550 pounds per square inch (psi) – low-strength
  - 900 psi – high-strength
- Lane width
  - 12-foot standard-width lanes
  - 14-foot widened-width lanes

Additionally, there was a design factor for drainage, where DGAB and LCB pavements were undrained and PATB pavements were drained.

Other design factors could only be considered on a project-specific basis. While the SPS-2 experiment nominated projects to capture wide distribution of climatic regions, subgrade soil types (fine vs. coarse) and traffic loading, there were no defined levels for these parameters. There was an effort to nominate projects so that an adequate amount could represent each climate region: dry-freeze, dry-non-freeze, wet-freeze, and wet-non-freeze. However, for traffic, only a minimum load level of 200 KESALs (thousand equivalent single axle loads) per year was stipulated. Agency construction and maintenance practices could also be considered project-specific factors.

The following analyses were completed to assess the impact of project-specific factors on project-wide performance:

- Impact of Climate on Pavement Performance
- Impact of Traffic on Pavement Performance
- Impact of Distress on Roughness
- Impact of Maintenance on Roughness

Because of the variability and the compounding nature of design factors, the analysis would not be possible to accurately quantify the impact that project-specific design factors have on performance. Instead, these analyses made relative comparisons of trends between projects. However, aggregating project-wide performance certainly increases the risk of bias from specific test sections that could be consider outliers because of material and construction issues. Michigan, Nevada, and Ohio are typically considered outliers among the SPS-2 projects, because they had several test sections deteriorate quickly, primarily due to material and construction issues.

3.0 IMPACT OF TRAFFIC ON PAVEMENT PERFORMANCE

While the core SPS-2 test sections had common designs, they were subject to different levels of traffic loading (with a minimum of 200 KESALs). Figure 1 shows the difference in traffic loading between states, in terms of measured and estimated truck count, and measured and estimated equivalent single-axle loads (ESALs). Measured truck counts are collected using equipment installed on-site. Measured ESALs are typically calculated from measured truck counts and information about the pavement structure. Estimated truck counts and ESALs are approximations provided by the agency based on different methods of calculation including nearby installations and trend analysis.

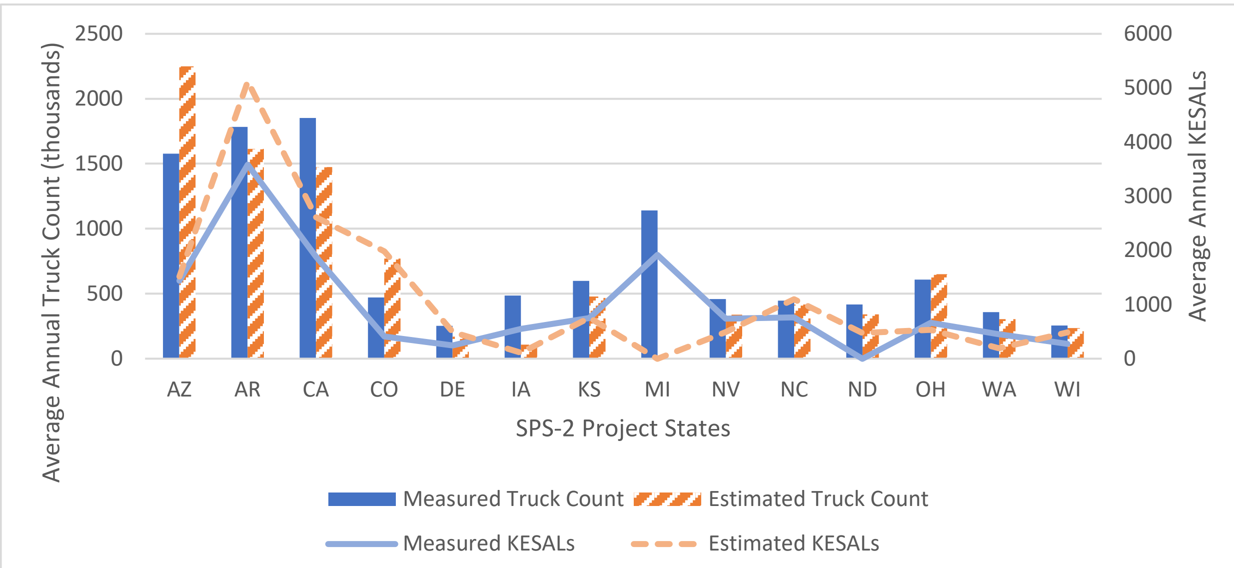

Figure 1. Average Annual Truck Volume by SPS-2 Project.

Traffic loading expressed in terms of ESALs measures damage to a particular pavement structure from ESALs, while truck volume indicates the count of trucks passing over the road. Because thinner pavements would deteriorate faster under the same truck volume than thicker pavements, the ESALs experience by the thinner pavement would be higher than the thicker pavement.

Arkansas had the highest average annual measured KESALs among the SPS-2 projects, followed by Michigan and California. However, California, Arkansas, and Arizona had the highest truck volumes, followed by Michigan. Delaware and Wisconsin had the lowest amount of traffic both in terms of annual KESALs (250 and 280 KESALs per year, respectively) and annual volume.

Traffic loading by project did not necessarily correlate with the overall performance of test sections within the project. Thinner pavements in Arizona, Arkansas, and California deteriorated faster in terms of transverse cracking than similar test sections in other states (excluding outliers such as Michigan, Nevada, and Ohio). However, there were other unique factors at these sites that may have impacted pavement performance, including climate, materials, and construction.

3.1 Analyzing Trends in Traffic Data

Figure 1 also demonstrates the significant inconsistencies between estimated and monitored truck volumes in states such as Arizona, California, Colorado, and Michigan. However, to perform an analysis on truck volumes, these inconsistencies needed to be rectified based on their year-to-year trend. The available LTPP traffic data were reviewed to establish trends in annual truck volumes. Issues and irregularities in annual truck volumes were identified and explained. In some cases, traffic data were unrealistic (possibly erroneous) and were disregarded from the trend analysis. Truck growth rates (an input parameter for MEPDG design) was used instead of cumulative ESALs in this analysis to determine the impact of traffic volume growth on roughness deterioration. Therefore, it was necessary to determine the rate of traffic growth with respect to observable trends in annual truck volumes for each state.

3.1.1 ARIZONA

Arizona has monitored traffic data from 1994 to 1996 and from 2007 to 2020, but there was a gap from 1997 to 2006 (only estimated traffic data were available). However, the estimated data from 1998 to 2006 did not seem to be realistic since it was three times more than the expected count for trucks. Since this sudden growth could not be explained, it was ignored. Because no truck volumes were available during this gap, the impact of traffic on roughness could not be analyzed for the period of 1996 to 2007. The measured truck volumes were mostly linear; there was a slight increase in volumes in 2007 attributed specifically to Class 9 trucks.

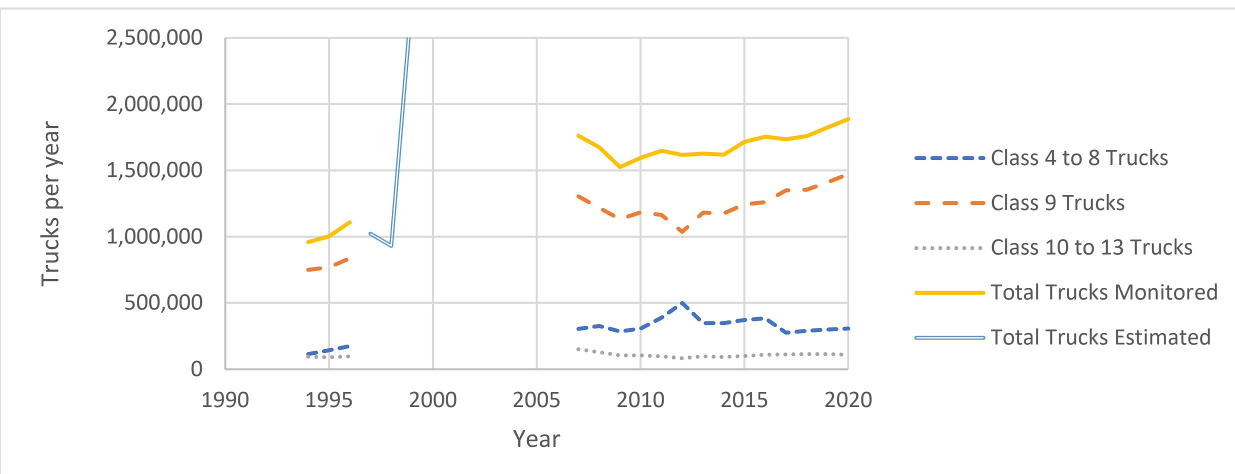

Figure 2. Arizona Truck Counts

3.1.2 ARKANSAS

Arkansas' monitored and estimated traffic data show a linear trend throughout the monitoring period. There were slight dips in Class 9 truck volumes in 1996, 1997 and 2004. However, the simultaneous increase in other trucks suggests there was a shift in the vehicle classification schema. Additionally, there were spikes in total truck volumes in 1998, 2007, and 2017.

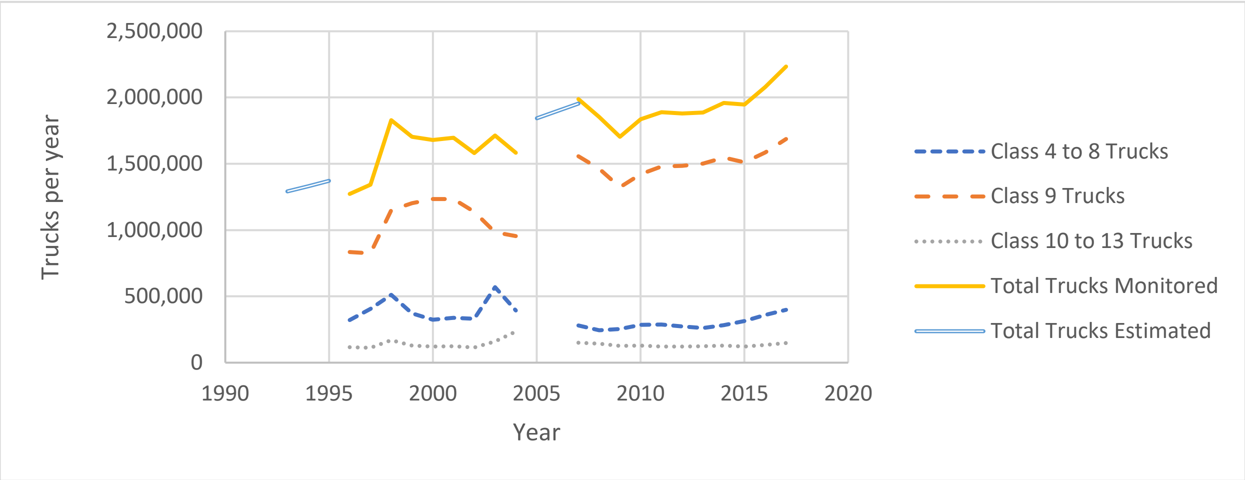

Figure 3. Arkansas Truck Counts

3.1.3 CALIFORNIA

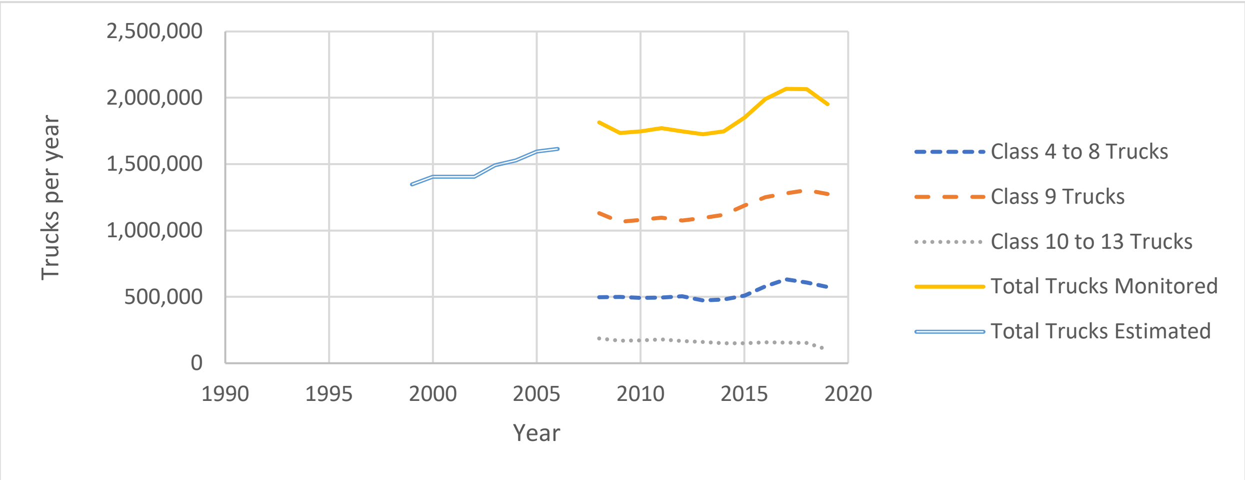

Figure 4. California Truck Counts

3.1.4 COLORADO

The truck volumes for Colorado were overestimated compared to the monitored truck volumes. Truck volumes showed a steady growth, with small spikes in annual volumes in the years 1995 and 2007. However, Class 9 truck volumes were steady from 2006 to 2020.

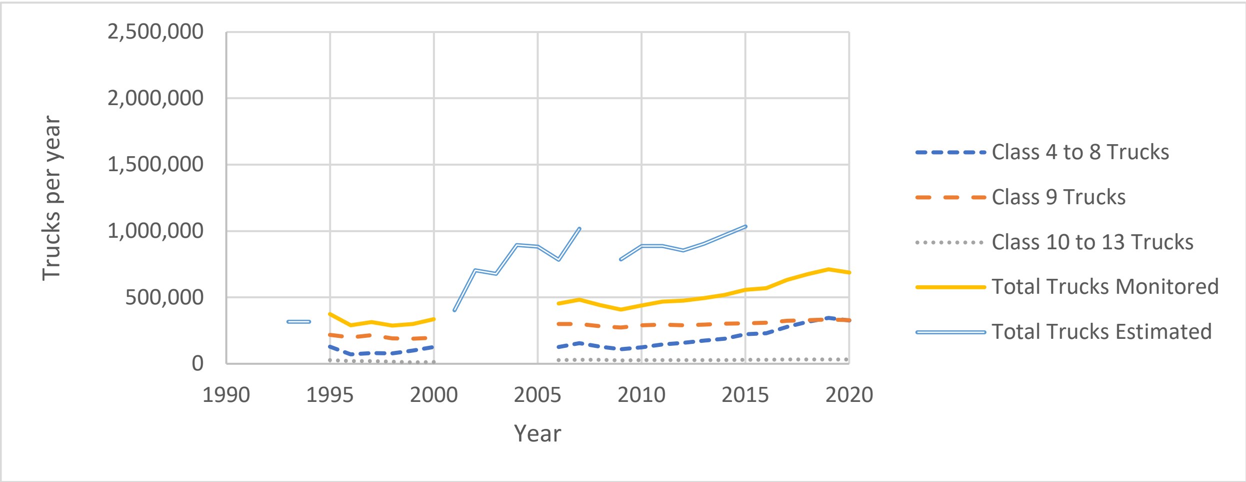

Figure 5. Colorado Truck Counts

3.1.5 DELAWARE

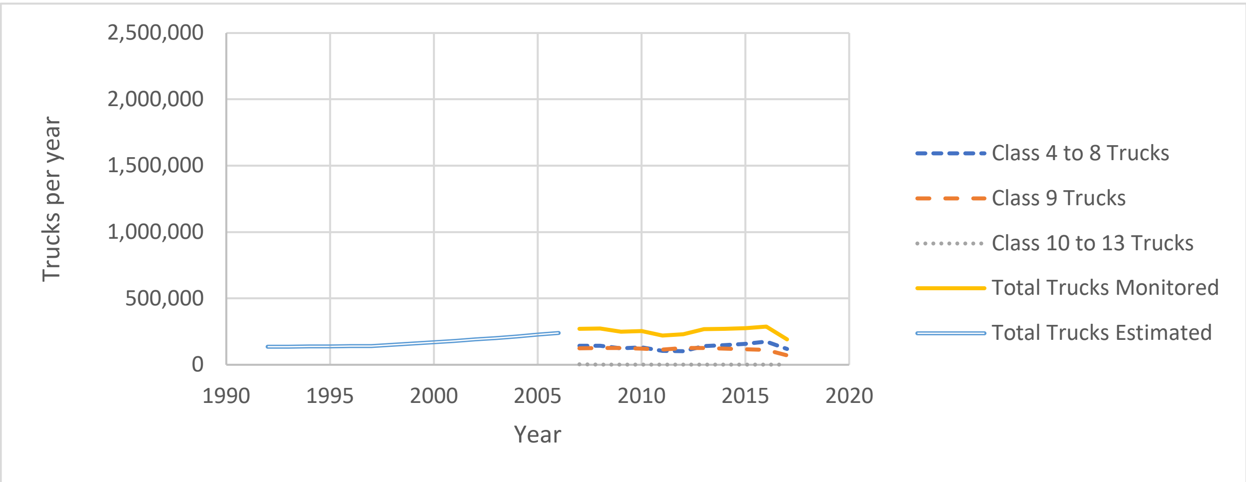

Figure 6. Delaware Truck Counts

3.1.6 IOWA

Iowa truck volumes had a significant increase after 1997. Thereafter, truck volumes steadily increased, although the growth rate of Class 9 trucks reduced after 2008.

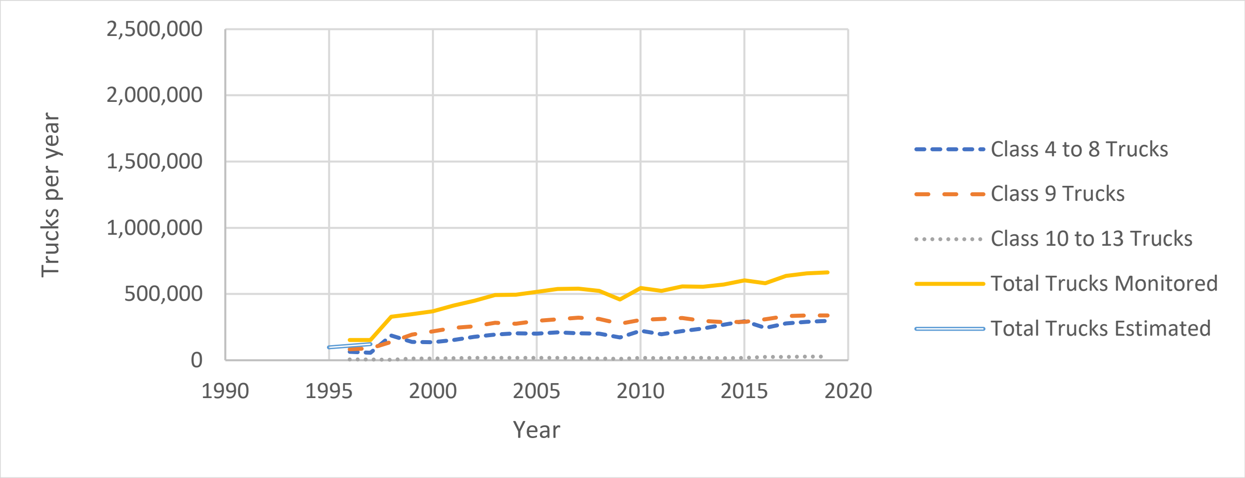

Figure 7. Iowa Truck Counts

3.1.7 KANSAS

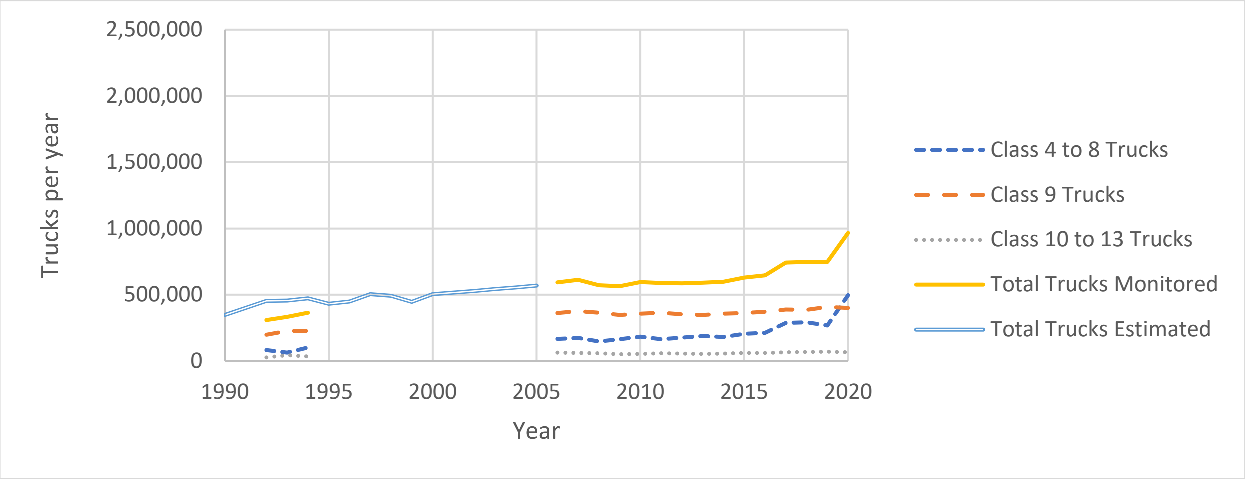

Figure 8. Kansas Truck Counts

3.1.8 MICHIGAN

Monitored truck volumes in Michigan showed a significant increase in Class 9 truck volumes from 1993 to 1998. Class 9 truck volumes remained steady from 1997 to 2007. Truck volumes declined in 2008, but then steadily grew from 2009 to 2017. There was traffic data issue in 2003 where some Class 9 trucks were likely misclassified as Class 8 trucks. This misclassification error may have caused total truck volumes to decrease slightly in 2003. Since there were no gaps in the monitored truck counts, there was no need for estimated truck counts.

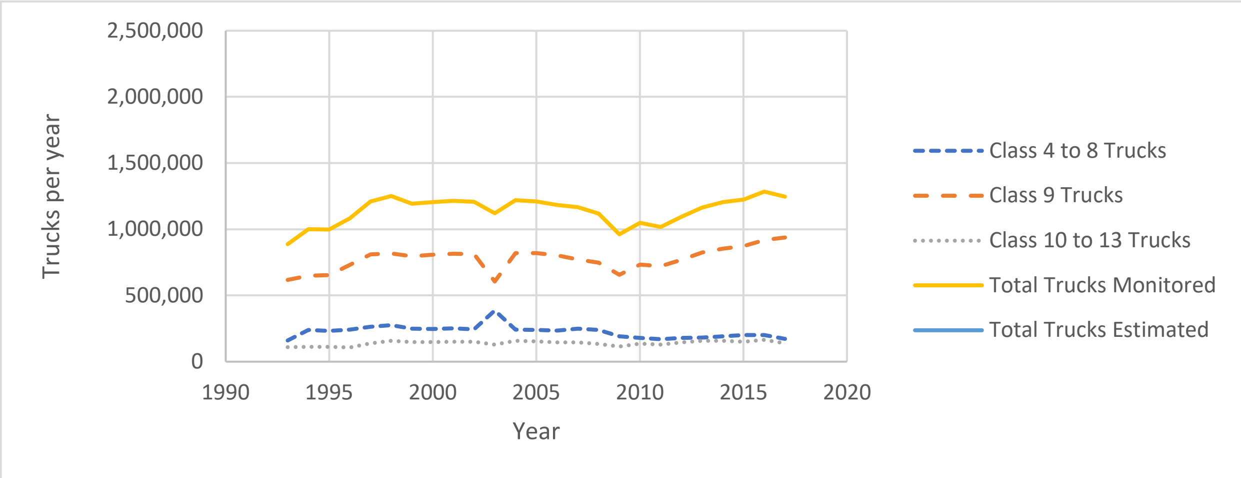

Figure 9. Michigan Truck Counts

3.1.9 NEVADA

Figure 10 inconsequential to the analysis of test section performance – depending on the time period each section was in study. Since there were no gaps in the monitored truck counts, there was no need for estimated truck counts.

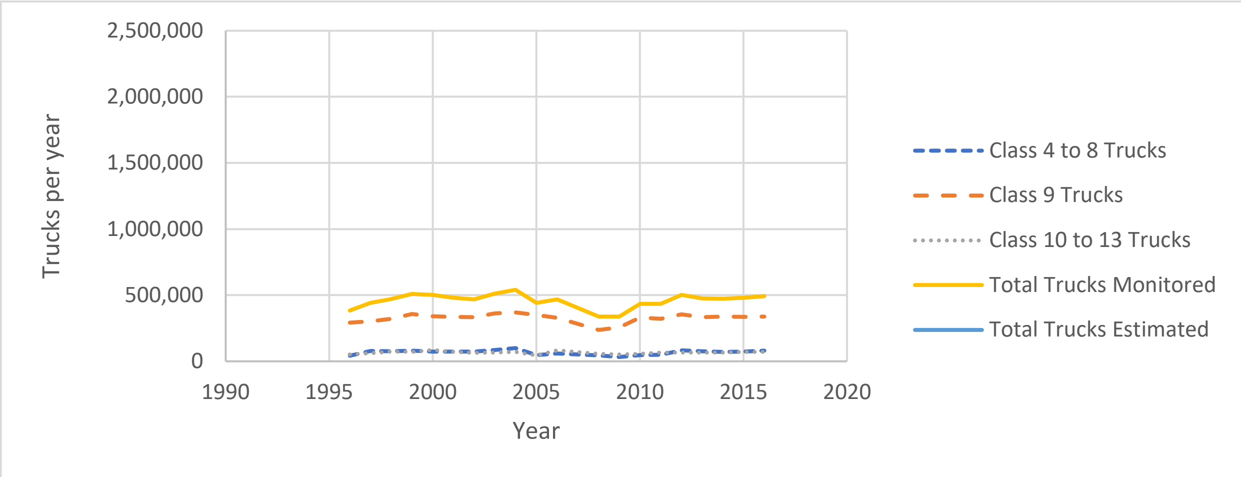

Figure 10. Nevada Truck Counts

3.1.10 NORTH CAROLINA

North Carolina Class 9 truck volumes steadily increased from 1993 to 2006. Truck volumes decreased from 2006 to 2012. If the estimated truck counts can be relied on, truck volumes began to increase again from 2012 to 2018.

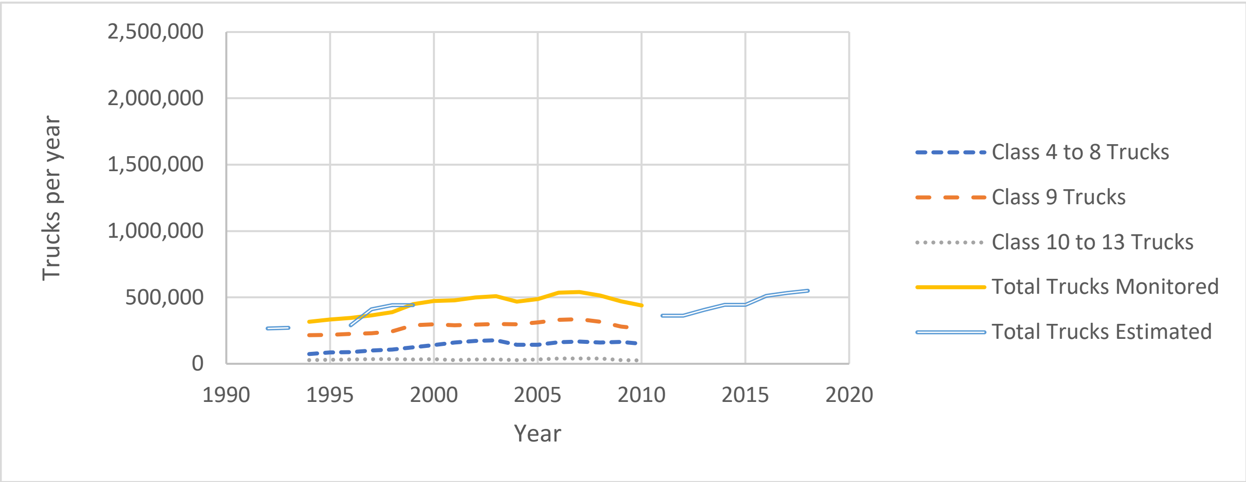

Figure 11. North Carolina Truck Counts

3.1.11 NORTH DAKOTA

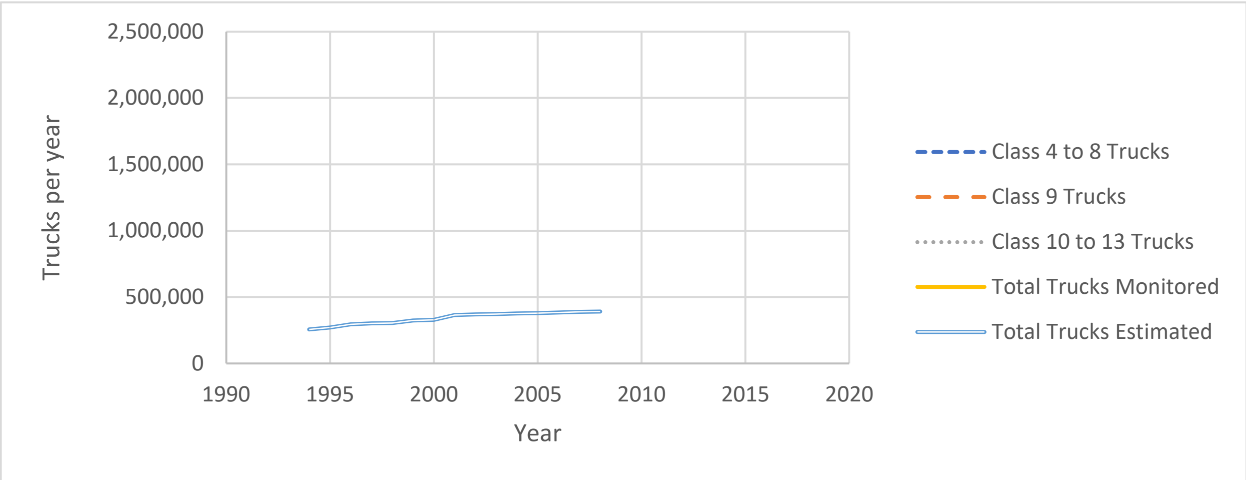

Figure 12. North Dakota Truck Counts

3.1.12 OHIO

Class 9 truck volumes for Ohio exhibited very little growth. There were some unusual dips in truck volumes in 1997 and 2001, but other Class 9 truck volumes remained in the range of 400,000 to 500,000 per year. There was another dip in Class 9 truck volumes in the years 2013 to 2016, but there was also a proportional increase in the volumes of trucks of other classes, which suggested a possible misclassification of vehicles by the traffic monitoring equipment.

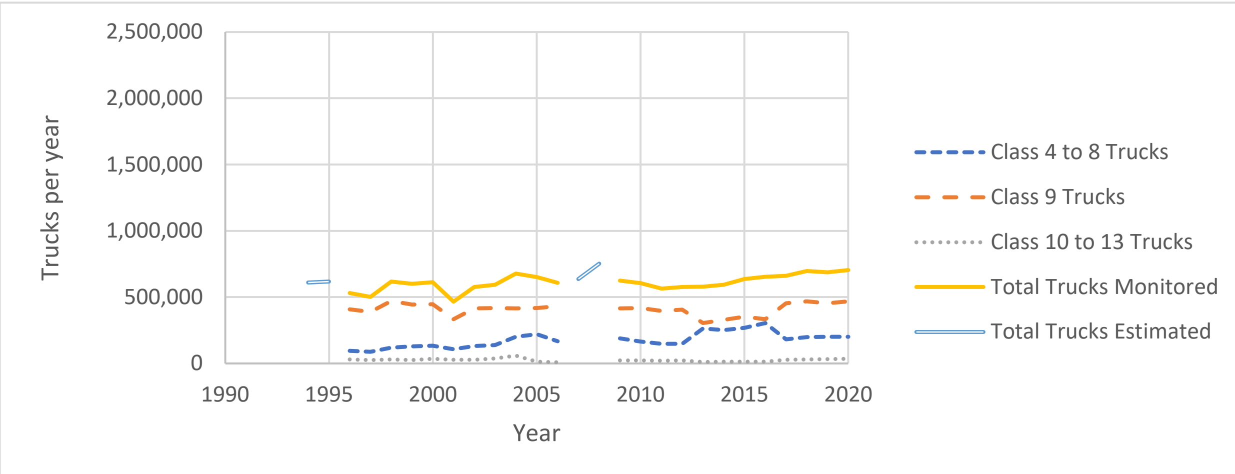

Figure 13. Ohio Truck Counts

3.1.13 WASHINGTON

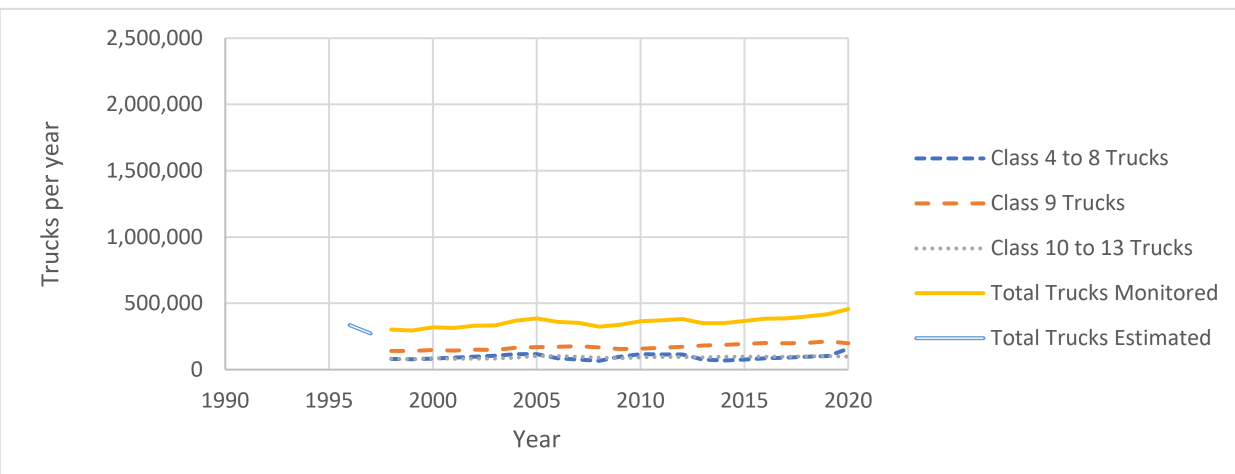

Figure 14. Washington Truck Counts

3.1.14 WISCONSIN

Wisconsin measured-truck volumes in 2001 were very low and not representative of the actual traffic. The estimated truck volumes indicated that truck volumes continued to grow from 2000 to 2007. From 2008 to 2015, truck volumes remained constant until 2016.

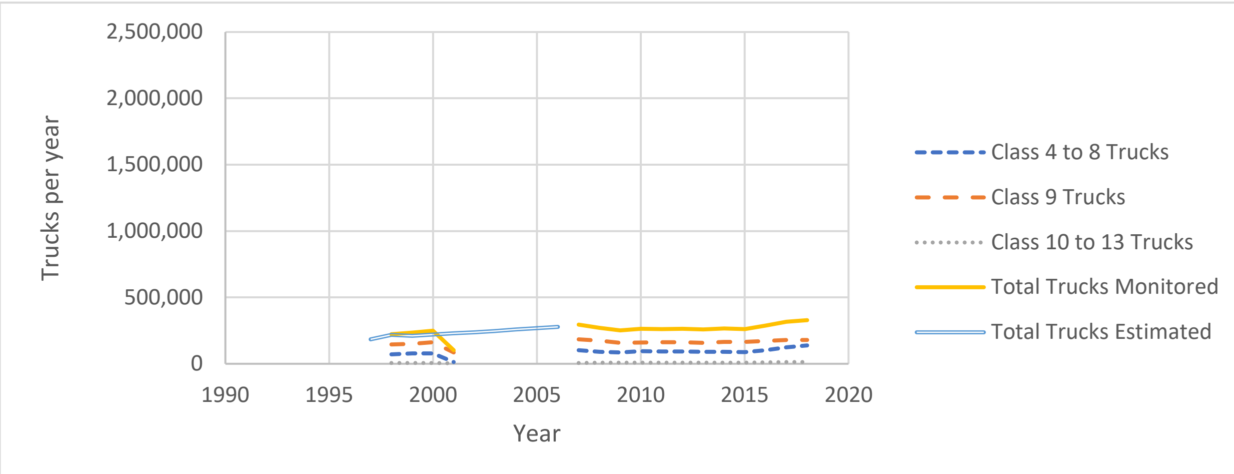

Figure 15. Wisconsin Truck Counts

Several states had notable common trends in annual truck volume growth. While truck volumes generally increased over time, often the highest volume growth was observed in the first 5 years of the SPS-2 study (from 1993 to 1998) – just prior to the dotcom bubble of 2000 – after which truck volumes resumed growth but at a slower growth rate. There were also noticeable dips in truck volumes during the period of 2008 to 2009, reflecting the impact of the 2008 economic recession.

Interpolation was used to develop an estimate for years where neither monitored traffic data nor an agency estimate were available. Figure 16 shows an example of how truck volumes were estimated to fill in the gaps of the dataset at the Arizona SPS-2 site. While the interpolated estimate shows a smooth transition between the volumes in 1998 and 2007, the change in annual truck traffic may have been more abrupt. The interpolated estimate was used to calculate the annual truck volumes in Figure 17 for comparison to MRI. The MRI was calculated as the average IRI of the left and right wheel path throughout the section.

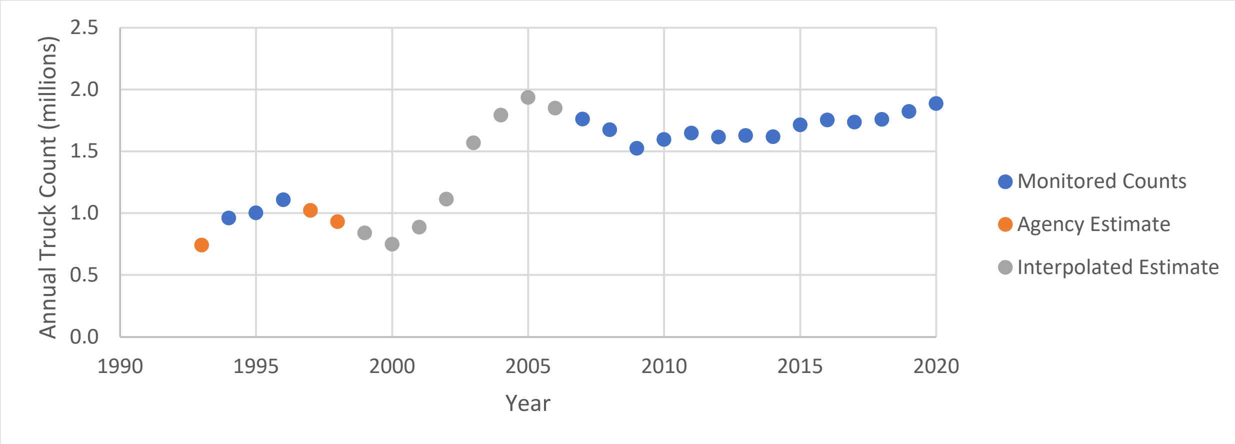

Figure 16. Arizona SPS-2 Annual Truck Volumes with interpolated estimates.

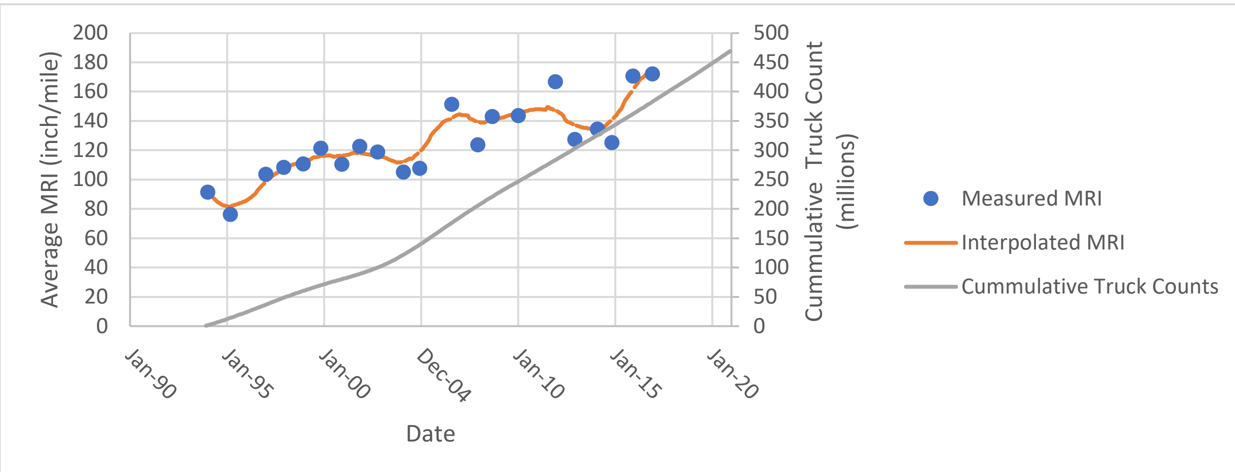

Figure 17. Arizona 040213 Annual Truck Volumes with Measured and Interpolated MRI.

Figure 18 shows the same information as Figure 17, but with cumulative truck volumes. This figure shows a notable inflection in the accumulation rate of truck traffic in 2003. Following this inflection, there was a slight increase in MRI in the following year – assuming that this increase was not random. The effect of traffic should affect all test sections on a project in the same way, but this sudden increase in MRI was not evident in other Arizona test sections. Considering that the inflection in the traffic data were based on an interpolation of the trend in truck volumes, it may be invalid to use it for correlation purposes.

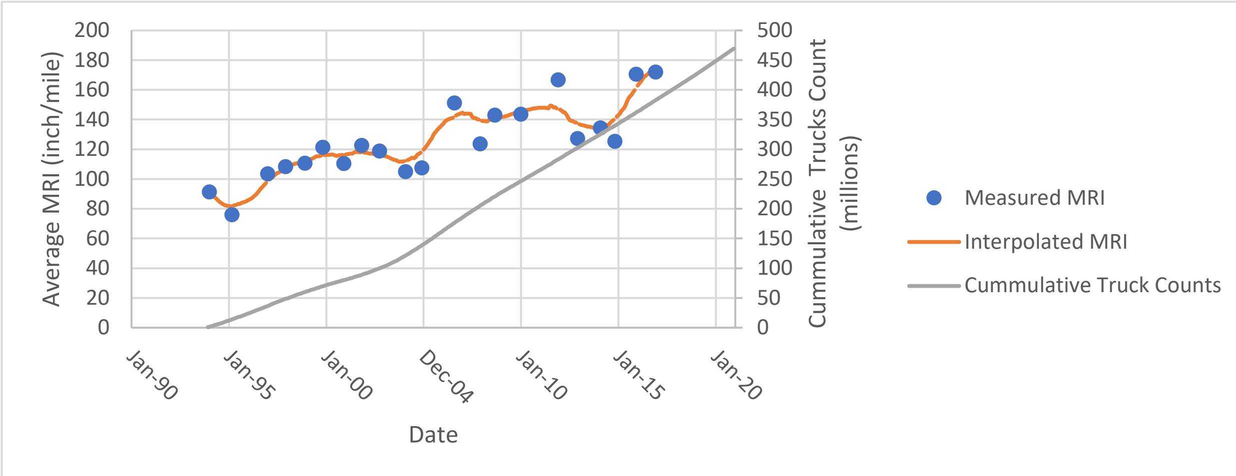

Figure 18. Arizona 040213 Cumulative Truck Volumes with Measured and Interpolated MRI.

To determine the impact of truck traffic loading on roughness in SPS-2 sections, sudden (outside of the trend) increases in MRI were identified and compared to truck traffic during the period of the sudden increase and prior to the sudden increase. Specifically, the comparison focuses on the change in traffic volume growth (expressly how truck volumes would accumulate over time). Profile measurements on LTPP sites were periodic but measured at irregular intervals; profile measurements were often taken every year but could sometimes be more than 3 years apart. It was expected that pavement roughness should increase with accumulated traffic. However, profile measurements were taken in different seasons or different times of the day. Thus, measurements could have been influenced by diurnal and seasonal variations from pavement curl and warp.

To mitigate some of this variability, this analysis used linear regression to interpolate MRI at 1-month intervals between profile measurements and then repeatedly applied a 6-month moving average to the interpolated MRI to smooth out the roughness curve. The resulting smoothened roughness curve possibly normalized some of the seasonal and diurnal variability inherent to the measured profile measurements.

However, it is arguable how effective the smoothened roughness curve (calculated using the method described above) would be in reducing seasonal and diurnal variability. Because of the irregularity of intervals between profile measurements, the smoothened curve would still hold some bias toward the seasonal and diurnal condition of profile measurements that were used for the initial interpolation. An increase in the deterioration rate of the smoothened roughness curve may be an indication of the relative change in the MRI deterioration rate at a specific point in time, or it could be completely artificial.

Profile equipment changes were another potential source of variability. The K.J. Law DNC690 profile equipment changed to the K.J. Law T-6600 in 1996. It then changed to the ICC inertial profiler in 2002 and, most recently, the Ames inertial profiler in 2013. With every change, LTPP performed a study to determine that the differences between new and old equipment were not too substantial.[1]

Appendix A lists the 2-year period where the rate of MRI increase (in the smoothened roughness curve) at each section was at its highest. The last 2 years of the smoothened roughness curve were ignored as the moving average was significantly influenced by the final profile measurements and their accompanying variability, whereas the body of the smoothened roughness curve would be constrained by previous and subsequent MRI measurements. Appendix B shows the MRI deterioration rate based on the smoothened curve, along with the actual MRI measurements, maintenance events, annual truck volumes, and distress indices for each test section. Based on these graphs, the MRI deterioration rate should be much more linear than suggested by the smoothening approach used in this analysis.

Comparing traffic volume growth to MRI deterioration rates by state yielded mixed results. There were often some cases where a change in traffic volume growth seemed to correspond to a change in MRI deterioration rate. However, there were also several cases where traffic volume growth and MRI deterioration rate did not seem to be related. This was especially true in test sections without significant MRI deterioration or MRI deterioration that was very close to linear. The concept of 'peak MRI deterioration' assumes that MRI deterioration is not linear or does not behave like a steady curve. However, many test sections could be interpreted to have a linear trend with variability coming from seasonal and diurnal curl and warp, or changes in the rater or equipment. The state-specific discussions following Table 1 provide additional context to the peak MRI deterioration information presented in the table.

Table 1 summarizes the information in Appendix A by state. The table shows, on average, the peak MRI deterioration rate and time of that peak for each test section. It also shows the relative change in traffic volume growth during and prior to the period of peak MRI increase. For some projects, pavement design factors affected test sections uniquely and caused peak MRI deterioration to occur at different times. Therefore, the year(s) in which peak MRI deterioration occurred typically varied by test section. Note that the 'Range of Peak MRI Deterioration' in Table 1 shows the range of years when project test sections achieved peak MRI deterioration. As explained previously, this peak is based on artificial data points. The extent of this range often varied from 5 to 10 years depending on the state. Arizona, Delaware, and Wisconsin were the only states where all the test sections showed a large increase in MRI deterioration at roughly the same time.

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[1] Simpson, A. L., and G. E. Elkins. 2013. *LTPP Profiler Comparison – 2013*. Federal Highway Administration.

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Table 1. Summary of Peak MRI Deterioration Rate and Concurrent Change in Traffic Volume Growth

State	Range of Peak MRI Deterioration	Project Averages			
		Peak MRI Deterioration Rate (inch/mile/year)	TVG[1] during Peak MRI Growth (trucks/year)	TVG[1] prior to Peak MRI Growth (trucks/year)	Percent Change in Traffic Growth (%)
Arizona	2004	19.797	183860	182150	-1%
Arkansas	2005-2011	21.515	93101	-19693	-121%
California	2004-2015	12.697	58691	4044	-93%
Colorado	2000-2010	5.902	19783	16009	-19%
Delaware	1998	22.596	8760	1460	-83%
Iowa	2009-2015	12.817	14126	10635	-25%
Kansas	1996-2004	12.127	13266	25266	90%
Michigan	1997-2006	61.103	40337	71905	78%
Nevada	1997-2002	23.47	40598	75689	86%
North Carolina	2003-2015	46.348	12219	18803	54%
North Dakota	2003-2015	11.639	24277	25209	4%
Ohio	1998-2014	16.532	21888	-17430	-180%
Washington	1998-2013	9.253	-1609	-1796	12%
Wisconsin	2001-2002	9.232	11567	16190	40%

[1] TVG—Traffic volume growth shown in this table is not expressed as a percent increase from the previous year but as a linear increase in truck count from the previous year (a negative value indicates a decrease in counts).

3.3.1 ARIZONA

In Arizona, all test sections showed an increase in smoothened roughness in 2004. However, this increase can be explained by the analysis approach, which artificially produced nonlinear MRI values. All test sections with high-strength PCC had peak MRI deterioration rates less than 12 inch/mile/year and all test sections with low-strength PCC had peak MRI deterioration rates higher than 15 inch/mile/year. All other design factors (i.e., PCC thickness, base type, lane width, drainage) had no impact on the peak rate of MRI deterioration. Even though all test sections had their greatest MRI increase at the same time, truck traffic volume growth from 2003 to 2005 was the same as the volume growth from 2000 to 2002. This was due to a lack of monitored traffic data from 1999 to 2006; linear interpolation of truck volumes through this gap would assume a fixed volume growth. The estimated truck volumes provided by the agency were disregarded because such a large increase in truck volumes did not seem realistic (see Figure 2).

3.3.2 ARKANSAS

Peak MRI increases occurred in 2005, 2007, and 2011 for Arkansas test sections. However, as the SPS-2 project with the highest amount of truck traffic, in most cases MRI continued to steadily increase until the test sections went out of study. Also, there were gaps and variability in roughness measurements that made trend analysis difficult. Section 050213 for example, appeared to drop in MRI from 258 inch/mile in May 2007 to 160 inch/mile in September 2008, just before going out of study in November of that year. The other test sections went out-of-study in 2013, but there was a gap in profile measurements from 2008 to 2011. Seven of the 12 sections (typically high-strength PCC) showed a relatively high increase in MRI deterioration and truck traffic volume growth in 2005. For these 7 sections, the traffic volume growth increased from 9,000 trucks per year to a volume growth of 157,000 trucks per year. However, with a total of 1.84 million trucks counted in 2005, this short-term increase in volume growth was not as significant.

3.3.3 CALIFORNIA

Most of the California test sections displayed peak MRI deterioration in 2004. However, this was caused by MRI measurements taken earlier in the day when curling may have caused increased roughness. As with Arizona, the peak MRI deterioration rate was higher in sections with low-strength PCC and less in sections with high-strength PCC. Section 060201 had its peak MRI deterioration in 2015 shortly before going out-of-study in 2017. For the sections with their peak MRI deterioration in 2004, traffic volume growth changed from no growth (from 2000 to 2003) to a volume growth of 52,000 trucks per year (according to agency estimates).

3.3.4 COLORADO

Eight of the 13 sections showed MRI deterioration in 2004. However, peak MRI deterioration rates were not very high compared to other SPS projects (deterioration rates did not exceed 10 inch/mile/year). Therefore, in this case, PCC strength did not appear to significantly impact the peak MRI deterioration rate. Like the Arizona site, there was a gap in monitored truck volumes and the estimate provided by the agency seemed too high to be realistic (see Figure 5). As a result, linear interpolation of truck volumes within the gap of monitored traffic data would not show any change in traffic volume growth. Like Arizona, it could not be determined if peak MRI deterioration had a correlation to traffic growth. Three sections had peak MRI deterioration in the range of 2006-2007, but again, the deterioration rates were relatively low and did not correlate to a growth in truck traffic.

3.3.5 DELAWARE

All test sections experienced peak MRI deterioration in 1998. Traffic volume growth changed from 1,460 trucks/year to 8,760 trucks/year during the peak MRI deterioration period. Sections with 14-foot lane widths had MRI deterioration rates between 16 and 22 inch/mile/year, while sections with MRI deterioration rates greater than 22 inch/mile/year all had 12-foot lane widths. At this site, lane width had more impact on peak MRI deterioration than other design factors (including PCC strength).

3.3.6 IOWA

Test sections with low-strength PCC had peak MRI deterioration in 2009, while those with high-strength PCC had peak MRI deterioration in 2014-2015. Traffic volume growth did not correlate to peak MRI deterioration for the low-strength PCC sections, but for the high-strength PCC sections, the traffic growth changed from 6,000 trucks/year to 24,000 trucks/year (a 300% increase).

3.3.7 KANSAS

Most of the Kansas test sections had peak MRI deterioration either in 1999 or 2004. None of the design factors consistently correlated to time or rate of peak MRI deterioration. Traffic volume growth also did not correlate with the increases in MRI. MRI for test sections at this site did not have a sudden increase; instead, the MRI fluctuated slightly from about 2000 to 2004. The lack of correlation to truck traffic growth may be because traffic growth was relatively consistent at this site (see Figure 8).

3.3.8 MICHIGAN

Most of test sections in Michigan had the highest MRI deterioration rate in the range of 1996-1998. From discussion with MDOT, low-strength PCC sections had failed due to joint deterioration. The few test sections that had peak MRI deterioration rates in 2003-2006 typically had high-strength concrete. As expected, the increase in MRI deterioration rate did not correlate to an increase in traffic growth. However, like Kansas, traffic growth flattened-out after 1997, which likely caused the MRI deterioration rate to decrease from this point forward. Five test sections that had the highest peak MRI deterioration rates were placed out-of-study shortly after (in 1998-2003). Michigan is an outlier in the SPS-2 experiment as several test sections degraded early, suggesting issues with construction or materials.

3.3.9 NEVADA

Almost all Nevada test sections showed peak MRI deterioration rate in 1997 (only Section 320201 peaked later, in 2002). These sections were in-study from 1993 to 2004 – except for two sections that went out-of-study in 1997 – at the apex of the MRI deterioration rate. Peak MRI deterioration rate did not appear to have any correlation to an increase in traffic growth or design factors. Truck traffic did not grow significantly after 1997 (as seen in Figure 10) which may have caused the MRI deterioration rate to also slow down. Nevada (like Michigan) is also an outlier in the SPS-2 experiment as several test sections degraded early, suggesting issues with construction or materials.

3.3.10 NORTH CAROLINA

All of the thin pavement sections in North Carolina went out-of-study in 2003 and the MRI deterioration rate was also at its highest at this time for these sections. The thin pavement sections did not correlate to an increase in traffic volume growth. Traffic growth slowed down between 2003-2012. The thick pavement sections still in-study had peak MRI deterioration rates in the range of 2015-2019, just as traffic volume growth increased again. This observation was not made to question the effect of cumulative traffic loading over time on roughness. Rather, it is noted that an inflection point in the rate change in traffic was in close to an inflection point in roughness deterioration. Within the group of sections with thick pavement, sections with PATB base had slightly lower MRI deterioration rates than sections with LCB base; PCC strength did not correlate significantly to the peak MRI deterioration rate.

3.3.11 NORTH DAKOTA

The MRI deterioration rates of North Dakota test sections were typically constant following the initial profile measurement. Estimated traffic at this site did not indicate any sudden increase or decrease in traffic volume growth. Because there were no significant changes in MRI deterioration and traffic growth, a relative correlation between these two measures could not be determined.

3.3.12 OHIO

Most of the thin pavement sections in Ohio went out of study in 2007. These sections had their highest MRI deterioration right before going out of study (2003-2005). Traffic volume growth did slightly increase around this time – specifically in 2003 – as seen in Figure 13. Most of the thick pavement sections are still in-study and peak MRI deterioration rate occurred toward the latest survey (2015-2019). Traffic growth increased in 2015; therefore, MRI deterioration rates at the Ohio test sections did correlate to traffic volume growth.

3.3.13 WASHINGTON

Most Washington test sections had peak MRI deterioration rate in either 2011 or 2013. Peak MRI deterioration rates were typically less than 10 inch/mile/year. These sections have performed well in roughness deterioration and peak MRI deterioration rate did not correlate to any specific design factor. Truck traffic growth increased in 2011, but then subsequently decreased in 2013. Fluctuations in both the MRI deterioration rate and the traffic volume growth were not significant enough to determine a correlation or lack thereof between the two measures. Sections 530208 and 530206 had peak MRI deterioration in 1998, but the available monitored traffic data were not sufficient to determine if there was a change in traffic volume growth. However, since sections 530206 and 530208 had similar roughness curves, their performance may be related to factors they have in common (i.e., high-strength PCC pavement on an LCB base).

3.3.14 WISCONSIN

Most of the Wisconsin test sections had their peak MRI deterioration rate in 1999 (2 years after construction). Because the peak MRI deterioration rate occurred so early into the study, it is difficult to determine whether traffic growth was a significant factor in MRI deterioration. Peak MRI deterioration rates were typically less than 11 inch/mile/year. Thin pavement with low-strength PCC sections had slightly higher peak MRI deterioration rates than sections with thick pavements and high-strength PCC. Traffic volume growth did flatten-out for a period after 2007

– as did the MRI deterioration rate – but there was no other significant correlation between the two measures.

3.4 Findings

As stated previously, the concept ‘peak MRI deterioration’ was based on an assumption of how roughness behaves over time. There would be no peak deterioration in a linear progression of roughness. If the roughness curve behaved in a parabolic manner, the peak deterioration would always be at the start of traffic loading. Without a way correct for the variability in roughness from curl and warp and other macro-level changes to pavement surface, it was not practical to relate changes in traffic growth to changes in MRI. The analysis relied on a smoothening procedure to account for roughness measurement variability. However, because the procedure could not be validated and made assumptions regarding the behavior of MRI, it was not reliable in describing the change in MRI deterioration rate.

It has been long established in pavement design methodology that cumulative traffic loading is a primary factor in modeling pavement performance. However, cumulative traffic loading also assumes an analysis period based on the design life. The premise of this analysis was that if the analysis period was shorter, cumulative traffic would be a function of traffic growth within that analysis period. Therefore, periodic changes in traffic growth would result in periodic changes in pavement performance. Ergo, since traffic loading was typically nonlinear, pavement performance could also be assumed to be nonlinear. However, describing pavement performance using MRI came with some challenges and assumptions, such as peak MRI deterioration, which limited the usefulness of the analysis.

In summary, peak MRI deterioration rates typically occurred in 1998, 2004, or in the most recent profile visit, depending on the section. In several cases, an increase or decrease traffic volume growth had some consequential effect on the MRI deterioration rate to varying degrees. Furthermore, steady traffic growth often correlated to steady MRI deterioration.

Among the SPS-2 design factors, PCC strength and pavement thickness had the most significant influence on MRI deterioration rate under traffic loading. This finding was based on the above project-by-project comparison between test sections and the relative time of their peak MRI deterioration and the severity of the peak MRI deterioration (as listed in Appendix A). While the consequence of PCC strength and pavement thickness on the timing of peak MRI deterioration was not evident in all projects, it was observed in some projects.

Peak MRI deterioration rates under 10-to-12 inch/mile/year indicated that the test section was performing well and would continue to do so. Note that the peak MRI deterioration rate is only describing an inflection point in the roughness deterioration curve and in no way indicates that the pavement is continuously deteriorating at a rate of 10 to 12 inch/mile/year. Appendix B shows plots for measured MRI and truck volumes over time for each section.

4.0 IMPACT OF CLIMATE ON PAVEMENT PERFORMANCE

For each project, Table 2 shows the climatic region and the average deterioration rates of mean roughness index (MRI), average wheel-path faulting (AWF), and percent (transversely) cracked slabs (PCS). Climatic region is defined the annual precipitation (AP) and the freezing index (FI). An AP of 20 inches or less qualifies as 'dry' climate and an AP greater than 20 inches, a 'wet' climate. A 'non-freeze' climate has a FI of 50 or less. FI is the sum of all average daily temperatures per year that were below freezing. An FI greater than 50 would define a 'freeze' climate.[2]

Table 2. Average Annual Precipitation and Freezing Index for SPS-2 Sites

State	Climate				Average Deterioration Rates		
	AP[1]	FI[2]	Climatic Region		MRI[3]	AWF[4]	PCS[5]
Arizona (AZ)	8	0	Dry	Non-freeze	1.4	0.001	0.6
Arkansas (AR)	53	28	Wet	Non-freeze	3.8	0.002	0.7
California (CA)	11	0	Dry	Non-freeze	1.1	0.001	1.6
Colorado (CO)	14	302	Dry	Freeze	1.2	0.000	0.3
Delaware (DE)	46	87	Wet	Freeze	1.2	0.001	0.0
Iowa (IA)	36	548	Wet	Freeze	1.4	0.000	0.1
Kansas (KS)	33	252	Wet	Freeze	1.0	0.000	0.1
Michigan (MI)	34	370	Wet	Freeze	12.6	0.004	2.4
Nevada (NV)	10	190	Dry	Freeze	7.6	-0.004	4.0
North Carolina (NC)	44	32	Wet	Non-freeze	0.8	0.000	0.6
North Dakota (ND)	25	1283	Wet	Freeze	1.3	0.002	0.0
Ohio (OH)	41	327	Wet	Freeze	2.5	0.000	3.2
Washington (WA)	12	207	Dry	Freeze	0.7	0.000	0.2
Wisconsin (WI)	33	913	Wet	Freeze	0.4	0.000	0.0

[1] AP – Annual precipitation (inch per year)
[2] FI – Freezing index (days)
[3] MRI – Mean roughness index (inch per mile per year)
[4] AWF – Average wheel-path faulting (inch per year)
[5] PCS – Percent (transversely) cracked slabs (percent slabs per year)

Table 2 shows that the highest average PCS deterioration rates were found in these outlier projects. Excluding the outlier projects (Michigan, Nevada, and Ohio), projects with typically higher average deterioration rates also had greater traffic loading. Figure 19 shows the average MRI deterioration rate of SPS-2 projects sorted by climatic region. There was no trend based on climatic region to demonstrate the impact of climate on deterioration. Outside the outlier projects, Arkansas showed the highest MRI deterioration rates and Wisconsin showed the lowest. However, this was the influence of traffic rather than climate. Arkansas, with the highest

[2] Jackson, N. and J. Puccinelli. November 2006. *Long-Term Pavement Performance (LTPP) Data Analysis Support: National Pooled Fund Study TPF-5(013)*. Report No. FHWA-HRT-06-121. Federal Highway Administration. Washington, DC.

traffic loading of 3,560 KESALs per year, had high MRI deterioration, while Wisconsin, with one of the lowest traffic loadings (280 KESALs per year), had very low MRI deterioration.

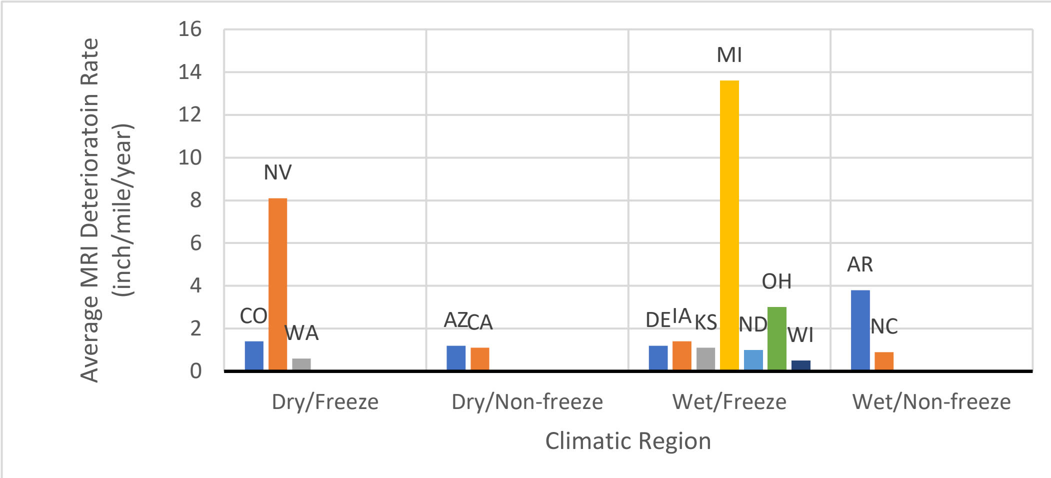

Figure 19. Average MRI Deterioration Rate by State and Climatic Region.

Figure 20 shows that average AWF deterioration rates were not impacted by the climatic region. Higher AWF deterioration rates were present in Arkansas. Arkansas, Delaware, and North Dakota, sites were in the 'wet' climate region. However, other 'wet' sites (e.g., Iowa, North Carolina) did not have higher AWF deterioration rates. In the case of Arkansas, the higher rate could be driven by higher traffic loads (as seen with the MRI deterioration).

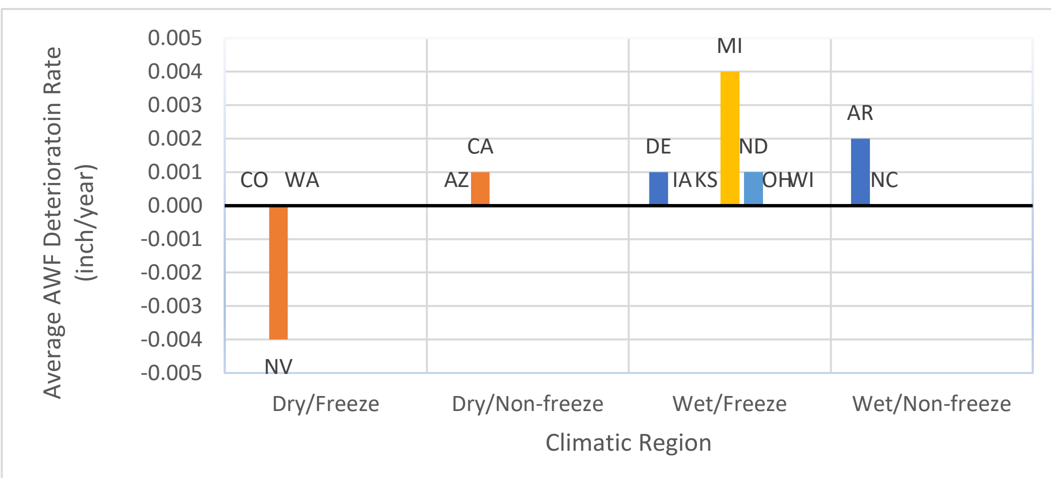

Figure 20. Average AWF Deterioration Rate by State and Climatic Region.

Figure 21 shows that all sites with 'non-freeze' climate had higher average PCS deterioration rates than 'freeze' climate sites. However, Arizona, California, and Arkansas can be explained by high traffic loading. The average deterioration rate for North Carolina was significantly influenced by two test sections: 370201 and 370205.

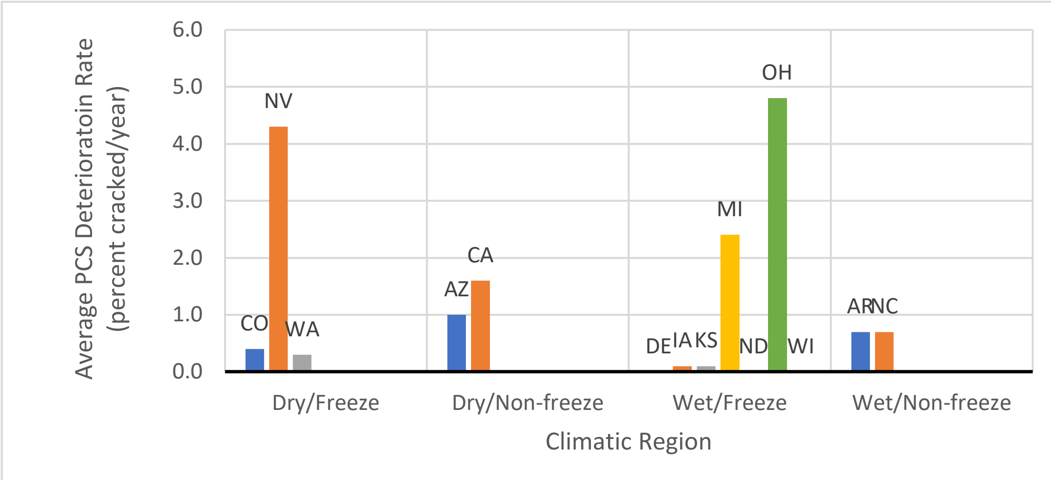

Figure 21. Average PCS Deterioration Rate by State and Climatic Region.

Whatever influence climate may have on pavement performance was overshadowed by other design factors, specifically traffic loading. MRI, AWF, and PCS are all condition metrics that typically deteriorate under loading. Climate related deterioration maybe more significant in the pavement subsurface (i.e., base and subgrade layers).

5.0 IMPACT OF DISTRESS ON ROUGHNESS

LTPP regularly performs manual distress surveys on active test sections. For concrete test sections, these distress surveys were intended to capture the quantity and severity of distresses such as longitudinal cracking, transverse cracking, durability cracking (D-cracking), patching, scaling, polishing, and map cracking. Table 3 summarizes the averages by state of the maximum distress that occurs on each SPS-2 test section. Where there is typically a significant amount of variability by state, there are a few common trends. Appendix B shows plots for distress over time for each SPS-2 test section.

Table 3 shows that most test sections experienced some amount of longitudinal and transverse cracking. D-cracking very rarely occurred on test sections. Although a few projects had very little to no patching, scaling, polishing, and map cracking, most projects had at least some. The Nevada SPS-2 is an outlier–having more than 100 feet of both longitudinal and transverse cracking on average. Longitudinal cracking was most significant in Arizona, Arkansas, California, and Colorado and could continue to increase as most of these projects are still actively in study. California and Ohio had the highest average amount of transverse cracking.

North Dakota and Ohio had the highest average amount of patching. North Carolina had the largest amount of scaling. Washington, Arkansas, Colorado, Delaware, and North Dakota, and had significant amounts of polishing. Map cracking was significant in several states, including Arizona, California, Colorado, Delaware, Kansas, North Carolina, and Washington. Polishing and map cracking are common for concrete pavements and typically a result of the volume of cement paste used in the mix. Therefore, test sections with 550 psi PCC strength would be more likely to have polishing, while test sections with 900 psi PCC strength would more likely have map cracking. The frequency of polishing or map cracking on SPS-2 test sections varied by project.

Table 3. Average by State of the Maximum Quantity Distress at Each SPS-2 Test Section

State	Longitudinal Cracking (ft)	Transverse Cracking (ft)	Durability Cracking (sq. ft.)	Patching (sq. ft.)	Scaling (sq. ft.)	Polishing (sq. ft.)	Map Cracking (sq. ft.)
Arizona	83.5	13.4	0	0	9	119	567
Arkansas	48.1	17	0	13	0	327	0
California	26.5	44.9	0	2	50	41	610
Colorado	38	5.7	0	0	18	297	215
Delaware	8.8	2.6	0	31	11	212	491
Iowa	3.1	5	0	17	2	70	0
Kansas	20.2	3.9	1	16	15	0	288
Michigan	4.5	8.6	0	7	1	56	65
Nevada	137	151.2	0	22	51	44	266
North Carolina	0.8	3.5	0	0	111	188	230
North Dakota	14.1	1.4	3	41	0	229	1
Ohio	10.5	49.4	0	50	0	0	111
Washington	17.8	7.3	0	0	7	422	270
Wisconsin	2	0	0	2	0	0	66
Average	**11.8**	**11.6**	**0**	**4**	**3**	**54**	**55**

5.1 Impact on Roughness by Type of Distress

Table 4 describes the thresholds used for evaluating the impact of distress on roughness. The threshold values were selected to provide sample sizes for comparisons that were roughly as equal as possible. Because most SPS-2 test section performed wells, the threshold values for most distresses were typically low to distinguish between minor and significant amounts of each distress.

Table 4. Assumed Thresholds for Defining Significant Amounts of Distress by Type

Distress Type	Minor Distress	Significant Distress
Longitudinal Cracking	≤10 ft	>10 ft
Transverse Cracking	≤10 ft	>10 ft
Durability Cracking	≤0 sq. ft.	>0 sq. ft.
Patching	≤5 sq. ft.	>5 sq. ft.
Scaling	≤5 sq. ft.	>5 sq. ft.
Polishing	≤50 sq. ft.	>50 sq. ft.
Map Cracking	≤100 sq. ft.	>100 sq. ft.

5.1.1 LONGITUDINAL CRACKING

Figure 22 shows that test sections with some amount of longitudinal cracking (10 feet or more) typically had higher rates of MRI deterioration. No difference in MRI deterioration was seen for test sections in Iowa, North Carolina, Ohio, and Washington, but for these projects, the MRI deterioration rate was usually low for all test sections. Test sections with high longitudinal cracking also had higher average MRI, except for Arizona, Colorado, and North Dakota.

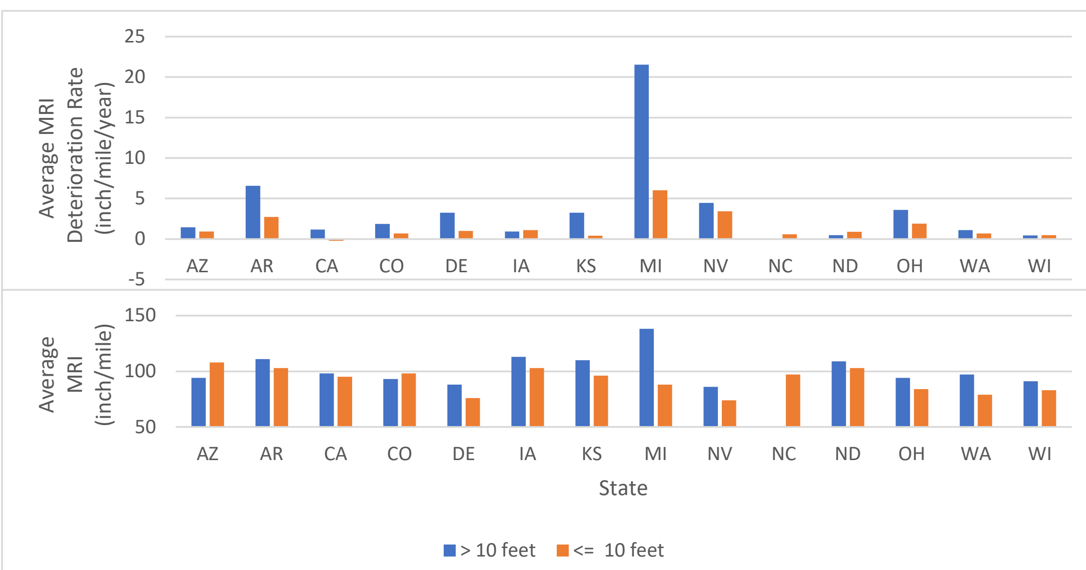

Figure 22.Average MRI and MRI Deterioration Rate by High and Low Amounts of Longitudinal Cracking.

5.1.2 TRANSVERSE CRACKING

Figure 23 shows that test sections with some amount of transverse cracking (more than 10 feet) had higher rates of MRI deterioration, except for in Arizona, North Carolina, and North Dakota. There were also several states where the MRI deterioration was too low for the deterioration rate difference to have any correlation to transverse cracking. Average MRI across the project was slightly higher when some transverse cracking was present on test sections (except for in Arizona, Kansas, North Dakota, and Ohio). Compared to longitudinal cracking, transverse cracking did not have significantly better or worse correlation to MRI deterioration or to average MRI.

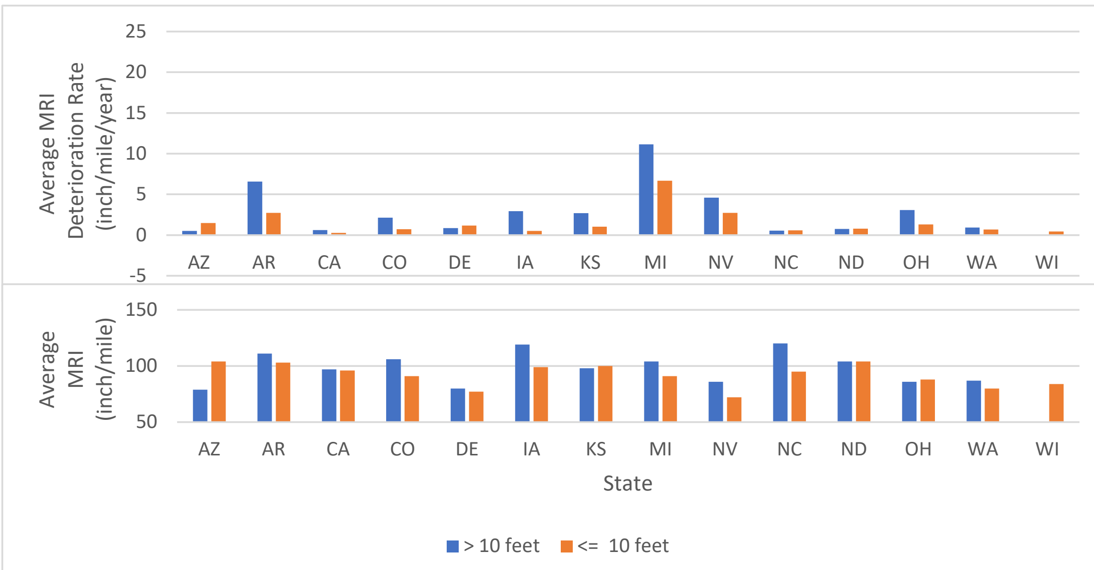

Figure 23. Average MRI and MRI Deterioration Rate by High and Low Amounts of Transverse Cracking.

5.1.3 D-CRACKING

Figure 24 shows D-cracking (more than 0 square feet) was not a common occurrence on test sections. Therefore, a relationship between D-cracking and MRI deterioration could not be assessed. Colorado, Kansas, Michigan, and North Dakota were the only states to exhibit some amount of D-cracking, but even among these states, there was no correlation between D-cracking and MRI.

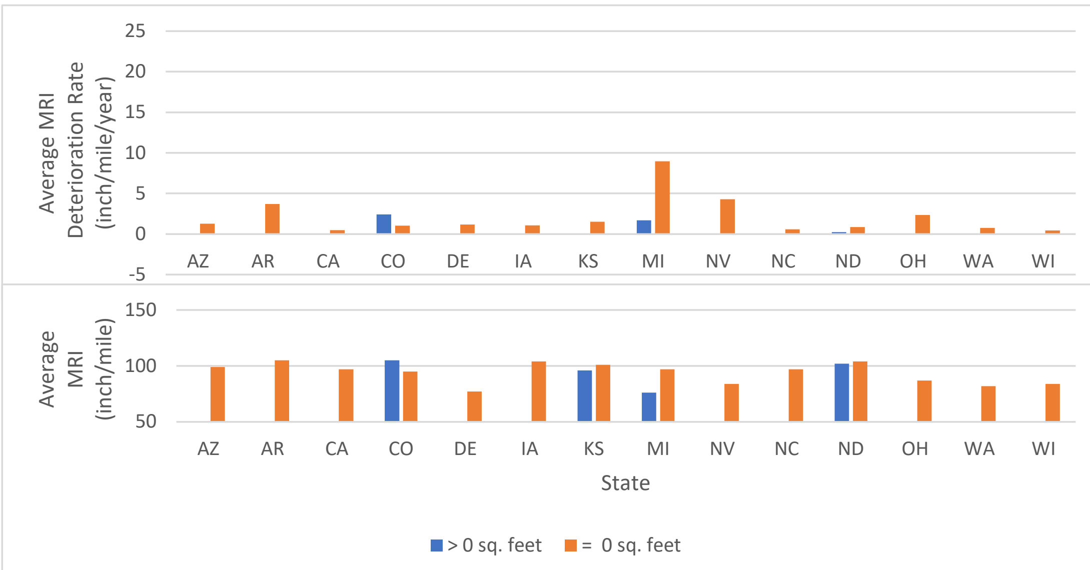

Figure 24. Average MRI and MRI Deterioration Rate by High and Low Amounts of D-Cracking.

5.1.4 PATCHING

Figure 25 shows that significant amounts of patching typically had higher MRI deterioration than test sections very little patching. On average, test sections in Arizona, Colorado, North Carolina, and Washington did not have significant amounts of patching (more than 5 square feet). In North Dakota and Wisconsin, there was no significant difference in MRI deterioration for test sections with and without patching.

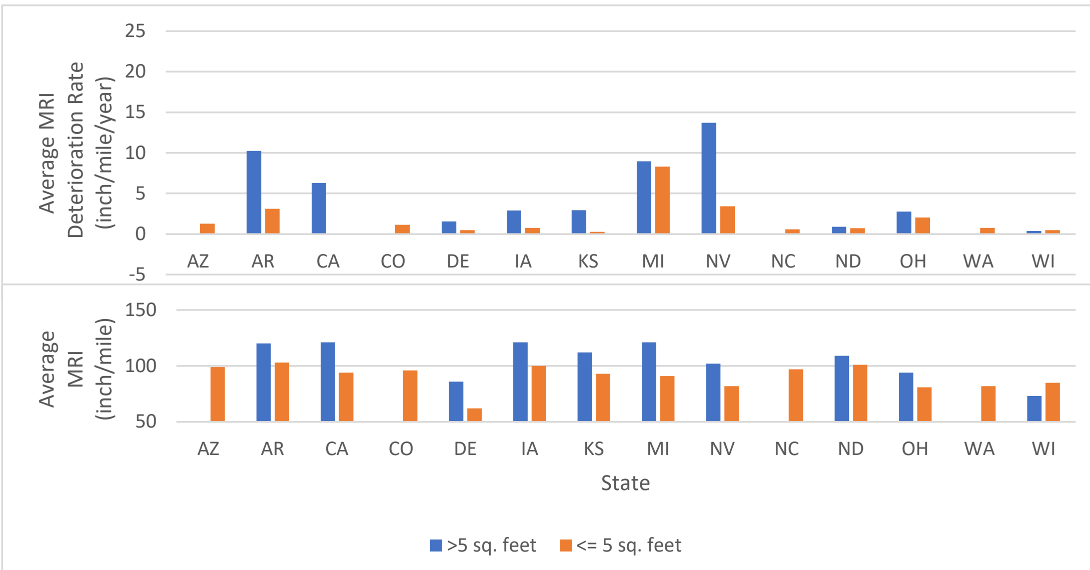

Figure 25. Average MRI and MRI Deterioration Rate by High and Low Amounts of Patching.

5.1.5 SCALING

Figure 26 shows that scaling did not have an effect on MRI deterioration rate. Scaling (more than 5 square feet) did not correlate to a higher MRI deterioration or higher average MRI. In several states, test sections with some amounts of scaling also had lower MRI deterioration rates, but this is unlikely to be related. Scaling was not a common occurrence on SPS-2 test sections and typically the amount scaling was small compared to other distresses. Therefore, it was difficult to evaluate whether scaling had any effect on MRI and overall, there was no consistent correlation between scaling and MRI deterioration rate. There were four states where test sections had no significant amount of scaling (more than 5 sq. feet): Arkansas, North Dakota, Ohio, and Wisconsin.

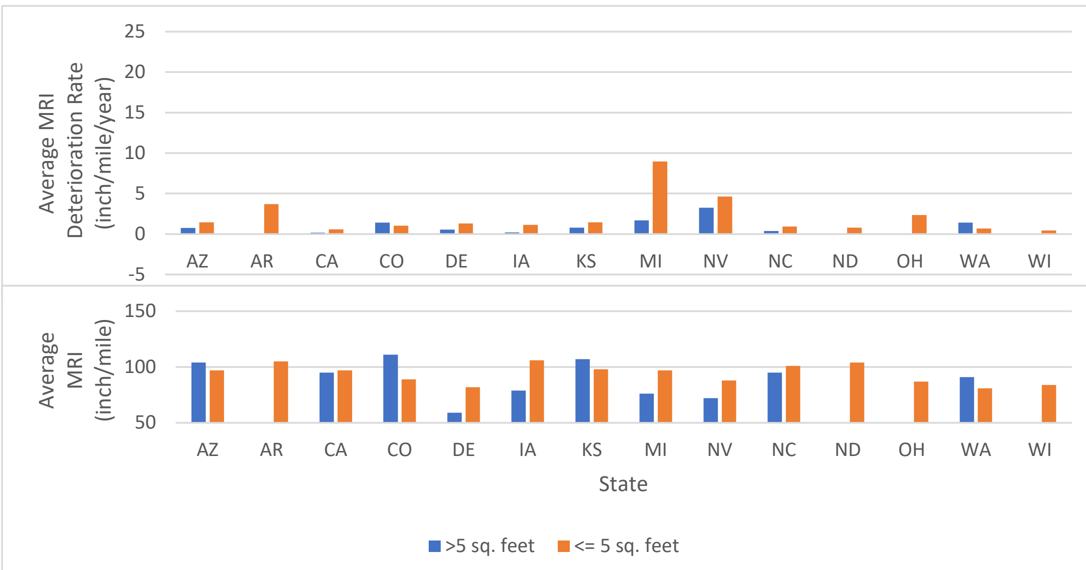

Figure 26. Average MRI and MRI Deterioration Rate by High and Low Amounts of Scaling.

5.1.6 POLISHING

Like scaling, polishing also had no impact on MRI deterioration or average MRI. Figure 27 shows that Kansas, Ohio, and Wisconsin test sections did not have significant amounts of polishing (more than 50 sq. feet) and could not be evaluated. However, states that had test sections with polishing showed no consistent correlation between polishing and MRI deterioration.

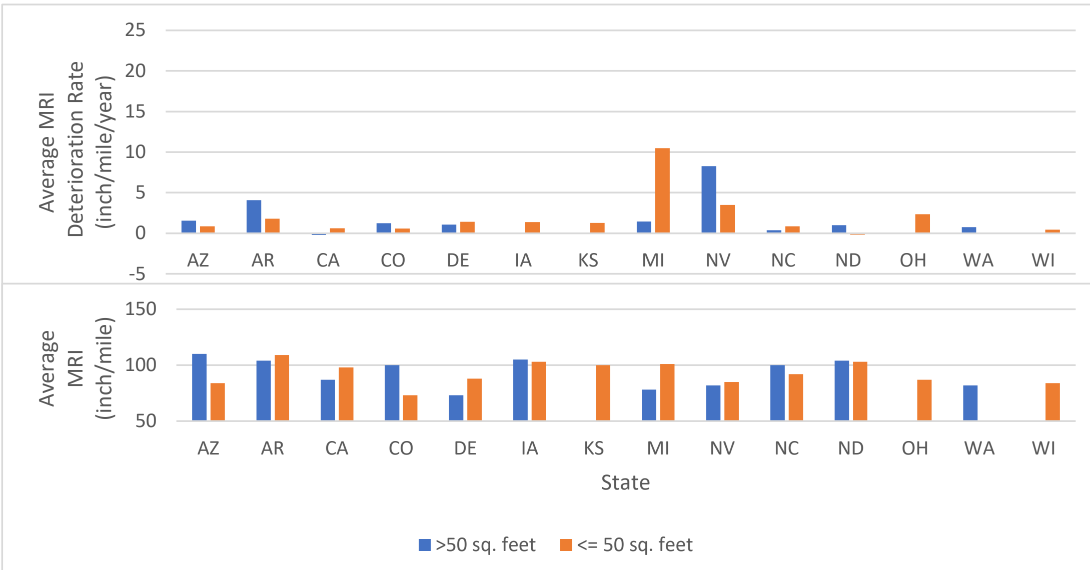

Figure 27. Average MRI and MRI Deterioration Rate by High and Low Amounts of Polishing.

5.1.7 MAP CRACKING

Figure 28 shows that map cracking had no impact on MRI deterioration. Test sections with high amounts of map cracking (Arizona, California, Colorado, Delaware, Kansas, Ohio, Washington, and Wisconsin) had a very slight correlation to higher MRI deterioration. However, the difference in MRI deterioration was so small that it could not be considered significant. Michigan and Nevada are outliers in that several test sections deteriorated quickly and before map cracking could develop. Test sections in Arkansas, Iowa, and North Dakota did have significant amounts of map cracking (more than 100 sq. feet). Average MRI also showed no correlation to map cracking.

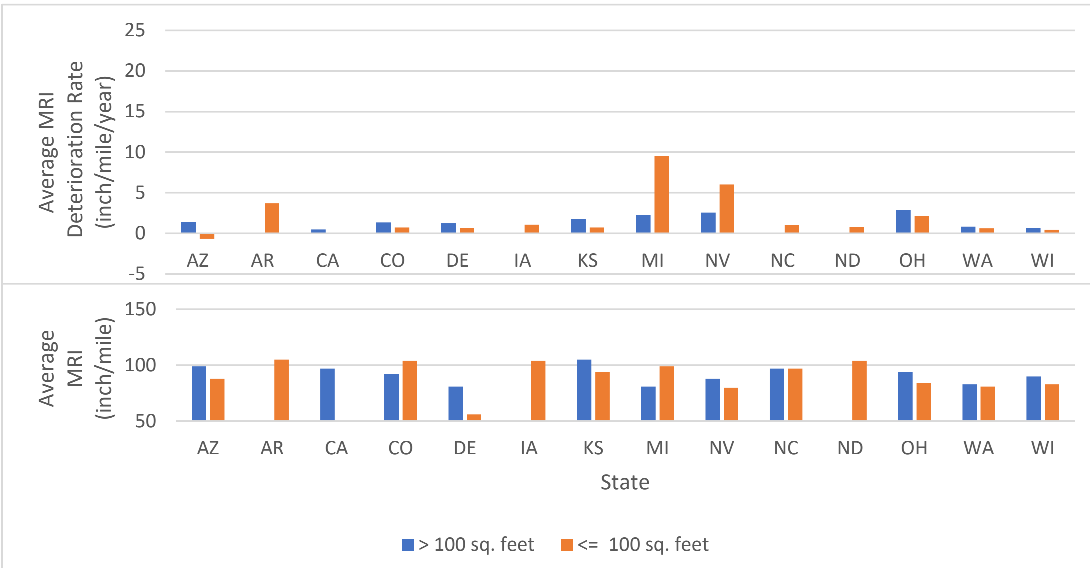

Figure 28. Average MRI and MRI Deterioration Rate by High and Low Amounts of Map Cracking.

5.2 Findings

Longitudinal and transverse cracking showed some correlation to MRI deterioration, but other distresses (i.e., D-cracking, patching, scaling, polishing, and map cracking) had little to no impact on roughness. Longitudinal and transverse cracking were expected to have a more direct impact on the structural capacity of test sections than surface texture issues such as scaling, polishing, and map cracking. D-cracking was not common on SPS-2 test sections so it was difficult to establish any relationship to roughness deterioration rate.

Table 5 summarizes the average difference between minor and significant amounts of each distress type, on average, of MRI and MRI deterioration rate. Three distress types are shown to consistently impact MRI: longitudinal cracking, transverse cracking, and patching. The other distress, D-cracking, scaling, polishing, and map cracking did not correlate to MRI. Scaling, polishing, and map cracking did not impact roughness, but D-cracking was so uncommon on SPS-2 test sections that the sample size of test sections with D-cracking is insufficient to determine whether there was a correlation.

Because a method of averages was used to identify the general trend, there is a risk of bias from test sections with severe amounts of a particular distress. To account for this potential, thresholds were defined for significant amounts of each distress to dilute most of the bias. Based on Table 5, patching had the most impact on MRI, followed by longitudinal cracking, and—tertiarily—transverse cracking.

Table 5. Summary of Impact on Roughness from Distress

Distress Type	**Average Difference in Performance when Distress is Significant instead of Minor**	
	Average MRI[1]	**Average MRI Deterioration Rate[2]**
Longitudinal Cracking (feet)	10.2	2.31
Transverse Cracking (feet)	5.9	1.29
D-cracking (sq. ft.)	-4.5	-2.01
Patching (sq. ft.)	16.7	3.11
Scaling (sq. ft.)	-4.7	-1.15
Polishing (sq. ft.)	0.7	-0.25
Map Cracking (sq. ft.)	4.4	-0.62

[1] Average of the net difference between average MRI when distress is significant and average MRI when distress is minor. A large positive value indicates that when distress is significant average MRI is higher than when distress is minor.

[2] Average of the net difference between average MRI deterioration rate when distress is significant and average MRI when distress is minor. A large positive value indicates that when distress is significant average MRI deterioration rate is higher than when distress is minor.

6.0 IMPACT OF MAINTENANCE ON ROUGHNESS

During the study period, maintenance events were performed on many SPS-2 test sections by State Highway Agencies. Sometimes these events were reported by the agencies, and other times they were documented during field data collection and review. The type and frequency of maintenance events can be an indication of pavements that are undergoing routine maintenance or those in need of repair**Error! Reference source not found.** shows the total number of maintenance events performed on SPS-2 projects while in the LTPP study. The table lists the type of maintenance event from the most frequent to the least frequent. The most-frequent maintenance events included lane-shoulder longitudinal joint sealing, asphalt concrete (AC) shoulder restoration, and partial-depth patching at the (transverse) joints. The least-frequent maintenance events were skin patching, full-depth patching other than at joints (patching near middle of the slab–possibly at the longitudinal joint), and PCC slab replacement.

North Dakota test sections had accumulated over time more maintenance events than test sections in other projects. However, about 40% of maintenance events in North Dakota were AC shoulder restoration. The second most common maintenance in North Dakota was longitudinal shoulder-lane joint sealing and partial-depth patching at the joints. While receiving frequent maintenance treatments, North Dakota test sections typically did well in terms of transverse cracking and other distress (except for section 380217). This implies that frequently application of maintenance treatments on North Dakota had an impact on maintaining good condition and extending the life of these test sections. In contrast, projects with test sections that typically deteriorated quickly, such as Nevada, Michigan, Ohio, and Arkansas, had a medium amount of maintenance events–21 to 40 throughout the monitoring period. Test sections that deteriorated quickly may have needed more maintenance, but typically did not remain in study long enough to accumulate large amount of maintenance events. These examples, demonstrate at even with maintenance there are other factors that can have significant influence on pavement performance.

Table 6. Summary of Maintenance Events per SPS-2 Project

Maintenance Event Type	**Number of Maintenance Events per Project**														
	AZ	AR	CA	CO	DE	IA	KS	MI	NV	NC	ND	OH	WA	WI	**TOTAL**
Lane-Shoulder Longitudinal Joint Sealing	-	14 (12)	20 (12)	-	5 (5)	1 (1)	13 (13)	8 (8)	-	-	45 (16)	-	-	-	**106 (67)**
AC Shoulder Restoration	-	-	-	-	-	13 (13)	-	3 (2)	-	-	73 (15)	10 (10)	-	-	**99 (40)**
Partial-Depth Patching at Joints	11 (7)	5 (3)	2 (1)	23 (9)	2 (2)	5 (5)	7 (4)	7 (6)	4 (3)	2 (2)	20 (10)	-	1 (1)	-	**89 (53)**
Transverse Joint Sealing	-	5 (5)	10 (7)	-	2 (2)	1 (1)	13 (13)	1 (1)	-	-	8 (8)	-	-	-	**40 (37)**
Partial-Depth Patching Other Than at Joints	8 (5)	2 (1)	3 (2)	4 (2)	3 (3)	2 (2)	-	-	6 (4)	-	3 (3)	2 (1)	4 (1)	-	**37 (24)**
Temporary Repair Patching*	13 (2)	-	-	-	2 (2)	2 (2)	3 (3)	-	-	1 (1)	4 (4)	1 (1)	-	3 (3)	**29 (18)**
Crack Sealing	2 (2)	3 (3)	3 (3)	-	2 (1)	1 (1)	-	-	13 (9)	-	5 (1)	-	-	-	**29 (20)**
Full-Depth Transverse Joint Repair Patch	-	-	-	-	5 (4)	-	8 (8)	1 (1)	-	-	5 (5)	9 (5)	-	-	**28 (23)**
PCC Slab Replacement	-	-	-	-	1 (1)	4 (2)	4 (2)	1 (1)	-	-	2 (1)	8 (5)	-	1 (1)	**21 (13)**
Full-Depth Patching Other Than at Joints	-	-	-	-	-	1 (1)	6 (6)	-	4 (1)	-	1 (1)	6 (3)	-	-	**18 (12)**
Skin Patching	-	-	-	-	9 (9)	6 (6)	-	-	-	-	2 (2)	-	-	-	**17 (17)**
TOTAL	**35 (17)**	**29 (24)**	**40 (26)**	**27 (11)**	**39 (37)**	**36 (34)**	**55 (50)**	**21 (19)**	**27 (17)**	**3 (3)**	**186 (84)**	**40 (29)**	**5 (2)**	**5 (5)**	**548 (358)**

– no occurrence of the maintenance event at the project
The number in parentheses is the number of test sections that received maintenance at each project.
*This type of patching refers to filling a hole in the concrete surface with a cold pre-mixed temporary patching material and compacting by truck. In contrast, partial- and full-depth patching are more permanent (long-term) repair strategies.

Table 7 shows the timing of maintenance events based on pavement age. In some cases, the same type of maintenance event occurred more than once on the same test sections within 5-year pavement age intervals. The table shows typically shows a normal distribution of maintenance events where maintenance events most frequently occur in the 15-20 pavement age interval.

Table 7. Summary of Maintenance Events per Five-Year Pavement Age Interval

Maintenance Event Type	Pavement Age Interval (years)						
	0-4.9	5-9.9	10-14.9	15-19.9	20-24.5	25-29.9	**Total**
Lane-Shoulder Longitudinal Joint Sealing	18 (18)	35 (31)	32 (32)	21 (21)	-	-	**106 (102)**
AC Shoulder Restoration	15 (15)	15 (15)	15 (15)	39 (39)	15 (15)	-	**99 (99)**
Partial-Depth Patching at Joints	8 (8)	9 (8)	16 (13)	35 (33)	20 (16)	1 (1)	**89 (79)**
Transverse Joint Sealing	2 (2)	10 (10)	15 (15)	13 (13)	-	-	**40 (40)**
Partial-Depth Patching Other Than at Joints	5 (4)	2 (2)	6 (5)	14 (12)	8 (6)	2 (2)	**37 (31)**
Temporary Repair Patching*	-	-	4 (3)	8 (5)	12 (9)	5 (5)	**29 (22)**
Crack Sealing	14 (10)	5 (4)	1 (1)	7 (6)	2 (2)	-	**29 (23)**
Full-Depth Transverse Joint Repair Patch	4 (4)	-	5 (5)	12 (12)	5 (5)	2 (2)	**28 (28)**
PCC Slab Replacement	3 (3)	1 (1)	4 (2)	6 (6)	1 (1)	6 (6)	**21 (19)**
Full-Depth Patching Other Than at Joints	1 (1)	2 (1)	2 (2)	10 (9)	1 (1)	2 (2)	**18 (16)**
Skin Patching	-	-	-	-	17 (17)	-	**17 (17)**
TOTAL	**70 (65)**	**89 (81)**	**102 (95)**	**187 (178)**	**82 (73)**	**18 (18)**	**548 (510)**

– no occurrence of the maintenance event at the project
The number in parentheses is the number of test sections that received maintenance at each project.
* This type of patching refers filling a hole in the concrete surface with a cold pre-mixed temporary patching material and compacting by truck. In contrast, partial- and full-depth patching are more permanent (long-term) repair strategies.

6.1 Impact on Roughness by Maintenance Type

LTPP records activities as 'Maintenance' based on the whether the improvement alters the original pavement structure as defined by the experiment. Therefore, improvements such as thin resurfacing, significant grinding, or shoulder replacements often fall into a gray area. For this analysis, it was important to distinguish corrective maintenance activities to repair poor condition from preservation activities to retard further deterioration. When the methodology to determine the benefit of a maintenance treatment is limited to only the immediate benefit, then the distinction between corrective and preventative maintenance is important in understanding that the long-term benefits are not easily measured but of enormous value to service life.

Naturally, there is some overlap; patching a pothole also prevents further water infiltration through the pothole, thus preserving the pavement substructure. Typically, preservation activities are intended to seal the pavement surface, preventing water, debris, or vegetation from entering gaps between joints and cracks and causing further expansion. Water infiltrating into the base or subgrade can cause damage to the foundation of the pavement through pumping or freeze-thaw action. Therefore, activities that perserve the pavement should not be expected to have an immediate impact on pavement performance metrics.

Two methodologies were used to evaluate how a maintenance event may impact the (MRI) deterioration rate of a test section following the application of a maintenance event. First, to determine MRI deterioration rate following the maintenance event, roughness measurements were segmented by the estimated date of maintenance. Linear regression was used to determine the roughness deterioration rate within each segment. With this, the change in the segmented deterioration rate could be computed and used to compare the change in deterioration before and after a maintenance event.

Because seasonal and diurnal variation in roughness measurements could cause unrealistic deterioration rates within the segmented evaluation periods, a smoothening procedure was first applied to roughness measurements to remove some of variability and estimate the monthly MRI values to be used in computing the segmented deterioration rates. The smoothening procedure in this analysis was performed as follows:

- Step 1:
  - (a) Compute initial MRI using linear interpolation all profile surveys.
  - (b) Compute the minimum MRI measured at the test section from all profile surveys.
  - (c) Set initial MRI from the linear interpolation to be no less than 45 inch/mile (this adjustment affects 13 test sections – mostly from Nevada and Michigan – that would otherwise be far below the minimum MRI measured at the test section).
  - (d) Average the values of the initial MRI from linear interpolation with the minimum MRI measurement.
- Step 2: Estimate monthly MRI based on linear interpolation between profile measurements (including the estimated initial MRI from Step 1).
- Step 3: Apply a 6-month moving average over the estimated monthly MRI values. Followed another 3-month moving average to further reduce variability.
- Step 4:
  - (a) Segment the monthly estimated MRI by maintenance events, and
  - (b) Compute the linear deterioration rate for each segment.

The first method quantifies the immediate change in deterioration after the maintenance event. The second method compares the deterioration rate after maintenance to the overall roughness deterioration during its monitoring period. Since it is possible for MRI deterioration with a segmented period to be impacted by other factors (such as traffic), it is important to evaluate the MRI deterioration rate relative to the performance of the pavement throughout its entire monitoring period. However, both methodologies typically arrived at similar findings.

Often, more than one type of maintenance was performed on a test section, such as crack sealing and (temporary) pothole patching. For this reason, quantifiable improvements in roughness should only be assessed as relatively positive or negative. Improvements in roughness deterioration due to maintenance activities must also be assessed by comparing how frequently a maintenance treatment results in improvement versus continued deterioration. For Tables 8 through 16, a positive change in deterioration rate indicates an increase in MRI deterioration (i.e., the pavement getting rougher) and a negative change indicates a decrease in MRI deterioration (i.e., the pavement getting smoother).

While MRI is a good condition metric to assess the overall condition of the pavement, MRI is the mean of IRI in the left and right wheel paths. For example, longitudinal cracking that typically travels the midline of the slab may not be captured by the profiling the left and right wheel paths. However, longitudinal cracking that goes unsealed will allow water infiltration and eventually lead to other distresses that would affect MRI. Therefore, sealing activities that repair longitudinal cracking along with other distress would have a positive effect on MRI in the long-term. Nevertheless, the benefit is in the long-term and may not provide data on immediate impact sought in this analysis.

Also, in some cases, the number of profile measurements between maintenance events are insufficient to accurately portray the change in MRI deterioration rate. Appendix B shows plots for each SPS-2 test section for MRI over time (among other things). Each plot identifies the timing of maintenance events and a depiction of the linear MRI deterioration rate between maintenance events. In Tables 8 through 17, the 'Average Change in MRI Deterioration' is based on the first method discussed above and represents the relative difference between the segmented MRI deterioration rate before maintenance and the segmented MRI deterioration rate after maintenance. For example, if the MRI deteriorate rate was 7 inch/mile/year before maintenance and 2 inch/mile/year after maintenance, the relative difference would be -5 inch/mile/year – a positive impact on roughness.

While a smoothening procedure was used on the MRI data to reduce variability from seasonal and diurnal changes, the variability was not eliminated and could lead to a positive or negative impact on roughness that was actually superficial. However, because this analysis intended to identify general and common trends among all SPS-2 test sections, some of the inherent biases were minimized.

6.1.1 LANE-SHOULDER LONGITUDINAL JOINT SEALING

Table 8 shows the change in deterioration rate after lane-shoulder longitudinal joint sealing was performed. Longitudinal joint sealing did not appear to have a consistent positive or negative impact on roughness. In most states, the positive and negative changes in MRI deterioration after maintenance were normally distributed. This suggests that longitudinal joint sealing will typically have no apparent effect on roughness deterioration. This result was expected as shoulders are not tied and offer no structural advantage to the travel lane.

Table 8. Change in MRI Deterioration Immediately After Lane-Shoulder Longitudinal Joint Sealing

Average Change in MRI Deterioration (inch/mile/year)	**Count of Maintenance Event per Project**														
	AZ	AR	CA	CO	DE	IA	KS	MI	NV	NC	ND	OH	WA	WI	**TOTAL**
< -7	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**1**
-7 to -3.1	0	2	3	0	0	0	0	0	0	0	3	0	0	0	**8**
-3 to -1.1	0	1	5	0	1	1	0	0	0	0	8	0	0	0	**16**
-1 to 1	0	4	9	0	3	0	8	2	0	0	15	0	0	0	**41**
1.1 to 3	0	5	2	0	1	0	4	5	0	0	12	0	0	0	**29**
3.1 to 7	0	2	0	0	0	0	1	1	0	0	6	0	0	0	**10**
> 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**

Note: the shades of yellow highlighting serve to illustrate the distribution of maintenance events by state. The strongest shade of yellow indicates where the highest concentration maintenance events occurred.

6.1.2 AC SHOULDER RESTORATION

Table 9 shows AC shoulder restoration was used significantly in North Dakota. Typically, shoulder restoration was performed on all test sections throughout the project. AC shoulder restoration was performed 6 times on North Dakota test sections throughout its monitoring period. Iowa and Ohio test sections also had 1 multi-section application of AC shoulder restoration. There was no indication that shoulder restoration had an apparent impact on roughness. As with lane-shoulder longitudinal sealing, this result was expected because shoulders are not tied and offer no structural advantage to the travel lane.

Table 9.Change in MRI Deterioration Immediately After AC Shoulder Restoration

Average Change in MRI Deterioration (inch/mile/year)	**Count of Maintenance Event per Project**														
	AZ	AR	CA	CO	DE	IA	KS	MI	NV	NC	ND	OH	WA	WI	**TOTAL**
< -7	0	0	0	0	0	1	0	0	0	0	2	1	0	0	**4**
-7 to -3.1	0	0	0	0	0	0	0	0	0	0	8	0	0	0	**8**
-3 to -1.1	0	0	0	0	0	1	0	1	0	0	14	1	0	0	**17**
-1 to 1	0	0	0	0	0	7	0	1	0	0	19	5	0	0	**32**
1.1 to 3	0	0	0	0	0	1	0	0	0	0	17	1	0	0	**19**
3.1 to 7	0	0	0	0	0	3	0	0	0	0	11	2	0	0	**16**
> 7	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**1**

Note: the shades of yellow highlighting serve to illustrate the distribution of maintenance events by state. The strongest shade of yellow indicates where the highest concentration maintenance events occurred.

6.1.3 PARTIAL-DEPTH PATCHING AT JOINTS

In most states, partial-depth patching at the joints had no meaningful impact on the roughness deterioration rate. In Table 10, several North Dakota test sections showed a slight increase in roughness deterioration after partial-depth patching, but there was no change relative to the overall section deterioration rate.

Table 10. Change in MRI Deterioration Immediately After Partial-Depth Patching at Joints

Average Change in MRI Deterioration (inch/mile/year)	**Count of Maintenance Event per Project**														
	AZ	AR	CA	CO	DE	IA	KS	MI	NV	NC	ND	OH	WA	WI	**TOTAL**
< -7	0	0	0	2	0	1	0	0	0	0	0	0	0	0	**3**
-7 to -3.1	3	0	0	3	0	0	0	1	0	0	3	0	0	0	**10**
-3 to -1.1	2	2	0	3	1	0	1	2	1	0	2	0	0	0	**14**
-1 to 1	4	1	1	4	0	1	2	1	1	2	4	0	1	0	**22**
1.1 to 3	1	0	1	3	0	1	1	2	0	0	9	0	0	0	**18**
3.1 to 7	1	1	0	5	1	2	2	0	1	0	2	0	0	0	**15**
> 7	0	1	0	3	0	0	1	0	1	0	0	0	0	0	**6**

Note: the shades of yellow highlighting serve to illustrate the distribution of maintenance events by state. The strongest shade of yellow indicates where the highest concentration maintenance events occurred.

6.1.4 TRANSVERSE JOINT SEALING

Table 11 shows the change in MRI deterioration after transverse joint sealing. While transverse joint sealing of test sections in Kansas and North Dakota resulted in a slight increase in MRI deterioration, the resulting deterioration was not significantly different from the overall deterioration rate of the test sections. This result was expected because transverse joint resealing is designed to prevent long-term damage to pavements by preventing the intrusion of water and debris into the pavement joint. Water infiltration can be the root mechanism in a variety of distresses that could lead to pavement failure. Therefore, while transverse joint sealing can extend pavement life, the immediate effect on the roughness deterioration rate would not be clearly apparent.

Table 11. Change in MRI Deterioration Immediately After Transverse Joint Sealing

Average Change in MRI Deterioration (inch/mile/year)	Count of Maintenance Event per Project														
	AZ	AR	CA	CO	DE	IA	KS	MI	NV	NC	ND	OH	WA	WI	**TOTAL**
< -7	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**1**
-7 to -3.1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	**2**
-3 to -1.1	0	2	1	0	0	1	0	0	0	0	2	0	0	0	**6**
-1 to 1	0	1	7	0	1	0	8	1	0	0	3	0	0	0	**21**
1.1 to 3	0	1	1	0	1	0	4	0	0	0	2	0	0	0	**9**
3.1 to 7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**1**
≥ 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**

Note: the shades of yellow highlighting serve to illustrate the distribution of maintenance events by state. The strongest shade of yellow indicates where the highest concentration maintenance events occurred.

6.1.5 PARTIAL-DEPTH PATCHING OTHER THAN AT JOINT

Table 12 shows the impact on MRI deterioration of partial-depth patching at locations other than joins. The results varied significantly across test sections on the same project. Some test sections decreased in MRI deterioration while others increased. The frequency of partial-depth patching events in Table 12 does not express the extent of patching performed; therefore, the immediate impact from section to section would vary. For example, Figure 29 shows Arkansas 050213 had an increase in MRI deterioration after partial-depth patching in 2003, but then showed significant decrease in MRI deterioration after partial-depth patching in 2006. However, the amount of patching performed in 2006 was 50 times more by area than the patching performed in 2003. Without this context, the two patching events in Arkansas would appear to be unrelated to the dramatic change in MRI deterioration. In effect, the extensive patching in 2006 improved MRI. While the negligible amount of patching in 2003 was not sufficient to deter the continued MRI deterioration.

Table 12. Change in MRI Deterioration Immediately After Partial-Depth Patching Other Than at Joint

Average Change in MRI Deterioration (inch/mile/year)	Count of Maintenance Event per Project														
	AZ	AR	CA	CO	DE	IA	KS	MI	NV	NC	ND	OH	WA	WI	**TOTAL**
< -7	0	1	0	1	0	0	0	0	2	0	0	0	0	0	**4**
-7 to -3.1	2	0	0	0	0	0	0	0	1	0	1	0	0	0	**4**
-3 to -1.1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	**2**
-1 to 1	4	0	1	0	1	1	0	0	0	0	0	0	3	0	**10**
1.1 to 3	1	0	1	1	1	0	0	0	0	0	2	0	1	0	**7**
3.1 to 7	0	0	1	1	1	1	0	0	2	0	0	1	0	0	**7**
> 7	1	1	0	0	0	0	0	0	1	0	0	0	0	0	**3**

Note: the shades of yellow highlighting serve to illustrate the distribution of maintenance events by state. The strongest shade of yellow indicates where the highest concentration maintenance events occurred.

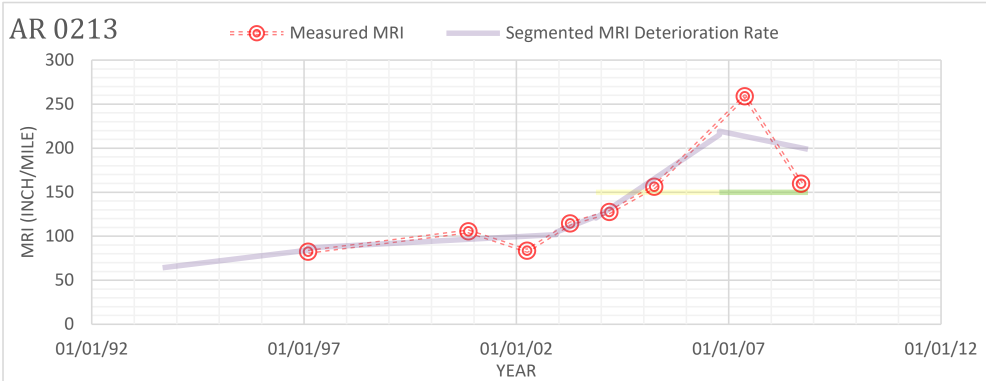

Figure 29.MRI Deterioration Rates After Patching Was Performed in 2003 and 2006.

6.1.6 CRACK SEALING

Table 13 shows the impact of crack sealing on MRI deterioration. In Nevada, there were a few cases where crack sealing decreased the deterioration rate, but these decreases were not significant compared to the overall MRI deterioration rate of the test section. Furthermore, Nevada is an outlier, since some test sections deteriorated quickly and were placed out-of-study within a few years. Nevada 320202, for example, apparently showed a decrease in MRI deterioration by 10 inches/mile/year after cracking sealing 1997, but this assessment is questionable as there were not enough MRI measurement data points to properly interpolate MRI deterioration throughout the 4-year monitoring period of 320202. Essentially, Nevada 320202 is an early failure outlier that lacks sufficient time-series roughness measurements to accurately assess an impact on roughness. However, Nevada subgrade was found to be inadequate and needed to be stabilized with lime before construction. It may be possible that crack-sealing slightly slowed the rapidly declining performance.

Crack sealing is fundamentally a preventative maintenance activity to prevent further infiltration by water and debris. The seal does not provide any structural benefit and typically would not affect MRI.

Table 13. Change in MRI Deterioration Immediately After Crack Sealing

Average Change in MRI Deterioration (inch/mile/year)	**Count of Maintenance Event per Project**														
	AZ	AR	CA	CO	DE	IA	KS	MI	NV	NC	ND	OH	WA	WI	**TOTAL**
< -7	0	0	0	0	0	0	0	0	4	0	0	0	0	0	**4**
-7 to -3.1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	**2**
-3 to -1.1	0	1	1	0	1	0	0	0	1	0	0	0	0	0	**4**
-1 to 1	0	0	2	0	0	1	0	0	2	0	0	0	0	0	**5**
1.1 to 3	0	0	0	0	1	0	0	0	1	0	2	0	0	0	**4**
3.1 to 7	0	0	0	0	0	0	0	0	2	0	1	0	0	0	**3**
> 7	0	2	0	0	0	0	0	0	2	0	0	0	0	0	**4**

Note: the shades of yellow highlighting serve to illustrate the distribution of maintenance events by state. The strongest shade of yellow indicates where the highest concentration maintenance events occurred.

6.1.7 FULL-DEPTH TRANSVERSE JOINT REPAIR PATCH

Table 14 shows impact of transverse joint repair on MRI deterioration. Full-depth transverse joint repair is patching located at the transverse joint, but does not necessarily include the entire joint. Ohio was the only project where some significant change in deterioration could be observed, but this change in deterioration was more negative than positive.

Table 14. Change in MRI Deterioration Immediately After Full-Depth Transverse Joint Repair Patch

Average Change in MRI Deterioration (inch/mile/year)	**Count of Maintenance Event per Project**														
	AZ	AR	CA	CO	DE	IA	KS	MI	NV	NC	ND	OH	WA	WI	**TOTAL**
< -7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
-7 to -3.1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	**1**
-3 to -1.1	0	0	0	0	0	0	1	0	0	0	1	1	0	0	**3**
-1 to 1	0	0	0	0	3	0	6	0	0	0	0	0	0	0	**9**
1.1 to 3	0	0	0	0	1	0	0	0	0	0	2	2	0	0	**5**
3.1 to 7	0	0	0	0	1	0	0	0	0	0	1	4	0	0	**6**
> 7	0	0	0	0	0	0	1	0	0	0	1	1	0	0	**3**

Note: the shades of yellow highlighting serve to illustrate the distribution of maintenance events by state. The strongest shade of yellow indicates where the highest concentration maintenance events occurred.

6.1.8 PCC SLAB REPLACEMENT

Table 15 shows there are a few cases – especially in Iowa, Kansas, and Ohio – where PCC slab replacement resulted in a decrease in MRI deterioration rate. Frequently, PCC slab replacement is performed in conjunction with other maintenance strategies, such as partial- and full-depth patching. Typically, the decrease in MRI deterioration occurred in test sections where there was a substantial amount of slab replacement or patching. Therefore, extensive slab replacement had the effect of reducing MRI by essentially replacing the rougher and more damaged slabs with new slabs.

Table 15. Change in MRI Deterioration Immediately After PCC Slab Replacement

Average Change in MRI Deterioration (inch/mile/year)	**Count of Maintenance Event per Project**														
	AZ	AR	CA	CO	DE	IA	KS	MI	NV	NC	ND	OH	WA	WI	**TOTAL**
< -7	0	0	0	0	0	2	1	0	0	0	0	1	0	0	**4**
-7 to -3.1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	**1**
-3 to -1.1	0	0	0	0	0	1	0	0	0	0	0	3	0	1	**5**
-1 to 1	0	0	0	0	1	1	1	0	0	0	0	2	0	0	**5**
1.1 to 3	0	0	0	0	0	0	1	0	0	0	1	0	0	0	**2**
3.1 to 7	0	0	0	0	0	0	1	1	0	0	1	1	0	0	**4**
> 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**

Note: the shades of yellow highlighting serve to illustrate the distribution of maintenance events by state. The strongest shade of yellow indicates where the highest concentration maintenance events occurred.

6.1.9 FULL-DEPTH PATCHING OTHER THAN AT JOINT

Table 16 shows the impact of full-depth patching (not at the joint) on MRI deterioration. In Kansas, this technique did not typically have an impact on MRI deterioration for test sections. Typically, patching did not have an impact on MRI deterioration rate unless a significant area of the pavement surface had been patched or replaced. For example, Ohio 390208 is an example of a test section where a significant amount of patching resulted in a decrease in the MRI deterioration rate.

Table 16. Change in MRI Deterioration Immediately After Full-Depth Patching Other Than at Joint

Average Change in MRI Deterioration (inch/mile/year)	**Count of Maintenance Event per Project**														
	AZ	AR	CA	CO	DE	IA	KS	MI	NV	NC	ND	OH	WA	WI	**TOTAL**
< -7	0	0	0	0	0	0	0	0	0	0	0	1	0	0	**1**
-7 to -3.1	0	0	0	0	0	0	0	0	2	0	0	1	0	0	**3**
-3 to -1.1	0	0	0	0	0	1	1	0	1	0	0	1	0	0	**4**
-1 to 1	0	0	0	0	0	0	4	0	0	0	0	0	0	0	**4**
1.1 to 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3.1 to 7	0	0	0	0	0	0	0	0	0	0	1	2	0	0	**3**
> 7	0	0	0	0	0	0	1	0	1	0	0	1	0	0	**3**

Note: the shades of yellow highlighting serve to illustrate the distribution of maintenance events by state. The strongest shade of yellow indicates where the highest concentration maintenance events occurred.

6.1.10 SKIN PATCHING

Skin patching was mostly used on Delaware and Iowa test sections. Typically, MRI deterioration did not consistently decrease after skin patching. Table 17 shows that some sections showed a minor decrease in these projects, but in just as many test sections, the deterioration continued to increase or stayed the same. Coincidentally, all these applications of skin patching were completed around 2014. Therefore, all test sections were nearly 20 years old at the time of treatment and skin patching may not have had significant impact. Based the available profile measurements, Section 380217 in North Dakota and Sections 190216 and 190220 in Iowa showed a slight decrease in MRI deterioration after skin patching.

Table 17. Change in MRI Deterioration Immediately After Skin Patching

Average Change in MRI Deterioration (inch/mile/year)	Count of Maintenance Event per Project														
	AZ	AR	CA	CO	DE	IA	KS	MI	NV	NC	ND	OH	WA	WI	**TOTAL**
< -7	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**1**
-7 to -3.1	0	0	0	0	1	2	0	0	0	0	0	0	0	0	**3**
-3 to -1.1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	**2**
-1 to 1	0	0	0	0	1	2	0	0	0	0	1	0	0	0	**4**
1.1 to 3	0	0	0	0	3	0	0	0	0	0	0	0	0	0	**3**
3.1 to 7	0	0	0	0	3	0	0	0	0	0	0	0	0	0	**3**
> 7	0	0	0	0	0	1	0	0	0	0	0	0	0	0	**1**

Note: the shades of yellow highlighting serve to illustrate the distribution of maintenance events by state. The strongest shade of yellow indicates where the highest concentration maintenance events occurred.

6.2 Findings

It is common knowledge and a standard of practice that maintenance events increase the life span of pavements and improve their ride quality. The long-term effects that maintenance has on roughness were difficult to assess. Maintenance treatments are expected to add service life to the pavement. However, the question of how much service life is added cannot be answered without a one-to-one comparison of test sections in similar conditions, both with and without regular maintenance. For example, while transverse joint sealing did not have an immediate impact on roughness according to MRI, the long-term effects that it may have had by preventing water infiltration were likely very significant.

Among all the maintenance activities performed on SPS-2 project during the LTPP study, most test sections showed very little correlation between a maintenance event and a subsequent 'immediate' decrease in MRI deterioration. As stated previously, a preventive maintenance treatment (preservation) would not levy an immediate change in MRI deterioration. Preservation treatments are intended to extend the service of the pavements in the long-term. However, MRI deterioration can only be assessed for the period from after the maintenance event until just prior to next event or until the end of the monitoring period. For sections that received maintenance toward the end of the monitoring period or were frequently revisited with routine maintenance, a significant span of years would not be available to assess long-term MRI deterioration.

When a decrease in MRI deterioration was observed, it was most commonly associated with test sections that received corrective treatments such as full slab replacement or extensive patching. Other maintenance treatments typically had no immediate effect on the MRI deterioration rate. If maintenance had some short-term effect on roughness, the significance of this improvement was not very sensitive in terms of the relative change in the MRI deterioration rate.

A final consideration is that some of these maintenance events are intended to repair rather than preserve the pavement. This implies that the test sections receiving a repair may be in worse condition than pavements receiving preservation treatment. This would not be unusual for many of the SPS-2 sections, which were purposefully constructed using relatively thin concrete layers (8-inch), relatively low-strength concrete (flexural strength of 550 psi), and on dense-graded aggregate base. Therefore, having test sections that continue to deteriorate after receiving a maintenance treatment would not be unusual if the pavement was in advanced stages of structural failure.

7.0 SUMMARY OF FINDINGS

In general, all project-specific factors (traffic, climate, distress, and maintenance) likely have some effect on pavement performance to varying extents. However, the compounding of several factors and, in some cases, the limitations in the available data, made the evaluation of the contributing impact of each project-specific design factor unfeasible.

Traffic was found to be the most influential project-specific factor. Although Nevada, Michigan, and Ohio were outliers, states with higher traffic loading deteriorated faster and states with less traffic loading were slower to deteriorate. The extent and type of deterioration often varied, but in terms of MRI and PCS, Arkansas, California, and Arizona had relatively high amounts of traffic and high deterioration rates. Wisconsin and Delaware, with minimal traffic loading, typically had lower deterioration rates for MRI and PCS. States in the medium traffic category likewise had relatively moderate MRI and PCS deterioration.

Climate was the most difficult of the design factors to evaluate. Based on the general trend, non-freeze climates deteriorated faster than freeze climates and dry climates deteriorated faster than wet climates. However, this trend was biased by the fact the sites with heavy traffic loading (Arkansas, California, and Arizona) were all in non-freeze climates and sites with minimal traffic loading (Wisconsin and Delaware) were all in wet climates. However, this observation still holds when looking exclusively at sites with only moderate amounts of traffic loading.

The impact of the overall condition of the pavement (in terms of distress and preservation treatments) on pavement performance was also difficult to assess due to the lack of both availability and consistency in test sections meeting specific conditions. In general, most SPS-2 test sections performed well, which limited the sample size of distressed test sections to evaluate. While some distresses were more common than others and could provide a large enough sample size for data analysis, it was also common that significantly distressed pavement had overlapping types of distress. Additionally, distresses should be compared in conjunction with maintenance and preservation treatments. Adding to the compounding complexity were other project-specific considerations such climate, traffic, and agency maintenance and preservation practices, as well as construction materials and practices.

The common thread between the distress and maintenance analyses was that pavement performance, in terms of MRI, was immediately affected by the presence of potholes or the extensive repair of potholes. Longitudinal and transverse cracking also immediately caused MRI to increase. Distresses that are typically considered to impact the functionality or cosmetics of the roadway – such as scaling, polishing, and map cracking – did not have a consistent impact on MRI. The analysis was unable to identify if D-cracking (typically considered to have structural impact) influenced MRI because it was uncommon on SPS-2 test sections.

As stated earlier, the impact of maintenance events on MRI is difficult to separate from other considerations. Foremost are the maintenance and preservation practices of the agency relative to condition of the pavement at time of maintenance. Not all test sections that needed maintenance received it and not all test sections that received maintenance were in need of it.

Maintenance and preservation treatments can be test section-specific or project-wide. The timing of treatments may be reactive to distress or based on a schedule. In this arena, the highest amount of variability comes from the differences between the agencies decision-making processes.

All in all, large-scale maintenance, such as extensive slab replacement or patching, were found to improve MRI. Other maintenance and preservation activities did not show an immediate impact on MRI. However, the long-term impact of such activities could not be assessed as there was no reference point for future performance to use for comparison. Moreover, it was not the goal of this study to determine the long-term benefit of preservation treatments, but how maintenance may have affected the current performance of SPS-2 test sections.

Appendix A

PEAK MRI DETERIORATION AND TRAFFIC GROWTH BY TEST SECTION

SHRP ID	Period of Peak MRI Growth	Peak MRI Growth (inch/mile/year)	Traffic Growth during Peak MRI Growth	Traffic Growth prior to Peak MRI Growth	Percent Change in Traffic Growth (%)
040213	2004-2005	29.7	183860	182150	1
040214	2004-2005	9.1	183860	182150	1
040215	2004-2005	52.9	183860	182150	1
040216	2004-2005	11.2	183860	182150	1
040217	2004-2005	16.7	183860	182150	1
040218	2004-2005	10.5	183860	182150	1
040219	2004-2005	23.0	183860	182150	1
040220	2004-2005	10.3	183860	182150	1
040221	2004-2005	17.4	183860	182150	1
040222	2004-2005	10.0	183860	182150	1
040223	2004-2005	20.4	183860	182150	1
040224	2004-2005	8.5	183860	182150	1
040262	2004-2005	37.7	183860	182150	1
040263	2004-2005	16.7	183860	182150	1
040264	2004-2005	22.6	183860	182150	1
040265	2004-2005	25.8	183860	182150	1
040266	2004-2005	20.2	183860	182150	1
040267	2004-2005	15.4	183860	182150	1
040268	2004-2005	18.1	183860	182150	1
050213	2005-2006	54.5	156807	8591	1725
050214	2011-2012	26.7	21559	-142210	115
050215	2011-2012	21.5	21559	-142210	115
050216	2005-2006	22.0	156807	8591	1725
050217	2005-2006	29.0	156807	8591	1725
050218	2005-2006	13.7	156807	8591	1725
050219	2011-2012	14.4	21559	-142210	115
050220	2005-2006	19.9	156807	8591	1725
050221	2007-2008	16.1	-22557	65089	-135
050222	2005-2006	15.2	156807	8591	1725
050223	2007-2008	11.5	-22557	65089	-135
050224	2005-2006	13.6	156807	8591	1725
060201	2015-2016	32.8	120700	-22000	649
060203	2004-2005	11.0	52013	0	-
060205	2004-2005	9.8	52013	0	-
060206	2004-2005	10.5	52013	0	-
060207	2004-2005	10.6	52013	0	-
060209	2004-2005	13.1	52013	0	-
060210	2002-2003	6.4	43435	58400	-26
060211	2004-2005	15.5	52013	0	-
060212	2004-2005	4.7	52013	0	-
080213	2000-2001	4.5	27942	-1650	1794

SHRP ID	Period of Peak MRI Growth	Peak MRI Growth (inch/mile/year)	Traffic Growth during Peak MRI Growth	Traffic Growth prior to Peak MRI Growth	Percent Change in Traffic Growth (%)
080214	2010-2011	5.4	29609	-6204	577
080215	2006-2007	7.3	24379	19635	24
080216	2006-2007	6.9	24379	19635	24
080217	2007-2008	9.0	-6204	19634	-132
080218	2004-2005	6.5	19634	19634	0
080219	2004-2005	3.2	19634	19634	0
080220	2004-2005	5.5	19634	19634	0
080221	2004-2005	4.0	19634	19634	0
080222	2004-2005	5.0	19634	19634	0
080223	2004-2005	8.4	19634	19634	0
080224	2004-2005	3.8	19634	19634	0
080259	2004-2005	7.2	19634	19634	0
100201	1998-1999	30.4	8760	1460	500
100202	1998-1999	19.4	8760	1460	500
100203	1998-1999	16.4	8760	1460	500
100204	1998-1999	26.5	8760	1460	500
100205	1998-1999	25.5	8760	1460	500
100206	1998-1999	21.7	8760	1460	500
100207	1998-1999	19.1	8760	1460	500
100208	1998-1999	28.6	8760	1460	500
100209	1998-1999	16.6	8760	1460	500
100210	1998-1999	19.6	8760	1460	500
100211	1998-1999	16.6	8760	1460	500
100212	1998-1999	28.5	8760	1460	500
100259	1998-1999	22.4	8760	1460	500
100260	1998-1999	25.0	8760	1460	500
190213	2009-2010	7.7	9989	12240	-18
190214	2014-2015	14.5	24127	6356	280
190216	2014-2015	13.4	24127	6356	280
190217	2009-2010	17.8	9989	12240	-18
190218	2014-2015	16.5	24127	6356	280
190220	2015-2016	17.4	4813	15448	-69
190221	2009-2010	10.6	9989	12240	-18
190223	2009-2010	8.9	9989	12240	-18
190259	2009-2010	8.6	9989	12240	-18
200201	1999-2000	17.2	5658	35953	-84
200202	2000-2001	7.2	34128	21353	60
200203	2004-2005	11.4	13688	12775	7
200204	1996-1997	8.9	35953	27513	31
200205	2004-2005	16.8	13688	12775	7
200206	2004-2005	16.1	13688	12775	7

SHRP ID	Period of Peak MRI Growth	Peak MRI Growth (inch/mile/year)	Traffic Growth during Peak MRI Growth	Traffic Growth prior to Peak MRI Growth	Percent Change in Traffic Growth (%)
200207	2004-2005	17.1	13688	12775	7
200208	1999-2000	13.3	5658	35953	-84
200209	1999-2000	8.1	5658	35953	-84
200210	1999-2000	9.9	5658	35953	-84
200211	1999-2000	9.9	5658	35953	-84
200212	1999-2000	11.6	5658	35953	-84
200259	2004-2005	10.1	13688	12775	7
260213	1999-2000	103.0	-23073	105998	-122
260214	2003-2004	109.1	5044	11583	-57
260215	2000-2001	237.4	11583	84452	-86
260216	2006-2007	23.1	-21279	5044	-522
260217	1999-2000	89.2	-23073	105998	-122
260218	1997-1998	140.7	84452	55772	51
260219	1996-1997	14.1	105998	112346	-6
260220	2006-2007	21.6	-21279	5044	-522
260221	1996-1997	10.6	105998	112346	-6
260222	2005-2006	14.0	-17982	-849	-2018
260223	1996-1997	9.0	105998	112346	-6
260224	1996-1997	10.8	105998	112346	-6
260259	1996-1997	11.6	105998	112346	-6
320201	2002-2003	24.3	16151	15496	4
320202	1997-1998	86.4	42821	81161	-47
320203	1997-1998	9.4	42821	81161	-47
320204	1997-1998	44.3	42821	81161	-47
320205	1997-1998	11.0	42821	81161	-47
320206	1997-1998	33.1	42821	81161	-47
320207	1997-1998	13.7	42821	81161	-47
320208	1997-1998	7.8	42821	81161	-47
320209	1997-1998	11.8	42821	81161	-47
320210	1997-1998	12.8	42821	81161	-47
320211	1997-1998	13.7	42821	81161	-47
320259	1997-1998	13.4	42821	81161	-47
370201	2003-2004	55.5	-15289	14674	-204
370202	2003-2004	53.8	-15289	14674	-204
370203	2015-2016	46.6	32850	21900	50
370204	2015-2016	48.7	32850	21900	50
370205	2003-2004	69.0	-15289	14674	-204
370206	2003-2004	56.7	-15289	14674	-204
370207	2015-2016	38.0	32850	21900	50
370208	2015-2016	40.8	32850	21900	50
370209	2003-2004	53.0	-15289	14674	-204

SHRP ID	Period of Peak MRI Growth	Peak MRI Growth (inch/mile/year)	Traffic Growth during Peak MRI Growth	Traffic Growth prior to Peak MRI Growth	Percent Change in Traffic Growth (%)
370210	2003-2004	65.9	-15289	14674	-204
370211	2015-2016	29.4	32850	21900	50
370212	2015-2016	21.8	32850	21900	50
370259	2015-2016	33.5	32850	21900	50
370260	2015-2016	36.4	32850	21900	50
380213	2012-2013	8.9	25490	25490	0
380214	2012-2013	10.0	25490	25490	0
380215	2015-2016	11.4	25490	25490	0
380216	2012-2013	12.3	25490	25490	0
380217	2012-2013	17.0	25490	25490	0
380218	2013-2014	30.6	25490	25490	0
380219	2015-2016	11.3	25490	25490	0
380220	2012-2013	7.1	25490	25490	0
380221	2015-2016	10.4	25490	25490	0
380222	2015-2016	5.9	25490	25490	0
380223	2015-2016	10.9	25490	25490	0
380224	2012-2013	6.4	25490	25490	0
380259	2003-2004	11.1	3650	20440	-82
380260	2012-2013	12.2	25490	25490	0
380261	2015-2016	18.3	25490	25490	0
380262	2012-2013	10.1	25490	25490	0
380263	2015-2016	7.3	25490	25490	0
380264	2012-2013	8.1	25490	25490	0
390201	2004-2005	15.4	28714	-19097	250
390202	2004-2005	15.3	28714	-19097	250
390203	2014-2015	11.7	28521	-14347	299
390204	1998-1999	8.8	49401	-39931	224
390205	2004-2005	24.7	28714	-19097	250
390206	2004-2005	19.2	28714	-19097	250
390207	2012-2013	16.8	6898	-73636	109
390208	2014-2015	30.2	28521	-14347	299
390209	2012-2013	19.6	6898	-73636	109
390210	2003-2004	11.0	50797	-67099	176
390211	2014-2015	13.7	28521	-14347	299
390212	2014-2015	27.7	28521	-14347	299
390259	2005-2006	18.4	-34834	64319	-154
390260	2014-2015	11.3	28521	-14347	299
390261	2014-2015	11.2	28521	-14347	299
390262	2014-2015	15.6	28521	-14347	299
390263	2014-2015	12.6	28521	-14347	299
390264	2005-2006	16.0	-34834	64319	-154

SHRP ID	Period of Peak MRI Growth	Peak MRI Growth (inch/mile/year)	Traffic Growth during Peak MRI Growth	Traffic Growth prior to Peak MRI Growth	Percent Change in Traffic Growth (%)
390265	2014-2015	15.0	28521	-14347	299
530201	2013-2014	10.3	-14776	17331	-185
530202	2011-2012	5.4	8114	-7360	210
530203	2011-2012	10.1	8114	-7360	210
530204	2011-2012	8.2	8114	-7360	210
530205	2013-2014	9.1	-14776	17331	-185
530206	1998-1999	18.5	10938	-62050	118
530207	2013-2014	11.2	-14776	17331	-185
530208	1998-1999	10.7	10938	-62050	118
530209	2013-2014	10.3	-14776	17331	-185
530210	2004-2005	6.0	26574	7075	276
530210	2013-2014	6.0	-14776	17331	-185
530211	2013-2014	8.0	-14776	17331	-185
530212	2013-2014	6.0	-14776	17331	-185
530259	2011-2012	9.8	8114	-7360	210
550213	1999-2000	13.2	13006	-	-
550214	1999-2000	10.5	13006	-	-
550215	1999-2000	8.8	13006	-	-
550216	1999-2000	9.4	13006	-	-
550217	2002-2003	4.3	9490	13006	-27
550218	2002-2003	4.9	9490	13006	-27
550219	1999-2000	7.3	13006	-	-
550220	1999-2000	7.4	13006	-	-
550221	1999-2000	9.2	13006	-	-
550222	1999-2000	9.7	13006	-	-
550223	1999-2000	7.8	13006	-	-
550224	1999-2000	7.6	13006	-	-
550259	1999-2000	10.1	13006	-	-
550260	1999-2000	16.0	13006	-	-
550261	2002-2003	8.0	9490	13006	-27
550262	1999-2000	10.4	13006	-	-
550263	1999-2000	5.7	13006	-	-
550264	1999-2000	10.5	13006	-	-
550265	1999-2000	11.2	13006	-	-
550266	2001-2002	12.6	-5219	25742	-120

Appendix B

GRAPHS OF MRI, DISTRESS, AND TRAFFIC BY TEST SECTION