NCHRP 20-24(37B)

Comparative Performance Measurement: Pavement Smoothness

Requested by:

American Association of State Highway
and Transportation Officials (AASHTO)

Prepared by:

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May 18, 2008

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LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AGC	Associated General Contractors of America
ASCE	American Society of Civil Engineers
CRC	Continually Reinforced Concrete
DOT	Department of Transportation
DMI	Distance Measurement Instrument
FHWA	Federal Highway Administration
FIPS	Federal Information Processing Standards
GAO	Government Accountability Office
GPS	Global Positioning System
GRIP	Governor Richardson's Investment Partnership
HMA	Hot-Mix Asphalt
HPMS	Highway Performance Monitoring System
HRI	Half car Roughness Index
IRI	International Roughness Index
LTPP	Long-Term Pavement Performance
MEPDG	Mechanistic Empirical Pavement Design Guide
MRI	Mean Roughness Index
NHS	National Highway System
NCHRP	National Cooperative Highway Research Program
PCC	Portland Cement Concrete
PI	Profile Index
PSD	Power Spectral Density
QA/QC	Quality Assurance/Quality Control
SCOQ	Standing Committee on Quality
SPS	Specific Pavement Studies

1. EXECUTIVE SUMMARY

COMPARATIVE PERFORMANCE MEASUREMENT FOR PAVEMENT SMOOTHNESS

Today's transportation agencies need to find ways to improve service and demonstrate tangible results for their customers – while operating under increasingly tight resource constraints. Comparative performance measurement is a potentially powerful technique for motivating and facilitating changes that result in improved performance. It motivates organizations to pursue improvements by showing them what their peers have been able to achieve. It facilitates improvement by identifying specific best practices that have led to good results. Establishing comparable measures can take considerable effort, but pays off when participating organizations learn from practices employed by their peers to improve their own performance. Comparative performance measurement efforts also have the important effect of shining a spotlight on current approaches to how data is tracked, how performance is being measured and how results are being used. Participating agencies have an opportunity to examine the consistency and accuracy of their measurement practices, learn about differences in measurement across agencies, and work towards a greater degree of commonality.

This report presents results of the second in a series of comparative performance measurement efforts sponsored by the American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on Quality (SCOQ), Performance Measurement and Benchmarking Subcommittee. The purpose of these efforts is to identify states that have achieved exemplary performance, find out what practices have contributed to their success, and document these practices for the benefit of other states. This effort focuses on pavement smoothness, and was co-sponsored by the AASHTO Standing Committee on Planning (SCOP) Subcommittee on Transportation Asset Management.

Pavement smoothness is an important performance measure for all states – travelers and shippers place high value on it, and several studies (Sime, 2000; Parera, 2002) have concluded that smooth pavement reduces vehicle operating costs. Because of the Federal Highway Administration's (FHWA) Highway Performance Monitoring System (HPMS) requirements, all states collect and report International Roughness Index (IRI) data for their National Highway System (NHS) roads. Planned changes to HPMS will encourage greater accuracy and consistency in measurement and reporting of IRI. The importance of this measure to states and the availability of relatively consistent data across agencies made pavement smoothness a good candidate for comparative performance measurement.

ANALYSIS OF PAVEMENT DATA PROVIDED BY 32 STATES

There was strong interest in this effort - SCOQ enlisted participation from 32 states. Each state provided two years of IRI data covering their Interstate highway networks, and completed a survey describing their IRI measurement and reporting methods. While several hurdles related to data consistency had to be addressed, a rich dataset was assembled that allows for comparisons of IRI across states by climate zone, pavement type and functional class (urban vs. rural interstate.) This dataset consists of over 1.2 million records of short (primarily .1 mile) highway sections. Assembling data for sections of uniform length made it possible to produce distributions of system length by IRI value. These distributions provided insights beyond what would have been possible through examination of average network IRI.

It should be noted that the analysis conducted within this project was performed with the understanding that current variations in IRI measurement practice make precise comparisons of IRI across states (or even across survey efforts within a state) difficult. It was assumed that measurement error on the order of 15% exists. That said, results showed substantial variation in pavement smoothness within the group of 32 states. Average length-weighted IRI ranged from 49 to 143 in/mile. The percentage of very smooth pavements (< 40 in/mi) ranged from 43% to less than 1%.

IDENTIFICATION OF HIGH PERFORMING STATES

Based on ranking of states within peer groups, twelve states were identified as high performers with respect to pavement smoothness. A notable finding from this ranking exercise was that the states ranked highest for rigid pavements were often different from those ranked highest for flexible pavements. Similarly, states that were ranked highest for their urban pavements weren't necessarily the top performers for rural pavements. Five states were selected out of the twelve for detailed interviews; the remaining seven states were asked to provide supplemental information about their practices.

PRACTICES CONTRIBUTING TO SMOOTH PAVEMENTS

The major conclusion from the investigation of the practices used by top performing states is that achieving pavement smoothness does not just happen; it requires a clear focus by the agency, and policies and programs that support that focus. Most of the practices identified were related to achievement of *initial smoothness* for newly constructed pavements, with the major themes being (1) use of end result ride specifications with financial incentives for good performance and (2) establishment of close working relationships with the contractor community. However, one top performing state had achieved results through a sustained pavement management program; another state had undertaken a smooth roads initiative involving management focus, commitment of resources, and public involvement.

Five agency practices and four contractor practices were identified as valuable for achievement of smooth pavements.

Agency Practices

Agency Practice #1: Strong Performance Management Orientation

Underlying the success of several of the top performing agencies was a strong performance management program including network-level pavement smoothness targets and deliberate investments, policies and programs aligned with those targets. Establishment of network-wide pavement condition performance targets was important to provide a focus for improvement efforts within pavement construction and maintenance programs and a basis for funding requests. Utilizing pavement smoothness as one of the factors for triggering maintenance or rehabilitation projects is one mechanism for providing alignment between performance targets and programs.

Agency Practice # 2: Use End Result Pavement Construction Specifications with Incentive Bonuses

High-performing agencies attributed much of their success to use of end-result ride specifications. These specifications do not prescribe specific construction methods, but rather put responsibility on contractors to achieve target performance levels, providing them with the flexibility to decide how to meet these targets. In some cases, incentive bonuses are used to gain contractor acceptance for end result specifications and provide motivation for improving practice. Some agencies set performance targets initially at values slightly smoother than what was currently being constructed, and then periodically tighten them as practice improves.

Agency Practice #3: Build Close Working Relationships with Paving Contractors

Establishment of close partnerships with contractors was cited by the high performing agencies as important to achievement of good results. These partnerships included involvement of contractors in task forces to set end-result pavement construction specification performance targets, holding pre-construction kickoff meetings to provide “just-in-time” training prior to construction as well as scheduling periodic sessions to address pavement quality issues or jointly identify opportunities to enhance smoothness. Some agencies conducted education and outreach programs that were jointly attended by agency inspectors, construction supervisors, and crew members. Some established recognition programs, with annual smooth pavement awards for the contracting community.

Agency Practice # 4: Integrate Customer Input

One high performing state involved the public in order to gage acceptable levels of pavement roughness. This input was used to strengthen the basis for pavement smoothness target setting.

Agency Practice #5: Pavement Management

One high performing state emphasized the importance of a sustained commitment to investment in strong pavement bases, preventive maintenance, and rehabilitation of pavements well before they become noticeably rough. These good pavement management practices lead both to smooth pavements and lower life cycle costs.

Contractor Practices

Contractor Practice #1: Materials, Placement and Finishing Techniques

Materials selection, materials placement and finishing techniques that contribute to achievement of smooth asphalt pavements include use of polymer or rubber-modified Hot Mix Asphalt (HMA) mixes, and minimizing mix segregation. For PCC pavements, techniques included minimizing hand finishing and timely application of the curing compound and joint sawing.

Contractor Practice #2: Equipment Deployment

Techniques noted in this category included use of material transfer devices to reduce risk of bumps to pavers, use of mobile hot plants, use of dedicated trucks to maintain high production rates, and ensuring a consistent paver speed.

Contractor Practice #3: Daily Testing and Adjustment

Daily testing of results using light-weight profilers can identify the need for immediate adjustments to improve smoothness.

Contractor Practice #4: Cultivating a "Quality Mindset"

Contractors interviewed as part of this effort emphasized the importance of cultivating a quality mindset within their organizations, communicating the importance of quality, and making necessary investments in equipment to achieve pavement smoothness targets. Some contractors provide bonuses to their crews to reward them for quality results.

IMPROVING FUTURE COMPARATIVE PERFORMANCE MEASUREMENT USING IRI

Improving IRI Measurement Accuracy and Consistency

The ability of agencies to use IRI-based performance measures and targets as a tool for improving their practices is currently limited by inconsistencies and inaccuracies in the measurement data. Improvements in accuracy and consistency have already been occurring, but further progress is needed. Six recommendations were developed to make IRI data more compatible across different agencies, thereby enabling an improved ability to discern practices leading to smooth pavements. These recommendations also aim to raise the accuracy of each agency's database, allowing for more valid trending analyses and comparison of IRI values across the network within individual states.

1. Encourage adherence to the AASHTO MP 11 Standard Equipment Specification for Inertial Profilers. Use of a recording interval less than 2 inches is a key element of this specification that is not yet standard practice because it can require expensive modification of existing profiler components.
2. Encourage rigorous application of regular calibration procedures and system checks, as documented in the AASHTO PP 50 Standard Practice for Operating Inertial

Profilers and Evaluating Pavement Profiles. Most importantly, use regular equipment calibration and daily system checks to ensure integrity of network IRI surveys.

3. Further develop AASHTO MP 11 and PP 50 for network profilers. These standards were written with construction quality assurance in mind, and can be improved based on current experience with network profiler application. Consideration should be given to adding specifications for real-time data quality checks.
4. Spot check profile data on control sections to ensure that profilers are functioning properly.
5. Verify IRI calculation software – wherever software is used to generate IRI values, they should be verified using a reference program. This is best accomplished via a collective effort involving profiler manufacturers.
6. Require profiler accuracy and repeatability testing as a condition of procurement contracts. Certify existing profilers against a defensible reference measurement, and upgrade them as needed.

Addressing Data Gaps that Limit Comparative Performance Analyses

One notable observation from this effort was that there was wide variation in states' ability to assemble the data that was requested: IRI data in 0.1 mile sections, along with pavement type, last treatment type and date, presence of a bridge, Annual Average Daily Traffic (AADT), Percent Trucks, County (for assignment of Climate Zone) and Functional Class. While some states faced data gaps – particularly for pavement types and treatment histories, the most common challenge faced was the lack of a convenient capability to join disparate linearly referenced data sets. This is a fundamental need that is being addressed by states within a much larger context than this comparative performance initiative. Nevertheless, making progress in this area is important to the future success of comparative performance measurement for pavement smoothness. The following recommendations should be considered by states wishing to get their "data house" in order to enable effective analysis, comparison and diagnosis of pavement smoothness results and identification of areas to target for improvement.

1. Maintain historical IRI data for 0.1 mile sections, and make this data easily accessible and easy to aggregate. While maintaining actual profile information provides maximum flexibility for processing to suit various needs that may arise, it would be beneficial for continued cross-state comparative performance measurement if states maintained their data in 0.1 mile sections.
2. Maintain information about pavement types with accurate spatial referencing. Pavement type breakdowns should at a minimum distinguish flexible, rigid and composite pavements, with finer breakdowns recommended. National support for standard pavement type classification schemes (with specific definitions and

crosswalks across existing classification methods) should be considered through an AASHTO initiative.

3. Maintain accurate pavement treatment history (both maintenance and rehabilitation) records, including both in-house and contractor work, accurate dates of last treatment, classification of treatment type and accurate spatial referencing of the treatment limits.
4. Maintain accurate information on bridge locations to enable analysis of IRI data sets with and without bridges.
5. Provide data integration capabilities that are accessible to end users, allowing for dynamic segmentation permitting analysis of IRI data together with pavement type, treatment history, bridge location, traffic, and functional classification.

2. INTRODUCTION

BACKGROUND

In 2004, the AASHTO Standing Committee on Quality (SCOQ) Performance Measures and Benchmarking Subcommittee initiated NCHRP 20-24(37) – Measuring Performance Among State DOT's. This initiative aims to establish a handful of comparative performance measures in key strategic focus areas – for example, project delivery, system condition, congestion, and safety; facilitate comparisons of these measures across a group of volunteer agencies; and use these comparisons as a way to identify and share best practices and lessons learned. On-time, on-budget project delivery was selected as the initial performance area. The final report for this initial comparative performance measures effort - Project 20-24 (37A) - presents data for 20 states, and provides a synthesis of 28 best practices from the nine top performing states.

Project 20-24(37B) continues the comparative performance initiative, focusing this time on pavement smoothness. The IRI was selected as the performance measure for comparison because all states must report IRI to the FHWA as part of their HPMS submittals, and considerable effort has been made in recent years to establish clear standards and protocols to improve IRI measurement and reporting consistency.

This effort is timely, considering both the recent HPMS Reassessment and the anticipated adoption of the new Mechanistic-Empirical Pavement Design Guide (MEPDG). The individuals working on the HPMS Reassessment have envisioned a broader use of the pavement condition information than in the past. As a result, there will be several changes in the type and frequency of data that will be requested of state highway agencies. Reliable IRI data will be essential for the success of this effort.

The MEPDG considers both structural and functional pavement performance characteristics in the analysis of estimated damage to a pavement over time. The IRI is the functional performance indicator used in the analysis. The roughness models are based on the initial as-constructed pavement smoothness and changes in smoothness due to the propagation of distress, site factors (such as subgrade), and maintenance activities. The default models incorporated into the design software have been calibrated at the national level using data from the Long Term Pavement Performance (LTPP) program. However, they are not representative of all conditions and regions of the country. For that reason, it is important that the models be calibrated and validated to conditions in each state or region. The use of more consistent data collection practices will lend itself better to regional calibration activities.

RESEARCH OBJECTIVES

The objectives of this research project were to facilitate the process of comparing the performance of peer state DOTs using the IRI; prepare, analyze and evaluate the performance data; and identify and document good practices related to achievement of smooth pavement. In addition to identifying causal links which may exist between network-level pavement smoothness and best practices, an important objective of this project was to facilitate future use of comparative analysis of pavement smoothness performance, by identifying analysis approaches and measurement techniques that can, over time, achieve a greater degree of consistency and comparability. While states measure pavement conditions in various ways, often using multiple indicators, this project was limited to comparisons of pavement smoothness on the Interstate System. This focus on the Interstate System eliminates much of the variability in IRI measurement that is related to measurement speed and speed changes, short segment lengths and the presence of traffic signals. It is important to note that some states employ different pavement construction and management practices on Interstates than for other roadways, so the results of this research should be considered valid for Interstates only.

LITERATURE REVIEW

A focused review of literature relevant to this project was conducted to establish an appropriate set of expectations for what can be achieved. The results of this review are organized into the following five observations about IRI and its variations across individual pavement sections and different states.

1. Network-level IRI data from different states contain baseline measurement error on the order of 15% due to differences in equipment, calibration practices, and variations across operators.

Issues related to comparability of IRI measurements from state to state have been the subject of many prior studies and reports. The 2000 Government Accountability Office (GAO) Report, "Managing for Results – Challenges in Producing Credible Performance Information" noted their 1999 finding that "IRI data were not comparable between states, because states differed in the devices, procedures, and mathematical simulations they used to calculate the index." Since then, as noted above, progress has been made to understand variations in protocols and methods, and to achieve a greater degree of consistency. A 2004 survey of 38 states conducted by California to identify other states with which they might benchmark IRI showed that most states reported IRI for the average of right and left wheelpaths in the outer lane, but there was less consistency with respect to inclusion of bridges, calibration frequency, section length reported, and collection frequency. Efforts to standardize data collection procedures have resulted in the increased use of the provisional AASHTO protocols, which are included as guidelines in the HPMS Field Guide.

A 2004 HPMS/IRI experiment conducted by Ohio DOT (ODOT) collected IRI data on Interstate sections in Kentucky, Pennsylvania, Maryland, Virginia and West Virginia and compared these data to the IRI statistics for the same sections that were reported by those states for the 2002 HPMS submittal. Sections on bridges and sections affected by construction zones were removed. All of the ODOT collected IRI values were higher than those that the states had reported to HPMS. Differences between the ODOT-measured value and the HPMS-reported value ranged from 1% (PA) to 29% (MD) – though the MD data were based on less than 12 centerline miles. The conclusions of the experiment were that there were too many variables and unknowns to fairly compare HPMS IRI data state to state, and the standard deviations of differences in IRI across the different samples and the relatively small number of samples precluded factoring the data to allow for valid comparisons.

The 2004 FHWA "profiler roundup" included high-speed profilers from 14 different state DOTs, most of which were in use for measurement of IRI in pavement management. They measured nine test sections of diverse surface texture. On seven of the nine sections, the average IRI values from this group of profilers covered a total range of 10-15% from each other. This effort also showed that not only was there "scatter" in the measurements, but there was also systematic upward bias in measurements for pavement sections with rougher surface textures. Other studies as part of the LTPP have indicated that profilometer measurements are less repeatable for longitudinally tined surfaces than transverse tined surfaces. Steve Karamihas, a member of the research team has authored several studies on the topic of profiler repeatability that confirm problems with repeatability of profilers with small height sensor footprint on tined and diamond ground surfaces (Karamihas, 2002; Karamihas, 2005a).

One notable finding of the 2004 roundup was that there was not better agreement in measurements across profilers of the same make and model than across profilers of different makes and models. This suggests a strong operator influence, even under well defined conditions. Operators can affect IRI very easily, and most often in ways that bias the values upward: (1) poor speed control can add artificial roughness to the profile, (2) wander within a lane affects the IRI, and favoring the outside of the lane usually causes an upward bias, (3) improper tire pressure or lack of Distance Measuring Instrument (DMI) calibration can cause a shift in section boundaries, (4) failure to observe calibration and recommended field procedures can cause poor data collection to go on for days without detection (e.g., forgetting to do the bounce test puts you at risk of collecting data with a malfunctioning sensor, but the numbers may not be off by enough to alert an operator). Adoption of strict, standardized equipment and operator certification processes have been suggested to address these issues.

2. Some differences in measurement and index calculation methods can be accounted for, based on the existing body of research.

Removal of bridges from the datasets is one important adjustment that is typically straightforward to do, so long as pavement sections with bridges are clearly identified. A second is adjustments to datasets that utilize the half car roughness index (HRI) rather than the mean roughness index (MRI). Such adjustments can be made for different pavement types based on regression equations developed from studies that have compared these two measures for individual sections. This adjustment was made as part of the Ohio experiment mentioned earlier. Other differences – for example, use of the "worst" lane rather than the outer lane, use of only the left or right wheelpath, etc. cannot be as easily accounted for, yet can introduce systematic biases that impede cross-state comparisons.

3. Differences in weather conditions are another major source of variation in IRI measurements that needs to be acknowledged.

Studies have also shown that IRI measurements are sensitive to temperature and moisture conditions. Moisture can cause the pavement subgrade to swell or shrink, which affects the profile and therefore the roughness. Frost heaves of subgrade and base layers can also cause variations in the pavement profile. NCHRP Report 434 (Project 10-47) included examples of this in seasonal measurements from the LTPP database (Karamihas, 1999). Jointed Portland Cement Concrete (PCC) can change by up to 40 in/mi throughout a 24-hour cycle (Karamihas, 2001). Thin asphalt on expansive clay can be much rougher when the ground freezes. Given that HPMS IRI data are based on a single pass (rather than an average of multiple observations), documentation of environmental conditions at the time of IRI data collection is extremely important.

4. True differences in IRI across individual pavement sections, and changes in IRI over time are attributable to numerous factors, including pavement type, pavement design and material properties, construction methods, traffic loadings and environmental conditions.

Numerous LTPP analyses have indicated that multiple interacting factors impact both initial pavement roughness and changes over time: pavement type, construction methods, layer materials and thicknesses, soil conditions, freeze-thaw cycles, and traffic loadings. Variations in roughness across new pavements can be significant – for example, a 2004 panel analysis published in the American Society of Civil Engineers (ASCE) Journal of Transportation Engineering showed variations in as-built IRI measurements for asphalt concrete pavements in Wisconsin from .4 to 1.6 m/km (25-102 in/mi) (Lee, 2007). These results indicate that complex interactions across variables can confound diagnosis of explanations for differences in roughness. They also indicate that it will be difficult to distinguish best practices in pavement preservation from best practices in new surface construction using a snapshot of system-wide roughness.

5. IRI does not tell the whole story about pavement condition and performance.

IRI is generally seen as a lagging indicator of pavement condition. IRI values can be quite good on pavements that have had obvious surface fatigue for years. Good examples of this can be found on many of the LTPP Specific Pavement Studies (SPS)-9 sites, where visible surface fatigue often appears before the IRI values suffer a commensurate penalty (Karamihas, 2007). At some point, the pavement finally starts to get potholes, and the IRI may increase suddenly and dramatically. It is also important to note that IRI can be temporarily boosted with relatively low cost overlays which may not be the best strategy from a life cycle cost perspective. Best practices for short and even medium term smoothness are not always best practices to achieve long term smoothness or maximize pavement life. Therefore, while we may use IRI as a comparative measure of pavement performance for pavement smoothness, as we look at best practices we need to recognize that the IRI tells us only part of the real story about pavement performance.

Given the above observations, while it may be difficult to say that state X with an average IRI value of 110 is higher-performing than state Y with an average IRI value of 120, it is reasonable to conclude that when states are ranked by average IRI, the highest ranked states probably do have smoother pavements than the lowest ranked states, and are likely to have pavement management, design and construction practices in place that are contributing to their results.

REPORT ORGANIZATION

The findings and recommendations of this effort are presented in section 3. Details on the overall timeline for the effort, and the methodology for data requirements specification, data gathering, and compilation are provided in section 4.

3. FINDINGS AND RECOMMENDATIONS

COMPARATIVE PERFORMANCE ANALYSIS

Analysis Results

Figures 1-9 present results of the comparison of Interstate pavement IRI values across participating states. IRI comparisons were made within peer groups. Peer groups were defined as combinations of pavement type (flexible or rigid), functional class (urban or rural interstate), and LTPP climate zone (dry no-freeze, dry-freeze, wet no-freeze, and wet-freeze). Generally speaking, the wet-freeze zone encompasses the northeast quadrant of the US (extending as far west as MN, IA and MO and as far south as KY and VA); the dry-freeze zone covers the northwest (extending as far south as KS, CO, UT, and NV and including northernmost portions of AZ and NM); the dry-no freeze covers the southwest (excluding coastal areas); and the wet-no freeze covers the southeast US as well as western coastal areas.)

In order to maintain anonymity, each state was assigned a number between 1 and 32[1]. The charts shown in the figures include one bar for each grouping of segments. In figure 1, each bar represents a single pavement type within a state. In figures 2-9, each bar represents a single functional class (urban or rural interstate) within a state for the pavement type and climate zone shown in the figure title.

Only the most recent year of data is shown on the charts. The left y-axis indicates the percentage of mileage falling below IRI cutoff values of 60, 94 and 170 in/mi. These cutoffs are represented by the blue, maroon and white portions of the bars respectively. The right y-axis is the length-weighted average IRI corresponding to the line that is superimposed on the bars.

Figures and highlights are as follows:

- Figure 1 – Initial Smoothness: includes flexible and rigid pavement groupings for pavement segments (from all states in all climate zones) that had a resurfacing or reconstruction treatment within 2 years of the IRI survey date. State 3 has the smoothest new flexible pavements; state 16 has the smoothest rigid pavements (of the 26 states providing this data).
- Figure 2 – Dry Freeze zone – flexible pavements. State 20 has the smoothest pavements for both urban and rural, closely followed by State 21 (for rural).
- Figure 3 – Dry Freeze zone – rigid pavements. State 16 has the smoothest pavements for both urban and rural.

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[1] Assignments of numbers to states were not made alphabetically.

- Figure 4 – Dry No Freeze zone – flexible pavements. State 22 has the smoothest pavements for both urban and rural, with State 12 a close second for rural.
- Figure 5 – Dry No Freeze zone – rigid pavements. State 22 has the smoothest pavements for both urban and rural.
- Figure 6 – Wet Freeze zone – flexible pavements. States 18 and 5 have the smoothest pavements for rural; State 23 is smoothest for urban.
- Figure 7 – Wet Freeze zone – rigid pavements. State 23 has the smoothest pavements for both rural and urban, with States 13 and 31 close behind for rural
- Figure 8 – Wet No Freeze zone – flexible pavements. State 3 has the smoothest pavements for both urban and rural.
- Figure 9 – Wet No Freeze zone – rigid pavements. State 3 has the smoothest pavements for rural; State 9 is smoothest for urban.

A total of 12 states were noted above as having smoothest (or being a close second) for one of the peer groups: states 3, 5, 9, 12, 13, 16, 18, 20, 21, 22, 23, and 31.

Figure 1 – Initial Smoothness

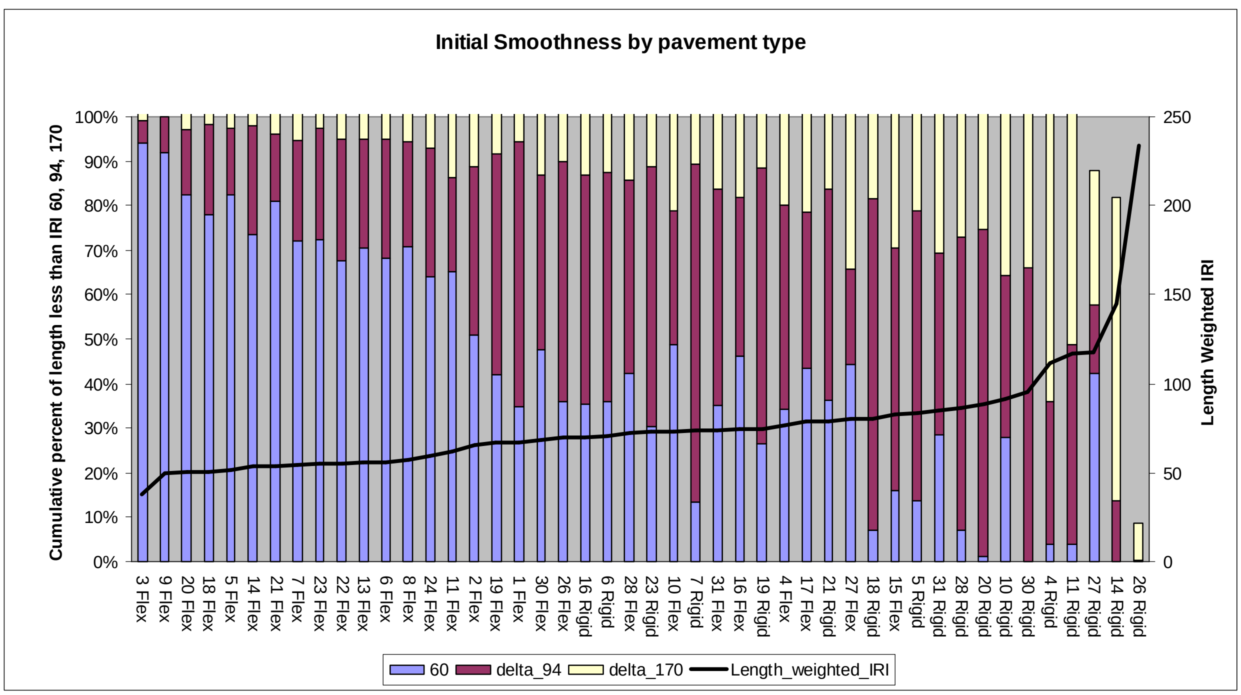


Figure 2 – Dry Freeze – Flexible

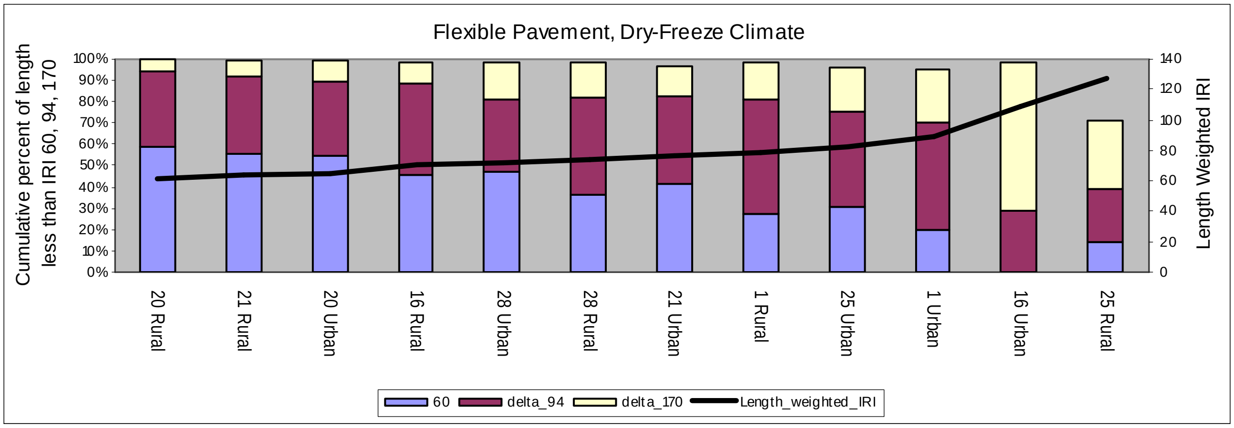


Figure 3 – Dry Freeze – Rigid

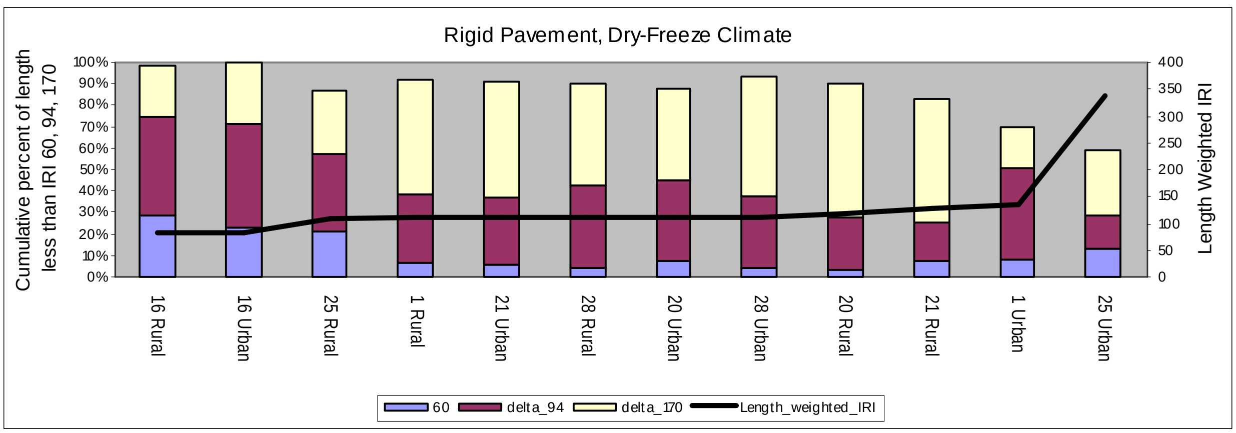


Figure 4 – Dry No Freeze – Flexible

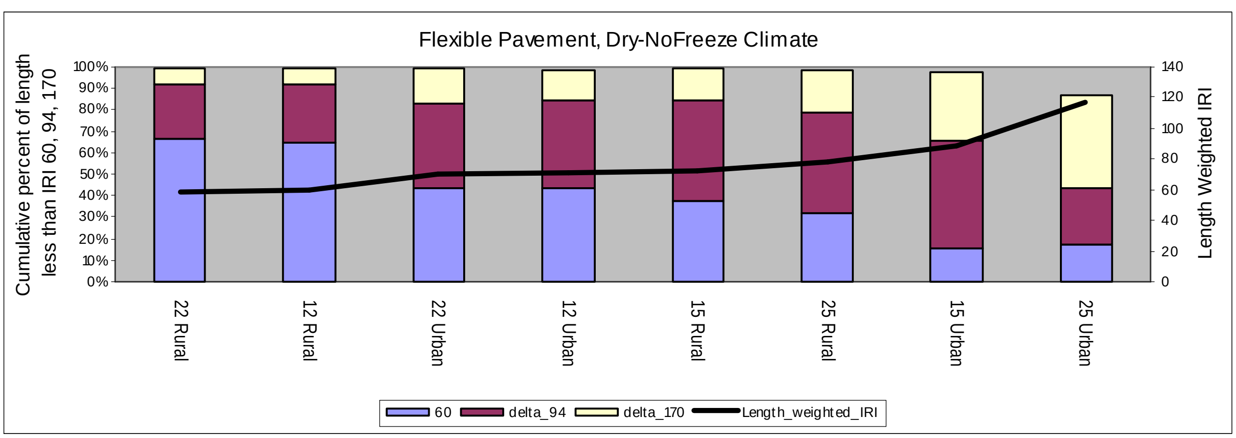


Figure 5 – Dry No Freeze – Rigid

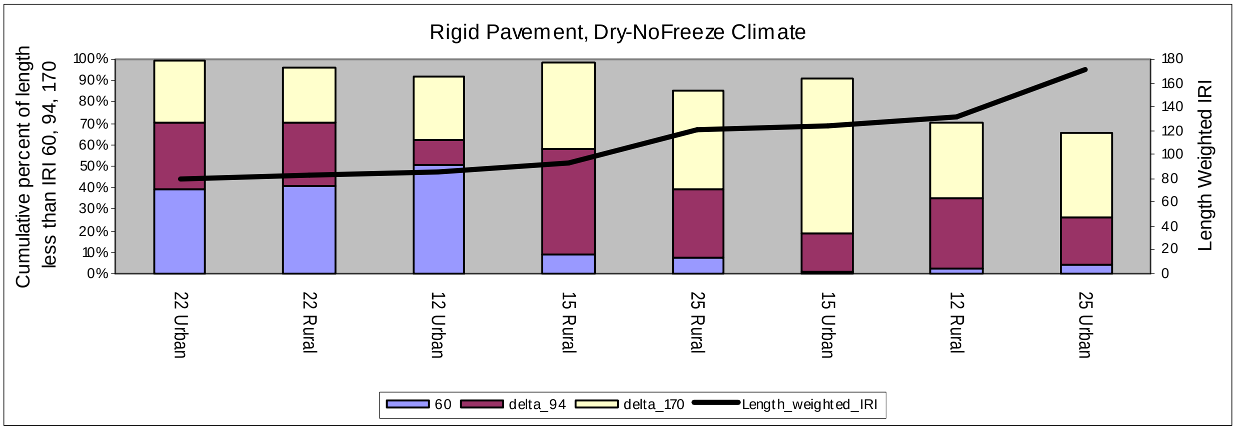


Figure 6 – Wet Freeze – Flexible

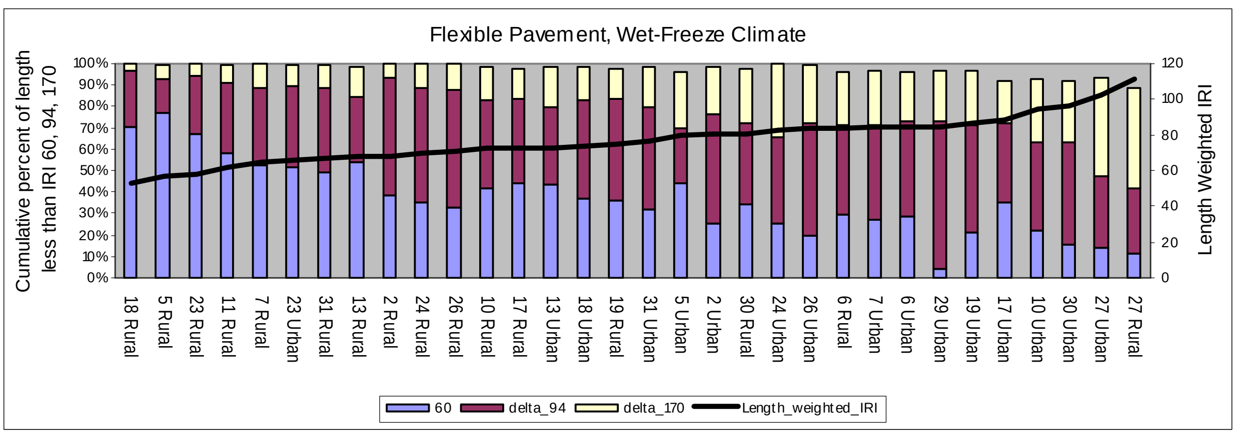


Figure 7 – Wet Freeze – Rigid

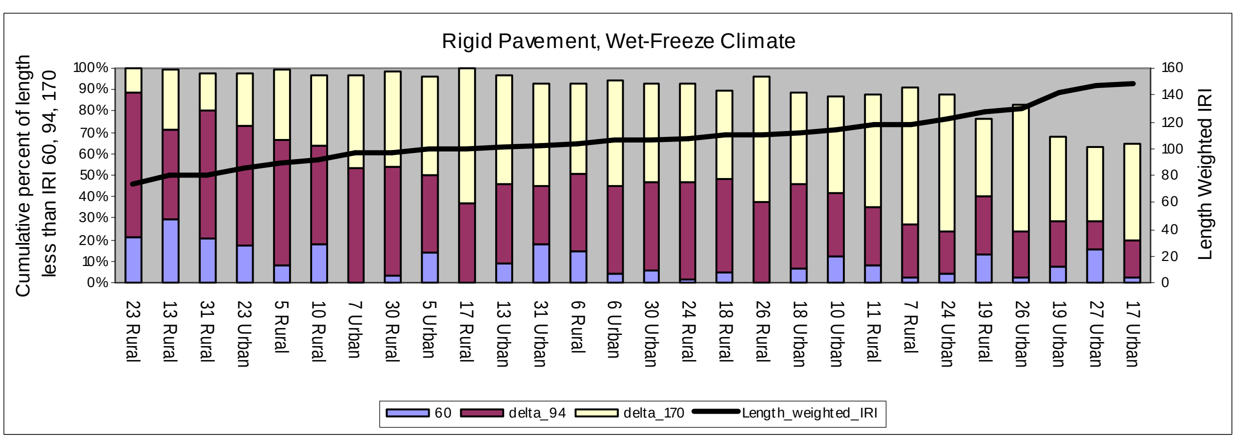


Figure 8 – Wet No Freeze – Flexible

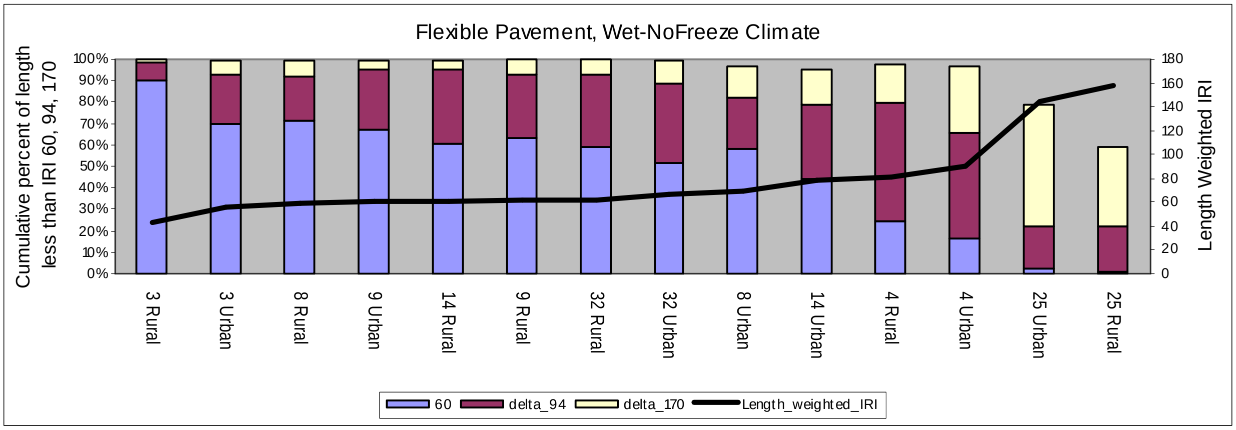
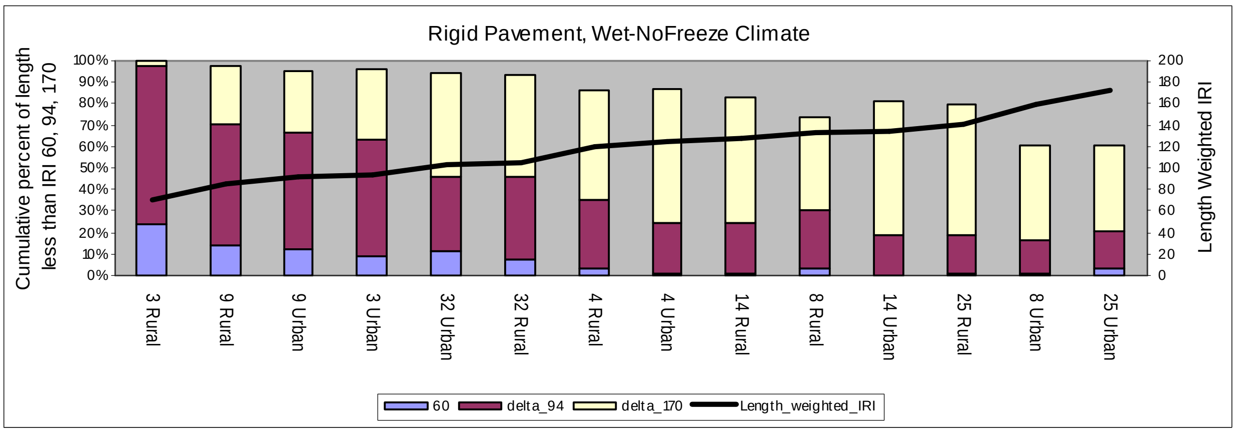


Figure 9 – Wet No Freeze – Rigid



Results Summary – Selection of States for Interviews

An additional ranking analysis was conducted in order to identify the top five states for detailed interviews. This analysis is shown in Figure 10. The top portion of the chart identifies the top five ranked states across all climate zones based on average IRI, and percentage of mileage less than 40, 60, and 95 in/mi. Lower cutoff values were selected to gain a better understanding of the lower end of the IRI distribution, providing insight into initial smoothness. Separate rankings were assigned for different combinations of pavement type and functional class (urban vs. rural). The bottom portion of the chart shows rankings within each climate zone based on average IRI.

Based on this analysis, the following five states were selected for interviews:

- State 3 (Wet No Freeze zone) had the smoothest overall system with average IRI of 49 in/mi and was ranked first in most of the categories. This state's Interstate system is comprised primarily (though not exclusively) of flexible pavements.

- State 22 (Dry No Freeze zone): had the second smoothest system overall, with an average IRI of 61 in/mi. This state was also second only to state 3 in the most flexible mileage at the very smooth end of the spectrum (43% smoother than IRI of 50 in/mi).
- State 12 (Dry No Freeze zone): had the third smoothest overall system, with an average IRI of 62 in/mi. This state ranked highest across all states for the percentage of very smooth rigid pavements. Examination of IRI distributions indicated that about half of the rigid pavements were much smoother than the rest.
- State 23 (Wet Freeze zone): had the fourth overall smoothness, with an average IRI of 65 in/mi. This state ranked first across all states for average IRI on rigid pavements. It is important to note that this state had the most dramatic decrease (improvement) in average IRI across the two years of data provided (2005-2006) – 17 in/mi overall; 30 in/mi for rigid pavements. The most recent year of data included very little mileage for rough rigid pavement, which suggested an aggressive and targeted rehabilitation program.
- State 20 (Dry Freeze zone): was selected for the top five, though it was tied with state 16 in this zone – state 20 had smoother flexible pavements; state 16 had smoother rigid pavements. State 20 was selected because it had higher traffic levels and a lower percentage of miles paved over the past five years. Therefore, the research team felt it would be useful to explore how this state has been able to achieve relatively smooth pavements with these factors working against it.

It was not a straightforward exercise to select only five states out of the pool of twelve that exhibited fairly smooth pavements within their peer groups. While study resources didn't permit the conduct of interviews for additional states, there were sufficient resources to conduct a brief survey, with limited telephone or email follow-up to identify practices being followed by the other seven states.

Figure 10 – Results Summary and Selection of States for Follow-Up

RED - Top 5 (interview) YELLOW - Survey with follow-up	Func Class	Pvmt Type	State	12	15*	22	25	1*	16	20	21	25	28	3	4*	8	9	14	25	32	2	5	6	7*	10	11	13	17	18	19	23	24*	26	27	29	30	31
	Climate Region:			Dry No-Freeze				Dry Freeze						Wet No-Freeze							Wet Freeze																
Avg IRI, bridges and toll roads included	ALL	ALL		3		2					5			1																	4						
Avg IRI no known bridges or toll roads	ALL	ALL		3		2					5			1																	4						
	URB	ALL		5		4								1			2														3						
	RUR	ALL		3		2								1		5															4						
	ALL	FLEX				3								1			5					2									4						
	URB	FLEX								3				1			2			5											4						
	RUR	FLEX				5								1								3							2		4						
	ALL	RIGID				2			3								4										5				1						
	URB	RIGID		4		1			2								5														3						
	RUR	RIGID							3					1													4				2						5
Pct Very Smooth (<40), no known bridges or toll roads	ALL	FLEX		5		2								1												3			4								
	URB	FLEX				2								1		5		3				4															
	RUR	FLEX		5		3								1												4			2								
	ALL	RIGID		1		3			4			5															2										
	URB	RIGID		1		2						4															3										5
	RUR	RIGID				2			4			5															1				3						
Pct Smooth (<60), no known bridges or toll roads	ALL	FLEX				5								1		3	4					2															
	URB	FLEX									4			1		3	2														5						
	RUR	FLEX												1		3						2							4		5						
	ALL	RIGID		1		2			3																		4				5						
	URB	RIGID		1		2			3																						5						4
	RUR	RIGID				1			3			5		4													2										
Pct Acceptable (<95), no known bridges	ALL	FLEX								4				1			2	5													3						
	URB	FLEX								3				2			1			5											4						
	RUR	FLEX								5				1				3											2		4						
	ALL	RIGID				3			2					5			4														1						
	URB	RIGID				3			2					5			4														1						
	RUR	RIGID							4					1													5				2						3
Rank within Climate Region - Avg IRI	ALL	ALL		2	3	1	4	5	2	4	1	6	3	1	6	3	2	5	7	4	7	6	15	2	9	5	4	10	11	14	1	12	8	17	16	13	3
	ALL	FLEX		2	3	1	4	5	3	1	2	6	4	1	6	3	2	5	7	4	10	1	15	5	11	3	6	13	4	12	2	8	9	17	16	14	7
	ALL	RIGID		2	3	1	4	3	1	4	5	6	2	2	4	6	1	5	7	3	x	4	7	10	6	11	2	15	9	14	1	8	13	15	12	5	3
	URB	FLEX		2	3	1	4	5	6	1	3	4	2	1	6	4	2	5	7	3	6	5	10	9	14	x	2	13	3	12	1	7	8	16	11	15	4
	RUR	FLEX		2	3	1	4	5	3	1	2	6	4	1	6	2	4	3	7	5	8	2	15	5	11	4	7	12	1	13	3	9	10	16	x	14	6
	URB	RIGID		2	3	1	4	5	1	3	2	6	4	2	4	6	1	5	7	3	x	3	6	2	9	x	4	15	8	13	1	10	12	14	11	7	5
	RUR	RIGID		4	2	1	3	3	1	5	6	2	4	1	4	6	2	5	7	3	x	4	8	13	5	12	2	7	10	14	1	9	11	x	x	6	3

* bridges included in the data - locations could not be identified by the state
x - no sections in this category

PRACTICES AFFECTING PAVEMENT SMOOTHNESS

The primary purpose of this study was to identify how states have been able to achieve smooth pavements in order to provide this information to others seeking to achieve similar results. Towards that end, interviews with the five states that emerged as leaders from the analysis were designed to cover a wide range of construction specification, construction methods, and agency practices. A questionnaire was developed to guide the interviews. (See Appendix B.) This questionnaire was used to gather a more limited – but nonetheless useful set of information from the seven other state highway agencies that were identified as having smooth pavements relative to their peers.

The findings from these efforts are summarized here and recommendations based on our findings are presented in the next section of the report.

Arizona DOT (State 22)

According to the participants in the Arizona DOT (ADOT) interview, which included two representatives from the contracting industry, ADOT places significant emphasis on smooth roads through its incentive-based, end result performance specification. The original specification was first developed in 1990 and applies only to HMA pavements. The specification rewards good contractor practices by establishing baseline IRI targets and financial incentives for contractors who construct pavements with IRI values of 2 points or more below the target. Penalties are enforced on sections with IRI values of 10 points or more above the target IRI value. As an end-result specification, ADOT avoids describing the means and methods to be used by the contractor. This results in a great degree of flexibility for the contractor to institute practices that result in smooth roads.

ADOT's program has matured over time based on both the Department's observations and the input of local contractors. The initial target values identified in the specification were largely based on measured values on new construction projects. After measuring constructed smoothness on a variety of projects, ADOT established its initial target values for acceptance several points below the measured values to create an incentive for contractors to improve their practices. The original specification made no provision for the roughness of the existing surface on overlay projects, but the current specification considers initial roughness in setting the target values. Different smoothness target values are set based on the type of roadway being contracted or rehabilitated and the number of opportunities the contractor has to improve smoothness. The target values and the incentive awards have been adjusted periodically as the market has matured, effectively tightening the specification with each adjustment. ADOT estimates that approximately 90% of its projects have either earned a bonus or incurred no penalty, while only 20% of the remaining 10% of the projects have had to correct their work (reflecting the highest possible penalty) and the balance incurring financial penalties. ADOT reports that rarely is a penalty applied to an entire project and rarely is the penalty over $10,000. Possible rewards, on the other hand, could be as high as $8,000 to $9,000 per lane mile. This reflects ADOT's intent to place more of an emphasis on bonuses rather than penalties.

Although industry feels the target values are set relatively high, the specification has allowed contractors to hit fairly substantial bonuses if they perform well enough. As a result of the potential bonuses, superintendents offer suggestions for improving smoothness in anticipation of the financial incentives that will pay back any additional expenditure. For instance, some contractors have placed an additional leveling course at their own expense to aid in achieving a smoother surface layer. They can afford to do this because of the size of the incentive bonus. The contractor with whom we spoke shares bonuses with the paving crews and superintendents in recognition of a job well done. Within his company this recognition has gone a long way towards having the crews take the time necessary to do their job well.

The contractors we talked with report that one of their primary focuses is the continuous operation of the paver to prevent any starts and stops. This focus is important because the contractors indicated that one stop of the paver can cause them to lose several in/mi in IRI. While one stop won't have a significant impact on smoothness, several stops of the paver can remove a contractor from consideration for the incentive bonus. The contractors reported that even with this focus on continuous operations, they do not typically use material transfer devices for delivering the HMA material to the paver. Instead, because the climate in Arizona is good year-round, bottom (belly) dump trucks are commonly used with windrow pavers. Where the climate is more challenging, other types of material handling devices may be considered. Fairly high production rates are achieved with the help of mobile mix plants that reduce the amount of time to deliver the mix to the job site.

Agency practices also contribute to smooth roads, as demonstrated by the Department's use of rubber in their friction courses for a number of years. ADOT also reported that they construct smooth concrete roads, but generally overlay them with one inch of an open graded rubberized friction course fairly quickly to reduce noise and heat levels in urban areas. ADOT also uses preventive maintenance treatments such as microsurfacing, but these types of treatments are done under procurement contracts rather than construction contracts so there is no QA/QC specification in place for these treatments. IRI is used as a factor in triggering rehabilitation treatments, but is rarely used in triggering preventive maintenance treatments. Most preventive maintenance is timed prior to roadway distress becoming evident.

Missouri (State 23)

The Missouri DOT (MoDOT) credits its 2005 Smooth Roads Initiative as one of the principal factors behind the smoothness of its Interstate highways. This Initiative provides an explanation for the dramatic increase in smoothness (18%) between the two years of IRI data provided for this study. The Initiative was begun at the request of MoDOT's new Director, who wanted to make a substantial impact on the public when he took office. The Smooth Roads Initiative was designed as a 3-year program to increase the number of miles of State routes in good condition. Under this program, pavements with an IRI value greater than 100 in/mi were diamond ground (if it had a PCC surface) or a thin overlay or mill and fill overlay was placed (if it had a HMA surface). In total, more than 2200 miles of pavement were addressed, with more than 75% of the roads receiving more than cosmetic treatments (which only address signs, safety, or striping improvements) that have improved IRI values by about 50 in/mi. The program's goals were completed within 2 years. A new initiative, titled *Better Roads, Brighter Future*, is attempting to bring 85% of the major roads within the State to *good* condition by the end of 2011. At the same time, the Department is focusing more on system preservation than on expansion projects.

To help establish criteria for projects to include in the Smooth Roads Initiative, MoDOT conducted *road rallies* with public participation to help determine the point at which roads are no longer considered to be "smooth" by road users. The participants provided their impression of overall road smoothness and gave input on the importance of each facility. The participants differentiated between smooth and rough road at an IRI of 100 in/mi on Interstates and 140 in/mi on collector roads. MoDOT also received useful information on the public's perceptions of various distress, signage, and pavement striping conditions. The road rallies included more than 200 people in six locations throughout the state.

Another factor contributing to the condition of the roads in Missouri is the development since 2004 of new end result specifications. A Task Force was created to rewrite the State's specification, shifting from a method specification to an end result specification. A number of contractors participated on the Task Force to develop the new specifications. Under the specifications, which include both HMA and PCC pavements, different tolerances are established for roads designed for speeds higher than 45 mph and those designed for speeds lower than 45 mph. The new specifications have been revised based on contractor input so that incentives of 103 to 105% of pay are earned based on the California profilograph reading with a zero blanking band rather than a 0.2 in blanking band. This provides an improved ability to capture shorter wavelength content, commonly called "chatter," that is annoying to the public, but may not protrude beyond the boundaries of the 0.2-in blanking band. Under the current specifications, projects constructed to less than 10 in/mi are paid at 105%, projects between 10 to 15 in/mi are paid at 103%, projects between 15 to 25 in/mi are paid at 100%, and projects with values above 25 in/mi incur penalties. (Note that this is a low cut-off for full pay – 29 in/mi is common.) MoDOT reports that bonuses are paid on the majority of construction projects and that contractors are making improvements to the types of equipment being used as a result of the new specifications. For instance, some of the contractors constructing PCC pavements have purchased their own diamond grinders and feel the equipment provides them a competitive edge. In addition, contractors are using equipment with GPS features and laser-guided screeds.

A number of outreach activities are in place to strengthen the relationship between the DOT and industry. The Department's outreach activities include quarterly meetings with industry to discuss common issues, which resulted in the recent changes to the State's specifications. Pre-paving meetings are used occasionally, but have primarily been limited to specialized projects or to projects with unusual issues that have to be addressed.

New Mexico (State 12)

The New Mexico Department of Transportation (NMDOT) has made substantial organizational changes to improve the smoothness of its highways in recent years. For instance, in 2003, the Governor signed into legislation funding for a $1.6 billion dollar economic benefit package called GRIP (Governor Richardson's Investment Partnership). This initiative provided approximately $600 million towards the Interstate system, which carries heavy traffic volumes made up of almost 50% truck traffic in some locations. Critical needs within the State were identified by a team assembled by the Cabinet Secretary of the New Mexico Department of Transportation, prior to the legislation being passed. The team had to sell the program to the legislature and did so by promoting it as a statewide program with substantial economic benefit to the State. The team also secured support from the cities and counties by communicating what the package meant to their geographic areas. GRIP focused on safety, economic development, and capacity projects, with more of a focus on capacity projects in urban areas and condition improvements in rural areas.

Another organizational change involved moving the Pavement Management Unit to Operations from Planning so there is a closer link between the field personnel and the pavement deterioration identified through pavement condition surveys. As a result of this change, there is less time that passes between the identification of areas requiring pavement maintenance and the application of the appropriate treatment. There is significant involvement by major universities in the State (University of New Mexico, New Mexico Institute of Mining and Technology, and New Mexico State) to conduct pavement-related research and to conduct the pavement condition surveys.

The Department has also made a concerted effort to extend the life of its pavements through pavement preservation initiatives since so much has been invested in improving the condition of the road network. The pavement preservation program is directed at the network level although the Districts have responsibility for selecting projects. On the Interstate highways, preventive maintenance treatments include bonded wearing course overlay, microsurfacing, thin hot mix overlays, and crack sealing.

Network conditions are reported regularly to upper management and politicians. Under the current *Good to Great* strategic plan, network-wide pavement statistics are reported on a quarterly basis. The report tracks the number of miles of roads in *good* condition as determined by a condition index rather than report an IRI value since politicians don't understand the more complex values. This report frequency helps keep the organization focused on its goals.

In addition to the organizational issues addressed earlier, NMDOT has also implemented changes to its smoothness specifications that have contributed to the construction of smoother roads. The NMDOT uses performance-based specifications on nearly every construction project led by the State. The smoothness targets established in the specification are intentionally set very high and they are tightened periodically with input from the Associated Contractors of New Mexico (ACNM). NMDOT reports that it took contractors about two years to adjust to the new specification when it was first developed in 2002, largely because of the switch to IRI measures. However, at least one contractor purchased equipment to monitor IRI to perform his own quality control checks rather than rely on others to perform the testing. NMDOT reports that incentive bonuses are currently being paid on most projects.

The current specification pays incentive bonuses for IRI values less than 55 in/mi, with similar values used for both HMA and PCC pavement. Between IRI values of 55 in/mi and 65 in/mi, the contractor is paid at 100% and penalties are incurred on IRI values above 65 in/mi. Smoothness targets are set based on input from the contractors and the success of the program is monitored regularly to determine if adjustments are needed. Contractors were not prevented from grinding any pavement surfaces to facilitate improving the IRI values prior to the final lift. However, to discourage too much grinding, NMDOT adjusted its requirements in a transitional specification so that the maximum payout is 95% if any grinding is done. A modification to NMDOT's existing specifications to limit grinding to defined "must grind areas" was adopted following a review of NMDOT's pavement process and specification by the FHWA. NMDOT realizes this may decrease their overall IRI values, but will monitor any changes in performance and make adjustments as needed. Supplemental specifications modifying IRI values may be developed based on data gathered from the use of the new specifications.

NMDOT's end result specification has had a positive impact on the contractor's focus on quality. The contractors encourage good practices among the paving crews by rewarding them when bonuses are achieved. Training has also had a significant impact on changing practices because the crews are better able to identify adjustments needed in the field to improve smoothness. Training courses are conducted through a cooperative effort between the Department and the ACNM at no charge (or little charge) to the contracting community. By training and certifying both the DOT and contracting crews together, there is increased consistency in the practices being used and the DOT can ensure that all participants are hearing the same message. Classes are taught on a 3-year cycle, which corresponds to the certification period. However, NMDOT is moving towards a 5-year certification cycle in the near future. The contractors report that the field staff use the material covered during training as an opportunity to discuss strategies for improving their practices with the paving crews. In addition to training the DOT and contractors, this type of training is provided to the Bureau of Indian Affairs as well as cities and counties within the State. New Mexico is also a member of the Western Alliance, which recognizes certifications provided by other states in the Alliance.

Pre-paving meetings are mandatory and additional meetings during construction may be required. These meetings are an important way for the DOT and the contractors to discuss any major issues associated with a construction project. The meetings also provide an opportunity to address coordination issues or to identify haul routes and methods of placement to be used. The contractor and their paving subcontractors attend these meetings, which are run by the DOT's Project Manager.

Tennessee (State 3)

With some of the smoothest roads in the country, the Tennessee Department of Transportation (TDOT) recognizes the importance of specifying and paying for quality through the use of incentive-based specifications. The smoothness targets included in the specifications have been developed with industry input and set at levels that are slightly tighter than what was previously being constructed. When the specification was first being developed approximately 15 years ago, it underwent a series of iterations over a period of about 7 years before reaching the targets being used today. Throughout the process, TDOT showed industry the as-built smoothness numbers being constructed to provide a comfort level with the values being incorporated into the specifications. TDOT meets with industry twice each year to address construction-related issues. These meetings provide an opportunity to discuss any proposed changes to the specifications prior to their implementation. Both TDOT and the contractors report that the meetings have helped to foster a more open work environment with a single focus on improving quality.

Incentive bonuses are paid on most Interstate projects and disincentives are rarely incurred. The use of incentives and end result specifications in conjunction with means and methods specifications has encouraged contractors to institute many practices that have resulted in smoother pavements. For instance, contractors have upgraded their equipment to include material transfer devices that help produce a more consistent product. On asphalt projects, target values are set for each project and a window of 10 points is used to bring them within minimum compliance.

Acceptance testing is performed using TDOT profilers to report IRI values on asphalt pavements and profile index values on concrete pavements. Incentive bonuses are not always shared with the paving crews, but the companies try to reward them in other ways. The contractors report that pride in a job well done is often a sufficient motivator for their crews. In addition, each year TDOT and the Road Builders Association bestow Smooth Pavement Awards on Interstate and non-Interstate projects in each of the State's four regions.

Training has always been a key factor for success. Training is required for TDOT inspectors and contractor lead personnel working on State projects. The Certified Roadway Inspector Course teaches best practices to improve smoothness. Participants include both supervisors and paving crew members. Each of the four regions offers a certification course annually with approximately 50 participants in each location. Individuals who graduate from the program are certified for a 5-year period before retraining is required.

Smoothness is one of the factors considered by TDOT in making project and treatment recommendations. TDOT is currently developing a pavement preservation program that utilizes proactive preventive maintenance treatments. Over the last 4 years, TDOT has won three national perpetual pavement awards on Interstates in rural areas and a fourth on a non-interstate route. Each of these highways has performed well for 35 years without major intervention. TDOT also reports that Tennessee's Interstates have been recognized as some of the smoothest stretches of highway by *Overdrive Magazine* (a magazine for truckers) for the past 5 years.

Washington (State 20)

The Washington Department of Transportation (WSDOT) reports that the contractors in the State are very quality oriented and regularly utilize good practices that result in a smooth, consistent product. Training has played a pivotal role in achieving smooth roads in the State. Various programs have been in place since the late 1980s to foster strong coordination between WSDOT and the HMA industries. For example, a one-day training class is offered to contractors and DOT employees at a minimal cost of $75 to present the importance of construction quality. In the last year alone, more than 400 people participated in the training class held in five venues around the State. A joint task force has been established to develop the training program each year.

WSDOT is one of the agencies that conducted a study on the relationship between as-built smoothness and pavement performance trends. WSDOT found some validity to the concept of building a road smooth so it stays smooth throughout its life, but reports that the difference was not significant. Perhaps the more significant impact on Interstate smoothness has been WSDOT's pavement management philosophy, which triggers treatments based primarily on the presence of 10% or more of high-severity alligator (fatigue) cracking. Other triggers for rutting and ride are rarely reached. As a result of this philosophy of early intervention, WSDOT has had to make few full-depth structural enhancements and the highways receive rehabilitation well before they are considered rough. Pavements are built on a strong structure, which has kept most cracking in the top surface so that thin overlays (45 mm) can be used to extend pavement service life. The typical overlay cycle on HMA Interstate highways is reported to be 13.9 years, with slightly longer cycles in the western portion of the State and slightly shorter cycles in the eastern portion of the State. WSDOT uses a comprehensive performance measurement and reporting process based on lowest life cycle cost pavement management. Pavement performance measures are reported regularly to the Secretary and reported annually to the Legislature, the Governor , the media and the public in the agency's *Gray Notebook* in the form of graphs, tables, narratives and maps showing the roads in fair or better condition (based on a combination of IRI, rutting and structural condition rating by pavement type). The Governor's and agency's performance goal is 90% of pavement in fair or better condition, with 93.5% of all pavement currently in fair or better condition.

WSDOT currently uses the California profilograph (0.2 blanking band) for acceptance testing of PCC pavements under its existing end result smoothness specification. This specification pays bonuses for values less than 4 in/mile, no pay adjustment for values between 4 and 7 in/mi, and a penalty for values above 7 in/mi including the requirement to correct to 7 in/mi or less.

A new IRI-based specification (for both HMA and PCC pavements) is expected to be implemented in a year or two. Under the new ride specifications, IRI is measured on 1/10-mile increments. Bonuses are paid for IRI values under 60 in/mi and action will be required for values greater than 95 in/mi. However, there are some contractor-related issues that need to be worked out through their specification committees (which have industry participation). Another difficulty with the use of IRI is the lack of a nearby calibration site for the contractors to calibrate their equipment for quality control. Currently, smoothness acceptance testing is performed by State personnel using a high speed profiler.

Pre-paving meetings are not required by WSDOT, but most of WSDOT's six Regions have adopted this practice through the use of *Just in Time Training* that covers issues related to a specific project immediately prior to construction. These 4- to 5-hour training sessions include both the contractor and DOT personnel.

For HMA, WSDOT rewards quality through its awards program that recognizes excellence in the industry. Together with industry, WSDOT offers six quality awards and two awards for smoothness that are awarded to DOT and contractors at an annual meeting. The recognition from these prestigious awards provides strong incentive for quality workmanship.

One of the challenges WSDOT is facing is the condition of its PCC pavements. Since these pavements deteriorate slowly, WSDOT has been able to concentrate its funding on other pavement types across the State. However, the PCC pavements have now deteriorated to the point that substantial rehabilitation is required, which will impact funding over the next several years. The State funds pavement preservation activities heavily, with approximately 2/3 of the funding allocated to these activities. To address the needs on the PCC pavements, some of the funding levels may be adjusted in the future.

Other States

In addition to the five state DOTs that were interviewed, a questionnaire was sent to the seven additional state DOTs listed below.

- Georgia DOT
- Kansas DOT
- Michigan DOT
- Montana DOT
- North Dakota DOT
- Ohio DOT
- Pennsylvania DOT

Because of the notable accomplishments each of these agencies had made in terms of achieving smooth roads, the research team investigated their practices further. A brief summary of the findings from this activity is provided.

- Five of the states specifically mentioned their end result ride specifications as a key factor that has contributed to smooth roads. The Montana and Ohio DOTs report that the specifications have improved quality by forcing contractors to use best practices in order to meet performance targets. Another desirable feature of end result specifications reported by the Pennsylvania DOT is the shift in responsibility for identifying and implementing quality workmanship from the agency to the contractor.
- One state listed the enforcement of their ride specification as a key factor to achieving smooth pavements. This is especially important when end result specifications are not used. Some states indicated the difficulty in enforcing method-based specifications was a factor in converting to performance-based specifications.
- The use of incentives was listed by several agencies as an important factor in gaining acceptance for the end result specifications by the contracting community. The use of bonuses has reportedly gotten the attention of both the contractors and the workers and has provided motivation for improving practice.
- The change to the use of zero blanking band specifications has reaped rewards in at least one of the states.
- In some states, acceptance testing is performed each day to keep problems from occurring over several consecutive days. Additionally, contractors have purchased high-speed profilographs so they can make adjustments quickly.
- Several states reported the use of pavement preservation programs that include preventive maintenance treatments to keep good roads in good condition longer.

FINDINGS RELATED TO MEASUREMENT CONSISTENCY

Several factors affect longitudinal profile measurements and the resulting IRI values, such as profiler design, the manner in which it is operated, the measurement environment, the pavement itself, and measurement timing (Karamihas, 1999). Among these, the factors of greatest concern in this study are those that lead to a bias in measured IRI over the pavement network, or some part of it. Unfortunately, many of these sources of error in IRI are impossible to track after the fact or could not be tracked within the scope of this study. Therefore, no statistical adjustment for these in state-wide statistics was possible. For example:

- **Inappropriate measurement conditions**: Measurement of profile in rain or over pavement with surface contaminants often artificially raises the IRI value.
- **Inappropriate measurement speed:** Hard braking, stops, or operating the profiler at speed below the intended range adds artificial roughness to measured profiles.
- **Omission of daily and periodic system checks:** In rare cases, data are collected using a profiler with a maintenance problem that would be detected by rigorous application of field calibration procedures and system checks. This may lead to unpredictable errors in IRI.

Other factors affect IRI values, even without measurement error. For example, IRI values vary with the specific lateral position of the profiler within a lane. In addition, the true IRI values on some types of pavement change significantly depending on the time of day or season of the measurement. These factors may strongly affect the IRI value of individual pavement segments, but some of their influence averages out over the course of a network survey.

This study obtained information about each state's profiler operation in a questionnaire or by analyzing long sample profiles. These data provided an opportunity to look for major sources of bias associated with profiler operation that could be studied mathematically. These include high-pass filter type, high-pass filter cut-off wavelength, low-pass filtering practices, and profile recording interval.

The potential bias in IRI associated with each aspect of the profiler calculation process was estimated theoretically by applying them to five idealized profiles with a range of spectral content. These five profiles were selected to cover a range of pavement types that are likely to appear within a common pavement network using past studies of pavement longitudinal profile properties (Sayers, 1986; LaBarre, 1970; Robson, 1979). All of the calculations were verified on a set of five measured profiles from natural road samples that were similar in spectral content to the five idealized samples. A detailed description of this method, and its application to profile measurement, is described by Karamihas (2005).

High-Pass Filtering: With few exceptions, the participating states apply a high-pass filter as part of the profile measurement process with a cut-off wavelength of 300 ft. In general, all of the profilers of a given make apply the same type of high-pass filter. The three most common filter types were cotangent, third order Butterworth, and an anti-smoothing version of the moving average. Each of these filters differ in how well they eliminate content for wavelengths longer than the cut-off, how well they preserve content for wavelengths shorter than the cut-off, and how much they distort the shape of specific features through non-linear phase shift. Note that the 300-ft wavelength setting for the moving average is not actually a cut-off wavelength. Rather, it is the base length of the average used within the filter. The theoretical and numerical study found a range of likely downward bias levels in IRI, where the highest underestimation of IRI (represented by a negative percentage below) occurs on “wavy” roads (i.e., roads where the long wavelength content is most significant):

- Cotangent filter, 300 ft cut-off: -0.4 to -2.8%
- Third-order Butterworth filter, 300 ft cut-off: < 0.1%
- Moving average anti-smoothing filter, 300 ft base length: < 0.1%.

Note that the low overall bias level caused by the moving average is actually the result of compensating errors. This is because the moving average increases the significance of some parts of the wavelength range of interest for the IRI, but decreases the significance of others. (Technically, it has high pass-band ripple.)

Recording Interval: Recording interval is the longitudinal distance between points within the stored profile. AASHTO (2003) recommends recording profile at an interval of 2 inches or less, based on a recent research study (Karamihas, 1999). However, changes in prevailing practice have lagged the recommendations. Of the profilers that provided data for this study, only a few adhere to the recommended 2-inch recording interval. (This is due to a combination of the expense involved in retrofit of profiler components or a lack of awareness of the potential level in IRI error.) However, every state used a sample interval of 6 inches or less in their most recent survey, which constrains the resulting error in IRI to less than 1.25% on most surface types. In the earlier survey, one of the profilers used a recording interval of 8 inches, and another used a recording interval of more than 13 inches. Depending on pavement surface type, recording profile at such large intervals can bias the IRI values by as much as 3%.

Low-Pass Filtering: In most cases, all the profilers of a given make applied the same type of low-pass filter. Nevertheless, the collection of profilers that provided data for this study used a large variety of filter types and cut-off values. In particular, most of the profilers set the filter cut-off values as a function of the recording interval, such that content within the profile at wavelengths at or near the recording interval were eliminated. The IRI algorithm eliminates much of the content within a profile below wavelength of 4 ft (Sayers, 1998) and nearly all of the content within the profile below a wavelength of 6 inches (Karamihas, 2005b) before calculating the index value. As a result, the low-pass filtering in most of the profilers was eliminating content that the IRI filter would eliminate anyhow. The only exceptions were in the profilers that recorded data at a very long interval, mentioned above, and one other profiler that used a low-pass filter with a cut-off wavelength of 1 ft. These profilers measured IRI with a systematic downward bias of up to 3%.

No direct adjustment was applied to state IRI data based on these estimates. However, they were considered when making the final decisions about which of the states to select for interviews among those with a high percentage of their system beneath key IRI thresholds.

Other more obvious sources of bias in IRI occur as a result of measurement practices, such as those associated with which lanes are measured, which type of index is calculated (left IRI, right IRI, MRI or HRI), aggregation length, and whether sections with bridges are weeded from the data. As described above, these differences were overcome to the extent possible by requesting data in as uniform a manner as possible and recognizing the potential bias level in data from states that could not fill the data request as defined.

One significant source of inconsistency in IRI measurement that was not considered in this study was the interaction between height sensor footprint and pavement surface macrotexture. A common example of this is the upward bias in IRI that occurs when a longitudinally tined pavement or a pavement with coarse macrotexture, such as a recently chip-sealed pavement, is profiled using a narrow height sensor footprint. This source of measurement error is well recognized. However, the bias level is difficult to predict, and the texture type and level associated with each IRI value was not known.

Assessment of the profile data for participating states revealed a potentially significant issue with profilers of a specific make and model used by three different states. Data from all three of these profilers exhibited the same unusual features within their spectral content that could not be traced to properties of the measured pavement. The source of this content was not diagnosed as a part of this project, and the extent of the system-wide error was not clear, so no adjustments to the data were made. However, the affected states were alerted about the issue. Detection of patterns such as these across states was a beneficial outcome of this project - without a cross-state comparison and investigation, measurement issues such as these would likely have gone undiscovered.

RECOMMENDATIONS

Synthesis of Practices

If there is one lesson that can be learned from the interviews of state highway agencies with smooth roads, it is that achieving smoothness does not just happen; it requires a concerted effort on the contractor's part, a clear focus by the agency, and policies and programs that support that focus. The construction of smooth roads is largely dependent on the use of appropriate construction techniques, but good planning and preparation are also important. Some of the most promising practices to emerge from this study are summarized here in the form of recommendations for states wishing to improve highway smoothness. The recommendations are organized into the three areas listed below.

- Construction specifications
- Construction practices
- Agency practices

Construction Specifications

Recommended practices:

- Use end result specifications that include incentives and disincentives.
- Involve industry in setting acceptable target values.
- Use IRI for acceptance testing. If a profilograph is used, compute PI with a zero blanking band.
- Establish specifications with targets that can be achieved through good construction practices – without extensive grinding.

Without a doubt, the use of end result ride specifications that include incentive bonuses for exceeding smoothness targets was the most frequently referenced factor contributing to smooth roads. An end result specification requires "the contractor to take the entire responsibility for supplying a product or an item of construction. The highway agency's responsibility is to either accept or reject the final product or apply a price adjustment that compensates for the degree of compliance with the specifications (TRB 1996)." An end result specification shifts the burden for using best practices to the contractor, which provides the contractor flexibility in deciding the techniques and processes that will be used to meet the targeted values. Incentive bonuses reward the contractor for exceeding agency expectations. The agency is protected from poor workmanship through the use of disincentives, or penalties, that force the contractor to correct any areas that do not meet the acceptable target values. Most agencies place more of an emphasis on awarding bonuses than instituting penalties.

Industry involvement in setting the target values was also noted by several agencies as a key to contractor acceptance of the end result specifications. Agencies mentioned the use of task forces comprised of representatives from both the DOT and industry that meet regularly to discuss quality issues. Several agencies reported that the target values included in the specifications were established based on measured properties from recently constructed projects. By setting the targets at values slightly smoother than what was currently being constructed, agencies were able to demonstrate the reasonableness of the values to contractors and to provide motivation for the contractors to improve their practices.

Although not a requirement, most of the DOTs with smooth highways have either adopted the IRI as the unit of measure for acceptance testing or are moving in that direction. The use of the IRI provides consistency in the way pavement roughness is monitored from the time of construction to the point at which it is reconstructed, since IRI is normally monitored as part of the network level data collection activities used in pavement management. The use of a zero blanking band also appears to provide benefits. For instance, some agencies have moved to a zero blanking band to pick up roughness that might be overlooked with a 0.2 blanking band, but produce higher-frequency vibrations in vehicles that are noticeable to the public.

One agency is modifying its existing specification to create a disincentive for excessive grinding on PCC pavements. Under their existing specification, which included grinding as a solution for correcting PCC segments outside the acceptable limits, they found that contractors were using grinding excessively as a strategy for earning incentives. A transitional specification is under development that will limit the amount paid to contractors if the smoothness values are met through grinding. The DOT is working with the industry to develop a specification that does not motivate the contractor to leave bumps to avoid the grinding penalty.

Construction Practices

Recommended practices:

- Require project kick-off meetings at the start of each project.
- Encourage the contractor's use of best practices.
- Use quality materials in construction.

Because of the number of agencies using end result specifications, the methods used for construction are no longer the responsibility of the DOTs. Instead, the contractor has the freedom to use its resources as he sees fit to meet the targets established for pavement smoothness. Therefore, the DOTs no longer dictate the method or the means for getting the work done.

However, the agencies interviewed for this study have implemented several strategies to help encourage the use of best practices by the contractor. One technique used to improve project planning and coordination is a DOT-sponsored kick-off meeting that is conducted immediately prior to construction. Typically required by the DOT, these meetings should involve everyone associated with the project, including DOT employees, the contractor's field personnel, and the paving crews. They provide an opportunity to identify any unique paving requirements, to discuss project management responsibilities and coordination issues, and to identify opportunities to enhance smoothness. One agency referred to the kick-off meeting as a form of just-in-time training.

There are other strategies that can be used to encourage the use of best practice by the contractor. The use of financial incentives under the end result specification is one such strategy. These bonuses, which typically range from 2 to 5% of pay, are awarded on each 1/10-mile paving segment that is smoother than the targets established by the DOT.

Several agencies also conduct training programs that are attended by both the contractor and the DOT to communicate why smoothness is so important and to point out areas that are critical to meet the target values outlined in the specifications. Joint efforts to learn about quality and the ways to achieve it also help foster a cooperative relationship to reaching a common goal. Several agencies indicated that the good working relationship between the DOT and the contracting community has enabled the State to tighten up its smoothness specifications periodically (in one case every two years) because of the improvements in practice.

Several examples of the contractor's use of improved practices to receive incentives were provided. For instance, some contractors mentioned their purchase of material transfer devices to reduce the risk of bumps to the paver, the addition of a leveling layer of HMA at the contractor's expense, the use of mobile hot plants, and the use of dedicated trucks to maintain high production rates. For PCC pavements, contractors mentioned the use of two stringlines of aircraft cable for grade control, minimizing the amount of hand finishing, and the timely application of the curing compound and joint sawing. Contractors for both HMA and PCC pavements mentioned the importance of a consistent paver speed to ensure smoothness.

In some cases, a portion of the incentive bonuses is passed on to the paving crews. This has increased the paving crew's focus on taking the time needed to address issues impacting smoothness. A couple of contractors have purchased light-weight profilometers at their own expense so they can test each day and make any adjustments to the paving process before the next day's paving is started.

It is also important to use good, quality materials for construction. Several states indicated they use either polymer- or rubber-modified HMA mixes in an effort to improve smoothness and address other pavement properties. At least one of the agencies overlays PCC pavements relatively quickly with HMA, but that practice is primarily oriented towards reducing noise and heat levels in urban areas rather than to improve smoothness. Additionally, contractors mentioned the importance of efforts to reduce mix segregation.

Agency Practices

Recommended practices:

- Performance management orientation, with alignment of practice to performance targets
- Strong pavement management program
- Establish a cooperative relationship with the contracting community.

Although agencies may incidentally construct smooth roads, the agencies interviewed during this study have aligned their policies and practices with pavement preservation programs, smoothness initiatives, and other types of programs that identify specific targets for maintaining smooth roads. At least one agency saw a large influx of new money as part of its Smooth Road Initiative. To support this initiative, Road Rallies were conducted to obtain public perceptions of smooth roads.

Other agencies have pavement management philosophies that support their focus on smooth roads. For instance, WSDOT triggers rehabilitation as soon as 10% of the section has medium severity fatigue (alligator) cracking. As a result, the agency is resurfacing routes well before the public considers them to be rough. This strategy is successful largely because WSDOT has constructed strong foundations for its pavements so most of the cracking is contained within the top pavement layers.

All of the agencies interviewed have strong education and outreach programs in place for both their inspectors and the contracting community. In NMDOT, the DOT and AGC conduct classes for the agency and contractors (as well as other public agencies) to help ensure that the same message is delivered to everyone. This has gone a long way towards improving the consistency in practices within the State. Most of these courses are provided at no or at little cost to the contracting community, again emphasizing the agency's commitment to improved practices.

Most agencies also reward good paving practices through paving awards that recognize significant accomplishments by the contracting community. The TNDOT, working in conjunction with industry associations, has had its Smooth Pavement Awards for more than 20 years. WSDOT has also made awards for quality, but the DOT recently added two additional awards for smoothness.

The agencies interviewed for this study have also established strong, cooperative relationships with the contracting community in their State. These relationships, which take time to develop, have gone a long way towards eliminating the "us versus them" philosophy that often exists where a more open relationship has not been developed. Several agencies host regular meetings with the contracting community to address quality issues and include industry on task forces to establish or modify smoothness specifications. As a result, both parties have a better understanding of the issues that must be addressed and are better equipped to reach a workable solution.

Measurement Consistency

A major benefit of this project was that it drew attention to the problems that complicate direct comparison of IRI data from different states. Currently differences in profiler design, profile measurement procedures, filtering and sampling practices, and calibration and system checks add bias and uncertainty to the process. Fortunately, all of these aspects of profile measurement can be specified in a way that leads to valid, time stable measurements of IRI that can be compared much more directly between agencies, and between surveys by the same agency. In the course of conducting this research, several activities were identified that would improve the integrity of Interstate IRI comparisons, as well as the validity of individual state IRI databases.

1. Encourage adherence to AASHTO MP 11. AASHTO MP 11 describes many of the elements needed in a profiler to help ensure that it will provide valid profile measurements. In particular, it specifies filtering and sampling procedures that do not bias IRI measurements. One key recommendation of MP 11 is recording of profile at an interval of no larger than 2 inches. In some cases, this would require expensive modification of profiler components. If a DOT is not prepared to bear this expense, they should seek to require a recording interval of 2 inches or less in their next equipment procurement.

Another specific source of bias identified in this research was the application of a cotangent high-pass filter with a cut-off wavelength of 300 ft. The theoretical study showed that on a road with roughness that is dominated by long wavelength content (i.e., very wavy roads), a change in cut-off value to 500 ft is required to eliminate most of the downward bias in IRI.

2. Encourage rigorous application of regular calibration procedures and system checks. Regular calibration and/or sanity checks of profiler sensors and daily system checks are essential to the integrity of network IRI surveys. These include items such as the bounce test, block testing of profiler height sensors, maintenance of a consistent tire pressure, and distance measurement instrument calibration. Three excellent sources for information about these and other important procedures are: (1) AASHTO PP 50, (2) National Highway Institute Course 131100, and (3) the manual provided by a profiler manufacturer. Operators should log the application of critical procedures so that suspected problems discovered after the fact can be diagnosed more easily.

3. Further develop AASHTO MP 11 and PP 50 for network profilers. These provisional standards were first proposed and balloted in 2003, then improved and approved again in 2007. In part, the standards were written with construction quality assurance in mind, and many of the improvements between 2003 and 2007 were prompted by lessons learned while applying them in that role. As per the two suggestions above, states that apply them rigorously to network profilers should be able to either confirm their effectiveness or provide suggestions for improvements.

Profilers currently perform fewer automated data quality checks than they could. The next revision of MP 11 should consider recommending some very simple real-time data quality checks, such as suspending data collection or marking data as suspect when: (1) the profiler operates outside of its recommended speed range, (2) the profiler experiences large (> 0.15 g) longitudinal acceleration, (3) either the height sensor or accelerometer reading reaches the end of its measurement range, or (4) an accelerometer or height sensor signal is not fluctuating as expected, based on the variations in the other sensor signals.

4. Spot check profile data on control sections. A very useful way to make sure a profiler is functioning properly is to periodically pass over the same section of road with known roughness. Many agencies do this at the start of each year of measurement. This practice, or at least periodic visits of a control section, can help identify measurement problems before several days of effort are spent collecting erroneous profile data. One useful variation on the practice is the inspection of measured profiles in addition to comparison of roughness values.

Another important spot check that can be performed on profile data is comparison of data from the same segments of road in successive surveys. Of course, this is only helpful as a data quality check if a segment of road is selected that has not been rehabilitated. If the profiles are expected to agree well, but do not agree at all, further investigation and possibly diagnosis of a measurement problem should follow.

5. Verify IRI calculation software. In the course of providing a profile sample for this study, one state provided the corresponding IRI values for 0.1-mile segments. These values, generated by the profiler's native software, did not agree with the values output by the 1998 version of RoadRuf or the underlying Fortran code (Sayers, 1996). The error was rarely larger than 1%, but any error in the first five significant digits should not exist. Whenever software is used to generate IRI values for a pavement management database, they should be verified using a reference program. This could be done one agency at a time, but a more efficient way to approach this would be through direct communication with profiler manufacturers in a collective effort.

RoadRuf, while correct, is 10 years out of date. ProVAL can serve as a reference program for verifying IRI calculations, but that would require that every release of the software demonstrate concurrence with the Fortran code published by Sayers (1996).

6. Require profiler accuracy and repeatability testing as a condition of the procurement contract. Certify existing profilers against a defensible reference measurement, and upgrade them as needed. Profiler procurement contracts should require certification of profiler performance as described in AASHTO PP49 (2007) before delivery is accepted. This would protect the purchasing agency against investment in deficient equipment, against wasted labor collecting invalid data, and compromised pavement management decisions. A very important aspect of this requirement, specified in PP 49, is testing of agreement in profile, rather than just IRI value. This helps identify potential problems that may not strongly affect the overall IRI on a limited number of test sections because of compensating error. The success of PP 49 depends heavily on the availability of a valid, defensible reference profiler. Research is underway by the FHWA to provide this.

The six suggestions provided here represent significant effort. Yet, together, they would require only a fraction of the effort that could be wasted collecting and analyzing data of poor quality, and a minute fraction of the public investment in infrastructure covered in just one week of network data collection.

Often, improvements in profiler performance are delayed, because they are viewed as changes and would threaten the continuity of historical databases. However, maintaining a less accurate measurement system in the interest of continuity is not tactically sound, since most of the things that compromise profile measurements do so in a manner that is not consistent among pavement surface types, and often not consistent over time. The suggestions above can make IRI data more compatible across different agencies, which would enable improved ability to discern practices leading to smooth pavements. More fundamentally, these suggestions also aim to raise the accuracy of each agency's database, allowing for more valid trending analyses and comparison of IRI values across the network.

Improving Value Added from IRI Measurement

As states move towards improved accuracy and consistency in IRI measurement, they can also be taking steps to ensure that IRI data is easily accessible and that other data needed to interpret and act on the IRI measures are available. Specific recommendations for obtaining greater value from future comparative performance efforts – both across and within agencies - are listed below:

Make IRI data for 0.1 mile sections easily accessible. IRI data should be readily available (without special effort) so that IRI on individual segments or subsets of the system can be easily mapped, and trends in IRI can be easily plotted. Information for short sections (e.g. .1

mile) should be available for aggregation for different purposes. While maintaining actual profile information provides maximum flexibility for processing to suit various needs that may arise, it would be beneficial for continued cross-state comparative performance measurement if states maintained their data in 0.1 mile sections. It is not always easy for states to re-process profile data, particularly when data collection has been outsourced. Further, storing the IRI values in a standard form should help individual states track changes in performance over time. Processing the data into 0.1 mile sections and reviewing IRI distributions against prior year data immediately would provide a means of quality checking and trouble-shooting the data while there is still an opportunity to diagnose and correct problems. Providing some redundancy by storing both profiles and 0.1 mile IRI values is also beneficial – if the raw profile data are lost or corrupted, or if the IRI calculation software cannot be run (due to changes in personnel, vendor relationships, or operating system changes.)

Maintain accurate information about pavement types. While all of the participating agencies could characterize their pavements as flexible or rigid, there were several that could not identify composite pavements due to the lack of subsurface information. Several agencies could not provide further breakdowns within rigid and flexible categories – for example, to distinguish jointed from continually reinforced concrete. Pavement type records should include at a minimum, breakdowns by Flexible, Rigid and Composite categories; with finer breakdowns of Rigid pavements by continually reinforced, jointed plain, and jointed reinforced; finer breakdowns of Flexible by original asphalt (no overlay), asphalt over asphalt, and open graded friction course; and finer breakdowns of Composite by asphalt over jointed concrete, and asphalt over CRC. Accurate spatial referencing of pavement types is also essential to enable association with IRI values.

One state noted that standardizing pavement classifications is not a trivial undertaking. For example, would a concrete pavement overlaid several times with asphalt so that the concrete layer is 12 inches or more below the surface be classified as asphalt or concrete? There is a need to establish rules of thumb to handle cases such as these, and to recognize that engineering judgment may be required for pavement classification.

Maintain accurate pavement treatment history records. Dates of last treatments, categorized by type of treatment, with accurate spatial and temporal referencing are fundamental to enabling analysis of IRI trends, and understanding relative impacts of pavement construction versus maintenance and management practices on pavement smoothness. Treatment records need to be complete, covering both in-house and contractor work.

Maintain accurate information on bridge location. Inclusion of bridges in IRI data has been the subject of much disagreement and debate. Current HPMS guidelines call for exclusion of bridges; the new guidelines will ask states to include the bridge data. Maintaining accurate records of bridge location is important to allow states flexibility to comply with HPMS reporting requirements and conduct analysis with or without bridges – as needs dictate.

Provide data integration capabilities. The ability to easily integrate IRI data sets with pavement treatment history, functional classification, traffic, and bridge location data is needed to understand factors contributing to variations in pavement smoothness. Ideally, this capability should be accessible throughout the agency, and not require commitment of information technology resources.

Next Steps

There are several worthwhile streams of activity from the effort that was undertaken for this project:

Outreach – Findings of this project should be communicated to state DOTs, their construction contractors, and IRI equipment vendors. This outreach should have three major components: (1) practices found to contribute to smooth pavements, (2) practices for improving IRI measurement consistency and (3) recommended minimum data elements to be maintained in order to enable effective comparative performance measurement for the IRI. Specific outreach mechanisms include conference presentations, webinars, and incorporation of these findings into training courses (e.g. under the National Highway Institute umbrella.)

Continuation – A second round of data collection should be considered in the 2009 time frame. This would help provide a better understanding of the impacts and payoff from smoothness initiatives over time. This initiative would ideally involve the same set of states. Based on the experience gained in the current effort, some changes to data specifications and further automation of collection methods could be undertaken to make the process easier on states and less labor intensive for the team responsible for data compilation.

Additional Analysis – The database assembled as part of this project contains a wealth of information that could be further mined to gain an understanding of factors influencing pavement smoothness. Examples of analyses that could be done are:

- Show how inclusion or exclusion of bridges impact overall roughness results.
- Where detailed pavement types (beyond flexible vs. rigid) are available, analyze variations in roughness by pavement type.
- Where treatment dates are accurate, analyze roughness differences by pavement age cohort.

Pavement Standards Initiative – Lack of standardized methods for classifying pavement types and treatments proved to be a barrier to assembling comparable information across states. While it is not realistic to expect that this standardization can (or should) be achieved across states, an effort to compile existing classification methods currently in use and develop crosswalks to a standard set of pavement types and treatments would be of value. Such an effort might build on the HPMS pavement classifications. This initiative could be considered as an action item on the part of the Standing Committee on Planning – Asset Management Subcommittee.

4. METHODOLOGY

The key activities in this project were:

(1) Requesting participation from state DOTs

(2) Developing the data request specification

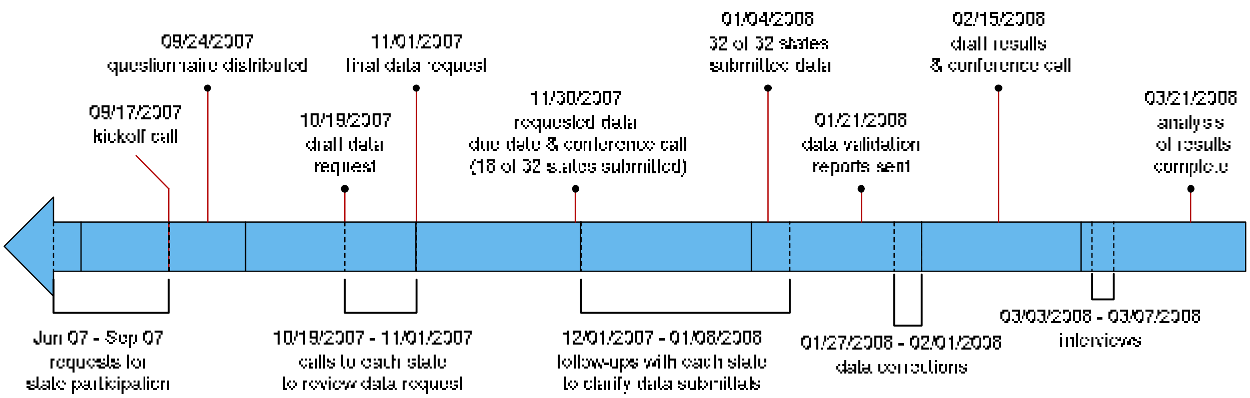
(3) Data compilation

(4) Data analysis and selection of states for interviews

(5) Identification of practices contributing to smooth pavements

Figure 11 shows the timeline of activities.

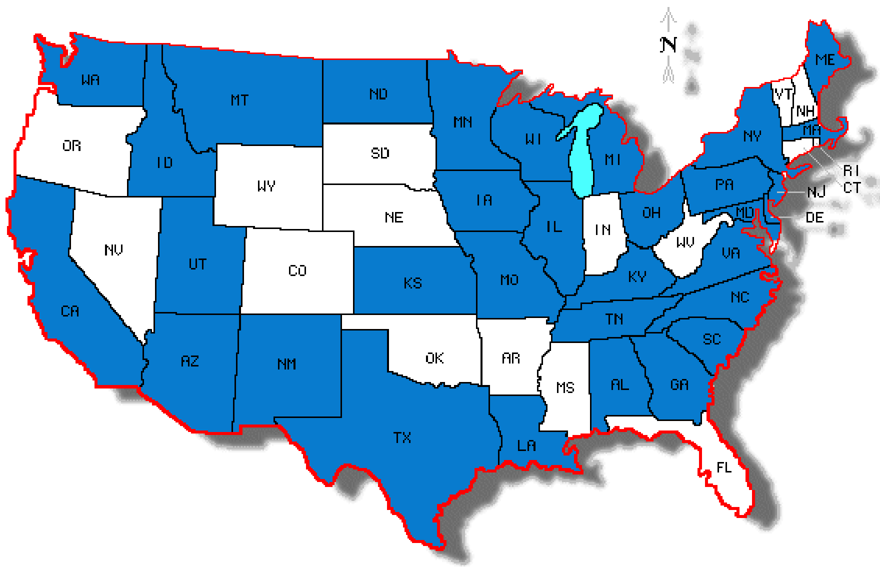
Figure 11 – Project Timeline



STATE PARTICIPATION

The AASHTO Standing Committee on Quality Performance Measures and Benchmarking Subcommittee enlisted participation in this project from 33 states. Thirty-two of the 33 were able to provide IRI data – one state could not due to resource constraints. These 32 states are shown (shaded) in Figure 12:

Figure 12 – Participating States



DATA SPECIFICATION

The initial task in the project was to specify a set of data to be assembled that would allow for comparison of IRI within peer groups across participating states. The process started with articulation of what we would like to have in order to make valid comparisons of IRI across states. It then involved an investigation of what information was available. A series of compromises were made to arrive at the least common denominator of information that could be provided by a majority of states.

Poll of the Participants

To kickoff the project, each of the participating states was asked to respond to the following question: "What do you predict will be the two most significant factors accounting for differences in Interstate IRI across states (EXCLUDING differences across measurement or calculation methods)." Responses are shown below:

Key Factors Impacting IRI	# Responses
Weather/Climate	12
Construction Methods, Quality, & Specifications	11
Pavement Management & Investment Level	11
Pavement Type	8
Pavement Age	4
Traffic	2
Availability of High Quality Construction Materials	1
Soil Characteristics	1
Terrain	1

Some respondents also offered their thoughts on measurement-related factors that impact IRI differences:

IRI Measurement-Related Factors
Averaging interval
Sampling rate
Simulation method, which wheelpaths included
Lanes and directions measured
Inclusion of bridges
Speed (on vs. off NHS)
Equipment calibration to uniform reference device
Equipment calibration to central test section
Equipment differences

Initial Memo and Conference Call

A memo was prepared reviewing project objectives and outlining candidate performance indicators, data adjustments for improved consistency, dimensions for construction of peer groups, and data sources (HPMS submittals vs. agency source systems). This memo also posed the question of how many years of data would be requested.

A draft questionnaire to be administered to all of the participants was also prepared. The purpose of this questionnaire was to assess data availability and differences in measurement practices across states, as input to formulation of the data request.

An initial conference call was held to discuss the memo and receive comments on the questionnaire. Based on questions that came up during this call, the following clarifications of the project objectives were made:

- The purpose of this project is not to do an in-depth technical investigation of factors affecting IRI, but to see what can be learned about best practice by looking at the relationship between IRI and pavement construction and maintenance practice.
- We will attempt to account for differences in measurement and reporting to the greatest extent possible. An important outcome of this project will be to recommend steps that might be taken to improve consistency and comparability in IRI measurements across states.
- This project does not require any new data collection – only already existing data will be required.
- This project is only looking at mainline Interstate IRI (ramps and frontage roads not included).
- Toll roads and turnpikes are to be included only if they are functionally classified as Urban or Rural Interstate.
- We are interested in looking at practices related to both initial construction and subsequent maintenance and rehabilitation. We are looking for a snapshot of IRI for all roads - not just IRI measurements for newly completed construction projects. Because this is a network level analysis, we will not be asking for detailed information about construction practices followed at specific sites.

The discussion of the draft memo resulted in the following decisions:

- IRI data would be provided from source systems; not from states' HPMS submittals.
- At least two years of data would be provided – ideally all states would submit data from the same two years, but that this would be determined based on the questionnaire results.
- Average IRI would be collected for relatively short uniform length sections to allow for examination of IRI distributions and calculation of a variety of statistics. Having distributions available is important for distinguishing variations in initial smoothness from overall network smoothness.
- We would collect information to allow for construction of peer groups based on functional class (urban vs. rural), climate zone, and pavement type.
- Differences in equipment will be considered based on questionnaire results, but the research team would not make systematic adjustments to account for these.
- We would request county for each pavement section to allow for use of the HPMS climate zones.

- Given the difficulty of obtaining comparable information on Interstate pavement investment levels across states, we would instead pursue obtaining information on the number of lane miles of paving work.
- We would try to obtain date of last treatment and a treatment type category to be able to segment the data by pavement age.
- Toll roads will be separated out as a peer group because these facilities have a dedicated funding source and are therefore generally in better condition.

Questionnaire Results

Results from the questionnaire are summarized in Appendix A. Key areas of inconsistency across states were identified and recommended approaches for the data specification were developed as follows:

Bridges. Inclusion of bridges in IRI data was perhaps the largest and most problematic area of inconsistency across states. There were a handful of states that do not include bridges in their IRI datasets and cannot add them back in; and a larger group that does include bridges in their IRI datasets and cannot remove them because locations cannot be accurately discerned. *It was decided to request participants to include bridges in the data submittal (where possible), but also identify (where possible) which sections were on bridges. This provided maximum flexibility for the analysis.*

Segment Length. The objective was to obtain segments of homogeneous length (0.1, 0.5 or 1.0 mile) from all states in order to produce cumulative IRI distributions. All but three states they could provide 0.1 mile sections, though some of these indicated that they would need to reprocess their data to do so. *It was decided to request IRI data in 0.1 mile segments – with smaller than 0.1 mile segments to be included at the end of routes. The few states that could not provide 0.1 mile segments were asked to provide the smallest segments available. Rather than using a straight histogram approach for data analysis, cumulative distributions of length-weighted IRI were used in order to accommodate sections of different lengths.*

Lane of IRI Measurement. Most states test the far right (outer) driving lane; some test multiple lanes; some test the worst lane. All of the states collecting multiple lanes said they would be able to report data for just a single lane. *It was decided to request data for the far right (outer) driving lane.*

One vs. Both Wheelpaths. Four of the states only measured IRI for a single wheelpath; the remainder measured both and average the two. *It was decided to request data for the average of two wheelpaths where available; one where not.*

IRI vs. HRI. All but one of the states could provide IRI - quarter car simulation. *The IRI (rather than the HRI) was requested.*

Pavement Type. The questionnaire defined eight pavement types: rigid jointed reinforced, rigid jointed plain, rigid continually reinforced concrete (CRC), flexible-original asphalt, flexible-asphalt over jointed concrete, flexible-asphalt over CRC, flexible-asphalt over asphalt, and flexible-open graded friction course and asked states if they could identify IRI sections according to these types. Nineteen states reported that they could do this, the remaining states indicated that they could not, or that this would take significant effort. Seven states could only report pavement type by either rigid or flexible categories. *It was decided to ask each state to supply their own pavement type categories, mapped to the eight listed above – with flexible and rigid being the minimum requirement.*

Pavement Age/Last Treatment Date. In order to distinguish practices for achieving initial smoothness from practices contributing to overall network-level smoothness, identification of pavement age or last treatment date was desired. In the questionnaire, 18 states indicated that they could provide this information for Interstates. An additional six indicated that they might be able to do it with some effort, and the remainder said the information was not available or would require too much effort to quality-check or compile within the confines of this project. *It was decided to request this information so that analysis could be conducted separately for newer pavements – for those states that were able to provide it.*

Data Template

A draft data template was prepared based on the analysis of questionnaire results. Calls to each participating state were made to walk through the template, obtain feedback and discuss concerns. The basics of the data request were as follows:

Two Years of Data. Two data sets were requested **-** one for 2006 (or 2005/2006 or 2006/2007 for states that collect half the network each year), and a second one for 2005 (or 2003/2004 or 2004/2005). We asked for each segment to be uniquely identified within each single-year dataset, but did not require that identifiers be consistent across the two datasets – since this would have added complexity for several states. Therefore, it is not possible with the dataset assembled to look at changes in IRI for individual segments across years.

Segments to be Included. The data request was for Interstate mainline sections – no ramps. Toll roads on Interstates were included, but states were requested to identify them as such. Bridge sections were to be included but identified (if possible).

Data Elements. Requested data elements were as follows: state ID, data set year, segment ID, existence of bridge on the segment (Y/N), toll facility (Y/N), date of IRI measurement, section length (0.1 mile requested), IRI in in/mi (from single outer lane average of both wheelpaths, quarter car simulation), county ID (for assignment of HPMS climate zone), pavement type, year of last full-depth reconstruction, year of last resurfacing (>1 inch of material added), functional class, AADT, percent trucks.

Single and Two-File Options. States were given the option of providing all of the data elements for the 0.1 mile sections, or alternatively, providing IRI and bridge identification data based on 0.1 mile sections and remaining data elements based on longer sections. Use of the two-file option required states to link each 0.1 mile section to the corresponding longer section.

Five Year Treatment Summary. States were asked to provide a table with the number of lane miles of pavement treatment by year from 2002-2006 (broken down by reconstruction/

rehabilitation/other.) These data was requested to allow the research team to look at how the average level of investment in paving related to smoothness.

Request for Profiles

The questionnaire helped identify possible sources of systematic bias in IRI measurement between the participating states. However, they did not identify every relevant aspect of profiler filtering and sampling practices of interest. To augment the questionnaire responses, and assist with analysis of the IRI data, the research team also requested one mile of profile data from each state. The request sought existing profile data from measurements performed in support of network-level IRI measurement, rather than supplemental measurements for this study. Inasmuch as each state was able to fill the request, this provided a means to verify the survey responses and seek other pertinent information about profiler operation directly from measurements that produced the IRI data.

These data provided:

- verification of key aspects of the survey responses, such as high-pass filter cut-off and profiler make,
- a means to ascertain the low-pass filter type and data recording interval,
- the opportunity to look for major measurement problems that the participants may not have been aware of, and
- a way to verify the theoretical calculations of filtering effects.

Most, but not all, of the participating states filled this request, and most of them provided profile data from the most recent collection effort. Typically, states that transitioned from one make of profiler to another over the time covered by the subsequent IRI data request provided profiles from both devices. In a few cases, these data covered the same road section. That was particularly useful.

DATA COMPILATION

Review of Tabular Data Submittals

As shown on the project timeline in Figure 11, about 18 of the 32 states were able to meet the requested November 30th date for submittal of data. States were given one month to provide the data; it actually took two months to obtain all of the data. There was significant variation in the level of effort required across states to compile the data. For many states, it was a simple matter of running a report; for others, manual work was required to fill in missing treatment history data and compile information from multiple systems. One of the biggest barriers to expedient data compilation was the lack of easily accessible capabilities to integrate (or dynamically segment) disparate linearly referenced data sources. The fact that the project focused on Interstate highways only greatly facilitated the data compilation process.

Even though a specific data template was provided for the data request, there were many variations in the format of data submittals. For example, some states did not provide separate data files for each year but rather combined data for both (or more) years of IRI data collection in a single file. Some states provided more than two files of data for each submittal – e.g. separate files for different pavement type, or separate sets of segments containing different subsets of the requested data items.

Additional issues faced in the data review and compilation stage were as follows:

- Several of the states that provided data using the two-file option did not provide complete information to allow for linking records across the two files. In some cases, link IDs were not unique; in other cases, native linear referencing was provided (e.g. route and milepost ranges) with different segmentations that needed to be matched. There were also several instances where there was data included in one file that didn't have a match in the other. Resolution of these problems required additional analysis and processing as well as multiple follow-ups.
- Two states categorized their bridge sections with a "bridge" pavement type rather than using a rigid or flexible classification. To maximize consistency in the data set, all sections identified as being on bridges were assigned a "bridge" pavement type category. Therefore, the final data set for analysis classifies sections as rigid, flexible, or bridge. It should, however, be noted that some states could not identify where their bridges were, so some of the sections classified as rigid or flexible for these states may in fact be on bridges.
- The data template did not specify whether AADT should be directional or for both directions of a highway section. Since IRI data were provided for each direction separately, directional AADT was used. Where states had provided AADT for both directions, this was divided by 2 to obtain directional AADT. This method is not strictly accurate, but was adequate for the purposes of this effort.
- The data template requested "Percent Average Daily Combination Trucks (FHWA vehicle classes 8-13) - HPMS Item 83." – but HPMS Item 83 is actually the Percent Peak Period Daily Combination Trucks. The result was that some states provided item 83, and others provided item 84. The research team ascertained which states provided each item, and then utilized summary data from 2005 HPMS submittals for each state to convert Percent Peak Period Daily Combination Trucks to Percent Daily Combination Trucks. Conversion factors were calculated and applied for each state and functional class.
- The data template requested the "year of last resurfacing - addition of 1 inch or more of material to the surface" and the "year of last full depth reconstruction." These definitions had to be clarified in several cases to allow for categorization of concrete repairs such as crack and seat with overlay. Any treatment in which materials were removed from the base was classified as reconstruction. Several states had difficulty providing complete information on last treatment dates. Some provided partial data –

for example, one state could only provide information for contract work (no in-house treatment information). Others provided the data that they were able to compile, but couldn't guarantee that it was complete. Available information was combined into a single element for each pavement section– year of last treatment (equal to the latest of the reconstruction and resurfacing dates). This data element was unavailable for about 30% of the total length, and is not strictly accurate for the states that could only provide partial information.

Compilation and Validation of Tabular Data Submittals

Following review of each data submittal and follow up with the state contact person as needed, data sets were loaded into a database (Microsoft Access was used.) Because of the variations in format, many submittals required development and application of custom transformations.

Data transformations included the following:

- If the two-file method (separate segment and section files) was used, the data in the two files were joined based on the segment IDs (or in some cases, county-route-milepost information). IRI segments that didn't match with any section records were excluded from the analysis.
- Where data were provided for multiple data sets in a single file, each year of data was separated out and assigned to a dataset.
- A new column for Pavement Type was added classifying each segment as Flexible, Rigid or Bridge. A column was also included for Original Pavement Type to preserve what was originally provided.
- A new column for Last Treatment Year was added, with the later of Reconstruction Year and Resurfacing Year.
- Columns for AADT and AADT_2WAY were included – with the directional AADT (as originally supplied, or as calculated) included as AADT, and the AADT for both directions (as originally supplied, or as calculated) included as AADT_2WAY.
- Columns for PCT TRUCKS, PCT TRUCKS DAILY, and PCT TRUCKS DAILY FINAL were defined. PCT TRUCKS contains originally supplied data for states that provided peak period percent trucks; PCT TRUCKS DAILY contains originally supplied data for states that provided daily percent trucks, and PCT TRUCKS DAILY FINAL contains either the values in PCT TRUCKS DAILY (if they existed), or the transformed PCT TRUCKS data based on the 2005 HPMS data for that state.
- A column for CLIMATE ZONE was added for the HPMS climate zone, assigned based on Federal Information Processing Standards (FIPS) county code.

- A column for LTPP CLIMATE ZONE was assigned based on a printed map[1] of LTPP climate zones as follows: AL, GA, LA, NC, SC, TN, and a portion of CA assigned to wet, no freeze zone; ID, WA, MT and a portion of CA assigned to dry freeze zone; AZ, NM, TX, UT and a portion of CA assigned to dry no freeze zone; and DE, IA, IL, KS, MA, JD, ME, MI, MN, MO, NJ, NY, OH, PA, VA and WI assigned to wet freeze zone.
- Missing attribute data were assigned a value of -1.
- Consistent formatting (e.g. numeric vs. character, right vs. left justified, trimmed vs. padded with blanks) was applied for all columns.

Following the data loading process, quality assurance checks were done to ensure, for example, that the mileages for each state in the database matched the mileages in the original submittals, and that sections with 0 length or IRI of 0 were excluded.

Queries were developed and applied to export each state's data to a standard validation report. These validation reports were transmitted to each state for review, along with a file containing their transformed raw data. This process allowed participants the opportunity to review the data prior to the analysis leading to selection of the top states. The validation reports contained the following information:

- Questionnaire - The original questionnaire that was completed for this project.
- Treatment Summary -the total lane miles of reconstruction, resurfacing/rehabilitation, and other (thin overlay, preventive maintenance) treatments over the past five years, with the average annual percentage of Interstate lane-miles of reconstruction + rehabilitation calculated based on the total Interstate lane-miles provided on the questionnaire.
- Useable Data Summary - a summary of data useable for the analysis (IRI>0, length>0), showing the number of records and lane miles by each major peer group classification value, for each of the datasets provided.
- IRI Summary - a summary of IRI results, including length-weighted average IRI, percent of length with IRI less than 60, 94 and 170 in/mi – for each year, by pavement type. A graph of cumulative length by IRI value was also included. The IRI summary data were provided first with bridges excluded, and then for all data.

A separate file containing the raw data that was loaded into the analysis database was also provided with the validation file.

A few states identified data issues, which were subsequently addressed by the research team.

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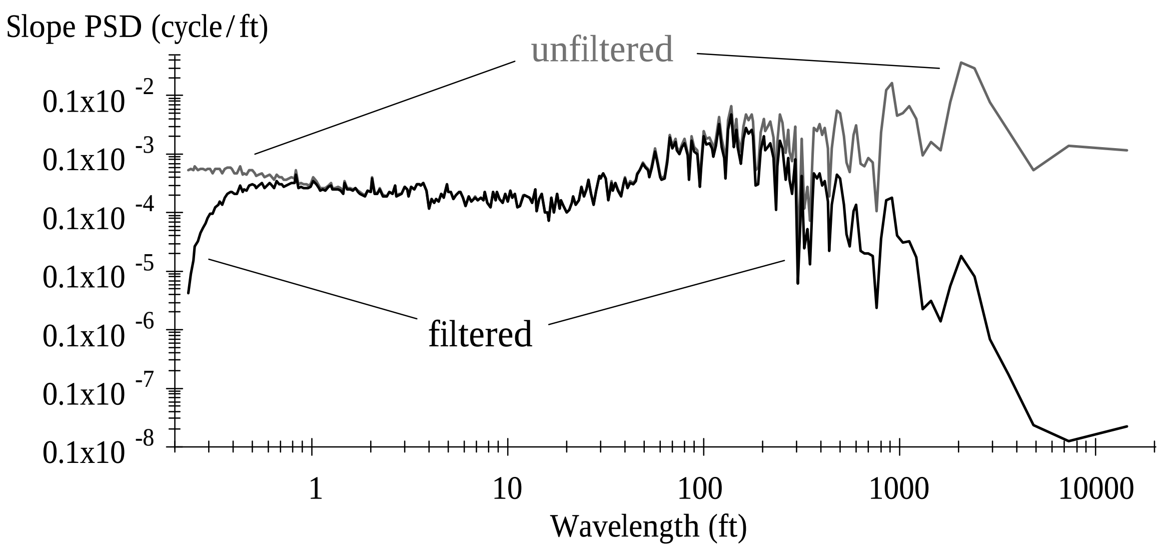
[1] A map of the LTPP climate zones can be found on page 10 of report FHWA-RD-96-208, "Pavement Treatment Effectiveness, 1995 SPS-3 and SPS-4 Site Evaluations, National Report"

Review of Profiles

As described above, profile data from most of the states provided a way to characterize the filtering and sampling practices used during network-level IRI surveys. With the exception of data recording interval, which appeared directly in the profile data file headers, the rest of the assessment was performed using power spectral density (PSD) plots. A PSD plot displays profile data as a function of frequency, rather than distance. The PSD function is scaled so that the integral (i.e., area under the curve) over any given frequency range is equal to the contribution of that range to the mean square of the signal. As a result, a PSD plot provides a way to find frequency ranges where the content within the profile is very low. In this manner, the PSD plot helps verify the presence of filtering and the wavelength used as the filter cut-off.

Figure 13 shows a version of the PSD plot for one of the submitted profiles in which the horizontal axis is wavelength. This plot is useful in three ways. First, a typical profile PSD plot displays content versus spatial frequency, which would have units of cycles/wavelength. Second, in most applications, the PSD function depends on temporal frequency (cycles/second), rather than spatial frequency (cycles/wavelength). Third, the plot shows PSD of profile slope, rather than elevation. This is done because the spectral content of a profile that has not been filtered is much more consistent with wavelength when slope is used rather than elevation. Sayers (1996) provides background on the definition of the PSD function and described these specialized plotting methods.

Figure 13 – Slope Profile PSD Plot



In Figure 13, the PSD function is displayed with and without the filtering applied. Note that the data were typically available only after filtering. The PSD plot from the unfiltered profile is only included here to help illustrate the effect of filtering. At the right side of the plot, the high-pass filter causes the PSD function to decrease as the wavelength approaches the cut-off wavelength of 300 ft. The PSD function decreases progressively as the wavelength increases beyond the cut-off value. Recognizing this without a PSD plot from the unfiltered profile is tricky, since there is no basis for comparison. However, the slope PSD of most paved roads share a common slope as the function reaches very long wavelengths (LaBarre, 1970; Robson, 1979). This helped estimate the filter cut-off wavelength.

At the left side of the PSD plot, the content rolls off sharply as the wavelength approaches the lower wavelength limit of the plot. The shape of the roll-off and the separation from the other trace provide the information needed to characterize the low-pass filter type and cut-off. Again, without the PSD plot from the unfiltered profile present, only estimates were possible.

Since only the filtered profile was typically available, the filter types and their cut-off wavelengths could not be derived precisely. However, the plots were inspected for suspicious content or content not consistent with survey responses. Further, each profiler manufacturer usually used the same (known) type of high-pass and low-pass filters in all of their profilers within the population covered by this study. That provided an expectation of what the PSD plots should look like at the extremes.

DATA ANALYSIS

Peer Groupings

The first step in the analysis was to construct peer groupings. In order to finalize the peer groupings, the distribution of data mileage based on available variables was examined. This distribution is shown in Table 1. Note that the figures include two years of data for each state[1] – so a state providing 10 directional miles for 2006 and 11 for 2007 would be shown as having 21 miles of data.

Table 1 – Breakdown of Entire IRI Sample Dataset

Variable	Value	Miles of IRI Data	Percent of Total
All Sections		115,199	100%
Bridge?	Yes	5,997	6%
	No	84,862	73%
	Unknown	24,339	21%
Functional Class	Rural	76,720	67%
	Urban	38,342	33%
	Unknown	137	<1%

[1] One state provided three years of data. While all three years were examined in the analysis, only the first and third year were included in the figures in Tables 1 and 2.

Variable	Value	Miles of IRI Data	Percent of Total
Pavement Type	Flexible*	79,603	69%
	Rigid*	29,456	26%
	Bridge*	6,008	5%
	Unknown	131	<1%
Toll Road/Turnpike?	No	106,315	92%
	Yes	4,014	3%
	Unknown	4,870	4%
Last Treatment Year Available?	No	32,086	28%
	Yes	83,113	72%
HPMS Climate Zone	1-Wet, Freeze	31,133	27%
	2-Wet, Freeze-Thaw	21,410	19%
	3-Wet, No Freeze	14,382	12%
	4-Intermediate, Freeze	16,974	15%
	5-Intermediate, Freeze-Thaw	1,492	1%
	6-Intermediate, No Freeze	5,787	5%
	7-Dry, Freeze	8,800	8%
	8-Dry, Freeze-Thaw	7,466	6%
	9-Dry, No Freeze	7,753	7%
	Unknown	3	0%
LTTP Climate Zone	Dry-Freeze	18,596	16%
	Dry-No Freeze	22,893	20%
	Wet-Freeze	53,941	47%
	Wet-No Freeze	19,769	17%

Variable	Value	Miles of IRI Data	Percent of Total
AADT Avail?	No	105	<1%
	Yes	115,094	100%
Pct Trucks Avail?	No	8,958	8%
	Yes	106,242	92%

* Flexible and Rigid categories include length from datasets where bridge locations were unknown, so these lengths may include bridges as well.

Ideally, construction of peer groups for comparative performance measurement should control for exogenous variables impacting performance, so that variations within each peer grouping reflect factors that are within the control of individual agencies. The desire to control for exogenous factors must be weighed against data availability and the practical need to avoid having too many peer groups relative to the number of data points.

Peer groups were constructed based on the LTPP climate zones, pavement type, and functional class (used as a proxy for traffic loadings). Table 2 shows the structure of the peer groupings that were used, and the breakdown of the total length in the database for each group. Records with missing values for LTPP climate zone, pavement type, or functional class were excluded. Segments on turnpikes/toll roads were also excluded. Note that one state (CA) has segments in multiple climate zones.

Table 2 – Length by Peer Group

Climate	Pavement Type	Functional Class	Miles of IRI Data
Dry, Freeze (6 states, 1 with bridges not identified)	Flexible	Urban	1,520
		Rural	10,023
	Rigid	Urban	1,228
		Rural	3,297
Dry, No Freeze (4 states, 1 with bridges not identified)	Flexible	Urban	3,581
		Rural	13,621
	Rigid	Urban	1,726
		Rural	1,845
Wet, Freeze (17 states, 2 with bridges	Flexible	Urban	12,297
		Rural	20,160

Climate	Pavement Type	Functional Class	Miles of IRI Data
not identified)	Rigid	Urban	4,532
		Rural	8,993
Wet, No Freeze (7 states, 1 with bridges not identified)	Flexible	Urban	4,755
		Rural	8,372
	Rigid	Urban	1,751
		Rural	2,785

In addition to the groupings above, an additional group was constructed to look at relatively new pavements - segments that had been resurfaced or reconstructed within two years of their IRI survey date. This group was taken from datasets provided by the 26 states that had treatment information available for at least some of their segments. For simplicity, only pavement type (not climate zone or functional class) was used to segment this group.

For each of the states, the following analyses were conducted:

- Length-weighted average IRI, and percentage of mileage with and IRI below 60, 94, and 170 in/mi were calculated for each peer group and each of the two years of data. Charts showing these statistics for each climate zone and pavement type were prepared for the most recent data year.
- Distributions of length-weighted average IRI were produced for each state.
- Sensitivity analysis was conducted for those states submitting data that included bridges to determine if any of these states would have been selected for interviews if average IRIs were 5-10% lower.
- Information on AADT, Percent Trucks, and the percentage of mileage treated over the past five years was assembled, and also considered during the selection process. All else being equal, states were favored that achieved smoother pavements under conditions that would tend to work against this – greater traffic and truck loadings, and longer paving cycles.

An initial cut was made to identify the twelve states with the smoothest pavements. Then, additional analysis (described in section 3) was performed to select the top five states for investigation. As discussed in section 3, a more limited investigation of practice was conducted for the other seven states in the top twelve.

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APPENDIX A – PARTICIPANT QUESTIONNAIRE

1	State (use 2 letter abbreviation)	AL, AZ, CA, DE, GA, ID, IA, IL, KS, KY, LA, ME, MD, MA, MI, MN, MO, MT, NJ, NM, NY, NC, ND OH, PA, SC, SD, TN, TX, UT, VA, WA, WI
2	Technical Contact Name	
3	Phone	
4	Email	
5	2006 Interstate Lane Miles - Rural***	
6	2006 Interstate Lane Miles - Urban***	
7	2006 Interstate Route Miles - Rural***	
8	2006 Interstate Route Miles -Urban***	
9	2006 Interstate VMT - Rural***	
10	2006 Interstate VMT - Urban***	
11	2006 Interstate Lane Miles on Toll Facilities	
12	2006 Interstate % Trucks – Rural	
13	2006 Interstate % Trucks – Urban	
14	Do you have a complete set of IRI data collected in 2006 covering your Interstate System?	2006-23 states 2007 but not 2006-3 states 2006/07-3 states (half each year) 2005/06 - 2 states (half each year) 2005 only - 1 state 2004 only - 1 state
15	For which prior years (between 2000-2006) do you have a complete set of Interstate IRI data?	AZ, ID, IL, KS, KY, ME, MN, MO, TX, UT, WA: 2000-2006 IA, NJ, NC, ND, OH, PA, SC, SD, WI: 2000-2006 (some or all on 2 year cycle) CA, MT: 2000-2005 DE: 2002-2004 GA: 2002, 2005, 2006 AL: 2002, 2004, 2006 LA,: 2000, 2002, 2005 MD: 2002, 2004 MA: 2004, 2006 MI: 2001, 2003, 2005 NM: 2003, 2004 TN: 2003, 2004, 2005 NY: 2001, 2003-04, 2005-06

		VA: 2005
15a	What changes in IRI equipment or measurement methods have you made that could impact comparisons across your last three years of IRI data?	10 states made changes that could impact results
15b	Have you changed construction specifications or incentives related to pavement smoothness over the period covered by your last three years of IRI data?	15 states made changes
16	IRI Measuring Equipment: Infrared, Laser, Ultrasonic, Multiple Types or Other	1-infrared, all others-laser
17	IRI Measurement by Contractor or In-house?	6-contractor, 1-both, all others-in house
18	IRI Equipment Make & Model	Pathway: 11 ARAN: 9 ICC: 8 Dynatest: 4 Other: 2
19	Frequency of IRI Equipment verification/certification	Answers not comparable – future questionnaires should distinguish calibration, certification, and verification
20	Wavelength on which data is filtered (feet)	Most: 300’
21	How do you benchmark equipment accuracy (e.g. comparison to reference device)	Use of reference device (dipstick, walking profiler, etc.): 12 Other (comparison to test section, cross-vehicle comparison, cross year comparison): 17 NA/None: 5
22	Do you use a control section (one that is measured many times throughout the season to make sure the system is stable?)	Yes-28 No-4
23	Do you measure IRI on both directions of undivided sections?	Both-15 Remainder No or NA
24	On which lanes do you measure IRI: All Lanes/Outer Lanes/Driving Lanes/Other (explain)	most: outer or right thru lanes 1 - worst lane 2- all lanes
25	If you measure IRI on more than one lane, do you have the capability to	All can report IRI for a single lane

	report it separately by lane?	
26	Does the average IRI you report to HPMS include a single lane or multiple lanes?	All but 2 report single lane
27	Do you measure IRI on both wheelpaths?	All yes
28	Does the average IRI you report to HPMS include one or both wheelpaths?	All but 4 states nclude both
29	Mathematical simulation used for IRI Computation: (quarter car or half car)	All but 1 (IL) do quarter car or both quarter and half car
30	Are bridges included in your IRI data?	Yes - 18 states No - 13 states Some years - 2 states
30a	If Yes, would you be able to remove bridges from IRI dataset or identify which sections are on bridges?	10 states could not remove bridges or would have difficulty doing so.
30b	If No, would you be able to add them back in?	4 states couldn't add them back in; 2 might have difficulty doing so.
31	Do you include construction work zones in IRI measurement?	3 do; others try not to.
32	What is the length of your data summary interval for HPMS reporting?	Not comparable - interpretations of this question varied.
32a	Would you be able to provide IRI data in .1 mile intervals?	No – 1 Maybe - 2 Yes – 30
32b	Would you be able to provide IRI data in .5 mile intervals?	No - 3 Maybe - 4 Yes -26
32c	Would you be able to provide IRI data in 1 mile intervals?	No - 2 Maybe - 2 Yes -29
32d	Ideally we would like to obtain three years of IRI data - would you be able to provide prior years of data for the same set of sections as the most current year?	Yes - 25 No-8
33	Number of Interstate universe sections in 2006 HPMS submittal	

34	Would you be able to provide VMT estimates for each IRI reporting section?	Yes-25 Possibly-5 NA/No-3
35	Do you measure pavement surface temperature as part of your IRI data collection process?	No-32 Yes-1
36	Would it be feasible for you to provide the date of the last treatment and the type of treatment (e.g. resurfacing, reconstruction) for each IRI reporting section?	Yes – 18 Possibly/partial - 6 No or probably not - 9
36A	If no, what information related to pavement age could you provide for each section?	
37	Would it be feasible for you to provide data on the number of Interstate lane miles of pavement resurfacing and reconstruction that you have done each year over the past 3-5 years?	Yes - 25 No or probably not - 8
38	Would it be feasible for you to provide a county identifier for each IRI reporting section?	Yes – 30 No/NA 3
39	Would it be feasible for you to categorize each IRI reporting section with one of the following pavement type categories: a. Rigid-jointed reinforced b. Rigid-jointed plain c. Rigid-continually reinforced d. Flexible-original asphalt e. Flexible-asphalt over jointed concrete f. Flexible-asphalt over CRC g. Flexible-asphalt over asphalt h. Flexible-Open Graded Friction Course	No or would take lots of work - 11 Remainder - Yes
39a	If no, what pavement type categories would you be able to provide?	

APPENDIX B – INTERVIEW GUIDE FOR SMOOTH PAVEMENTS PRACTICE IDENTIFICATION

NCHRP 20-24(37)B – Comparative Performance Measurement: Sharing Good Practices

Congratulations! Based on the data collected as part of this study, it appears that your agency's practices have resulted in very smooth interstate pavements. Although you were not selected as one of the five agencies to be interviewed in detail, the IRI values you reported compared favorably to those in the selected agencies. Therefore, the research team is expanding the search for best practices to include you and six other state highway agencies through this web survey. The objective of this survey is to further identify practices that have contributed to the smoothness of the interstate highways in your state. The information you provide will be incorporated into the final report, which will provide a summary of state practices that result in smoother roads.

Please identify specific practices that you feel have contributed to the smoothness of the highways within your agency. Space is provided at the end of the survey if you need to explain any of your answers. Thank you in advance for your timely completion of the questionnaire.

Name of the individual completing the survey: _____

Agency: _____

Position: _____

Item	Yes	No
Pre-Paving		
1. Are pre-paving meetings held with the contractor to discuss the project requirements and personnel responsibilities for achieving smoothness?	☐	☐
HMA Materials and Mix Design		
1. Do you optimize the mix design by taking into consideration factors such as compaction, lift thickness, segregation, and cost?	☐	☐

Item	Yes	No
2. Are there adequate plans in place for checking the consistency of the produced mix and for correcting deficiencies or inconsistencies in the produced and delivered mix?	☐	☐
3. Is the temperature of the mix checked both at the plant and paver for consistency?	☐	☐
4. Are visual observations of the mix made behind the paver to check for workability, segregation, or density problems?	☐	☐
5. Is a method available to modify the job mix formula if workability or finishing problems are encountered?	☐	☐
HMA Mix Delivery		
1. Do you develop plans for loading the trucks to minimize temperature and mix segregation?	☐	☐
2. Have you developed procedures so the mix is transferred to the paver in a manner that does not bump the paver?	☐	☐
3. Do you use a material transfer vehicle?	☐	☐
PCC Materials and Mix Design		
1. Do you optimize the mix design by taking into consideration factors such as workability, durability, segregation, and cost?	☐	☐
2. Is there an adequate plan for checking the consistency of the produced mix and correcting deficiencies or inconsistencies in the produced and delivered mix?	☐	☐
3. Are visual observations of the mix made behind the paver to check for workability, segregation, or finishing problems?	☐	☐
4. Is a method available to modify the job mix formula if workability or finishing problems are encountered?	☐	☐
Grade Control (HMA and PCC Pavements)		

Item	Yes	No
1. Has the contractor developed a procedure for control of the pavement profile (such as the use of dual stringlines in PCC pavements)?	☐	☐
2. Has the contractor established a quality control procedure for checking the finished grade (or profile) of the: a. subgrade, subbase, base, and pavement in PCC pavements? b. intermediate layers or milled surface in HMA pavements?	☐	☐
3. If a stringline is used, are there processes in place to ensure it is installed precisely, adequately supported, and offset outside the area affected by construction traffic?	☐	☐
4. Does the contractor have an established a procedure for regularly checking and maintaining the stringline?	☐	☐
5. For HMA pavements, des the ski run off the smoothest possible surface for grade control?	☐	☐
6. Does the contractor regularly check the sensors for proper height and sensitivity?	☐	☐
7. Have the design features of the roadway (grade, superelevation transitions, bridges, railroad crossing, intersections, manholes, and so on) been accounted for in the layout and staking of the pavement?	☐	☐
Pavement Foundation (HMA and PCC Pavements)		
1. Are procedures in place to ensure that a smooth, stable subgrade and base have been constructed and trimmed properly?	☐	☐
2. For HMA overlay projects, is the existing pavement evaluated for its suitability as a paving platform?	☐	☐
3. For HMA overlay projects, is a milling or a leveling course used to correct rutting and surface roughness?	☐	☐

Item	Yes	No
4. For PCC pavements, are0.9 m (3 ft) stable tracklines provided for the paver's operation?	☐	☐
Paving Speed and Delivery Rate (HMA and PCC Pavements)		
1. Do you specify that adequate delivery vehicles are available to match the production rate of the plant and the planned forward speed of the paver?	☐	☐
2. Are there contingency plans in place if the production or delivery of the mix to the paver is slowed or halted?	☐	☐
3. Do you ensure that the head of the mix in front of the paver (or screed for HMA pavements) consistent?	☐	☐
4. For HMA pavements, do you require that the top half of the auger flight exposed?	☐	☐
Compaction (HMA Pavements Only)		
1. Do you specify that a rolling pattern is established that consistently achieves the specified density?	☐	☐
2. Are there procedures in place to ensure that the rollers keep moving (or if they do stop, are they parked off the hot mat)?	☐	☐
Construction Joints (HMA Pavements Only)		
1. Do you require the contractor to have a plan for constructing transverse joints?	☐	☐
2. Do you require any of the following at the start of paving?	☐	☐
Checking the existing pavement with a straightedge?	☐	☐
. Selecting joint locations to allow for a smooth, level pavement?	☐	☐
Preparing the existing pavement by sawing or removing taper material from the previous day's paving?	☐	☐
. Placing sufficient thickness to allow for	☐	☐

Item	Yes	No
compaction?		
Use of starting blocks to ensure sufficient material is placed at the front of the joint?	☐	☐
Placing the normal head of material in front of the screed before the paver starts off the joint?	☐	☐
Bringing the paver up to normal operating speed as quickly as possible?	☐	☐
Minimizing handwork on the joint?	☐	☐
Checking the profile of the joint before compaction is applied?	☐	☐
Providing adequate room to compact the joint transversely?	☐	☐
3. Do you require any of the following at the end of a paving day?	☐	☐
Running the paver in a normal fashion up to the joint location?	☐	☐
Keeping a constant head of material kept in front of the screed as the paver approaches the joint location?	☐	☐
Keeping a constant volume of material in the hopper as the paver approaches the joint location?	☐	☐
Using runoff boards on the roller for constructing a butt joint?	☐	☐
4. When tying into bridges, railroad crossings, or existing pavement, are there procedures in place to minimize handwork and/or allow for adequate compaction?	☐	☐
Embedded Items (PCC Pavements Only)		
1. Do you have procedures in place to ensure the paver and vibrator setup have accounted for the use of embedded items, such as reinforcing steel and dowel bars in the pavement?	☐	☐
Finishing and Curing (PCC Pavements Only)		

Item	Yes	No
1. Do you have processes in place to ensure that the majority of the finishing is being performed by the paver, not the finishers?	☐	☐
2. Do you limit the finishes to edging, surface sealing with a bullfloat, and checking the pavement profile with a 3 to 8 m (10 to 25 ft) straightedge?	☐	☐
3. Do you verify that environmental conditions are conducive to the placement and curing of PCC concrete (temperature, humidity, and wind speed)?	☐	☐
4. Do you ensure that an adequate curing medium is being applied to the PCC pavement as soon as practical?	☐	☐
5. Do you have processes in place to ensure that transverse and longitudinal joints are cut into the pavement in a timely manner to prevent random cracking?	☐	☐
Equipment Maintenance (HMA and PCC Pavements)		
1. Do you require production, delivery, and placement equipment to be checked and properly maintained to minimize breakdowns during the paving process?	☐	☐
2. Do you require the equipment to be cleaned on a regular basis to prevent old mixes from being introduced into the new mix?	☐	☐
3. For HMA pavements, do you check trucks before loading to ensure that cold material is not mixed?	☐	☐
Motivated and Trained Workforce (HMA and PCC Pavements)		
1. Have adequate incentives for smoothness been developed to motivate the contractor?	☐	☐
2. Has the use of warranties on construction projects led to smoother roads?	☐	☐
3. Does the contractor pass part of the incentive along to the paving crew?	☐	☐

Item	Yes	No
4. Have you provided training for the paving crew on the importance of pavement smoothness and their role in achieving it?	☐	☐
5. Is feedback provided to the paving crew on the level of smoothness obtained on each job?	☐	☐
Profile Measurement (HMA and PCC Pavements)		
1. Do the contractor and the paving inspection team understand the pavement smoothness specification?	☐	☐
2. Do you require the profiling equipment to be properly calibrated/correlated?	☐	☐
3. Are smoothness data collected on a daily basis?	☐	☐
4. Are the pavement profiles analyzed to identify potential areas of improvement?	☐	☐
Pavement Preservation and Investment Levels		
1. Do you have a pavement preservation program in place that emphasizes the use of preventive maintenance treatments?	☐	☐
2. Are smoothness performance measures used to allocate funding for pavement improvements?	☐	☐
3. Does your agency have initiatives in placed that focus on improving pavement smoothness?	☐	☐
4. Has there been an increase in funding recently to address pavement smoothness issues?	☐	☐
5. Is smoothness a key factor in identifying and prioritizing pavement improvements in your agency?	☐	☐
6. Are smoothness measures reported to upper management regularly?	☐	☐
7. Has the increase in asphalt prices significantly impacted your ability to provide smooth roads to the public?	☐	☐

Item	Yes	No
8. Have you recently implemented maintenance practices that have improved the smoothness of your roads (such as the use of incentives or disincentives on maintenance projects)?	☐	☐
Other Practices		
1. Are there other practices you feel have significantly impacted the smoothness of roads in your state? If so, please explain in the comment box.	☐	☐

Comments: