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Best Practices for Achieving and Measuring Pavement Smoothness, A Synthesis of State-of-Practice

by

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16. Abstract

Pavement smoothness specifications have evolved significantly over the past decade. More and more states are moving away from profilograph-based smoothness specifications to IRI-based specifications. Unfortunately, a limited history with the usage of IRI-based specifications has led to some confusion over how best to structure a specification in terms of test methods and profiling equipment, thresholds for full pay/incentive/disincentive, and requirements for localized roughness or “must correct” areas. This limited history has also led to contractors who were used to profilograph-based specifications struggling to achieve the same level of quality under IRI-based specifications. This synthesis summarizes the current state-of-the-practice for IRI-based pavement smoothness specifications in the US. It highlights recent and current research related the pavement smoothness and provides general best practices for construction to help achieve requirements for IRI-based specifications.

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LTRC appreciates the dedication of the following Project Review Committee members in guiding this research study to fruition.

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Southeast Transportation Consortium

The RAC Region II has initiated a collaborative research program consortium through the Transportation Pooled Fund (TPF) Program. The research program is called the Southeast Transportation Consortium (STC) and is intended to encourage coordination among member states, as well as provide resources and management of collaborative studies. The Consortium intends to address high priority transportation research topics of common interest to the southeastern and adjoining states. Louisiana serves as the lead agency in the STC.

BEST PRACTICES FOR ACHIEVING AND MEASURING PAVEMENT SMOOTHNESS, A SYNTHESIS OF STATE-OF-PRACTICE

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CHAPTER 1. INTRODUCTION

Pavement smoothness specifications have evolved significantly over the past decade. More and more states are moving away from profilograph-based smoothness specifications to International Roughness Index (IRI)-based specifications. Unfortunately, a limited history with the usage of IRI-based specifications has led to some confusion over how best to structure a specification in terms of test methods and profiling equipment, thresholds for full pay/incentive/disincentive, and requirements for localized roughness or "must correct" areas. This limited history has also led to contractors who were used to profilograph-based specifications struggling to achieve the same level of quality under IRI-based specifications. Therefore, there is a need to synthesize the state-of-the-practice for IRI-based specifications, and a further need to synthesize best practices for construction of asphalt and concrete pavements to achieve these specifications.

It is important to note that pavement smoothness specifications and practices are effectively a moving target. States are continually refining specifications based on evaluations of existing programs and improved technology. As such, this synthesis represents a snapshot of current practices, challenges, and knowledge gaps, and is not intended to be a document of recommended practice.

Objectives

The objective of this research was to provide a synthesis of state-of-the-practice that will summarize existing practices for IRI-based specifications for asphalt and concrete paving. The specific goals of this synthesis were to document and summarize:

1) Ongoing and completed research related to pavement smoothness. Much research has been completed over the past 10-15 years regarding both best practices for paving under IRI-based specifications as well as structuring IRI-based specifications. Pavement profiling technology has evolved rapidly and specifications and test methods must be updated to keep pace with these changes. Research related to the reliability of pavement profiling technology and research on new technologies, such as "real-time smoothness" measurement behind the paver have been completed in recent years, and are documented herein.

2) Best construction practices/techniques for achieving required pavement smoothness. Along with new IRI-based specifications come new considerations with respect to the paving operation. Different aspects of the paving operation (mixture designs, material delivery,

paver operation, finishing/rolling, etc.) affect the pavement profile, as measured by an inertial profiler, differently than they affect the pavement profile measured using a profilograph.

3) States' specifications/criteria for pavement smoothness (longitudinal profile as measured by IRI). No two states' IRI-based specifications are identical. States use different methods for measurement of pavement profiles (agency testing vs. contractor testing, high-speed vs. lightweight profilers, single-point vs. line lasers), have different thresholds for full pay vs. incentive pay vs. disincentive pay, have different methods for reporting (continuous vs. fixed interval), and have different requirements for localized roughness or "must correct" areas. This synthesis seeks to compile and summarize this information such that distinctions, advantages, and disadvantages of various states' practices can be understood.

4) Technologies and practices for IRI collection and processing. IRI-based specifications necessitate measurement of pavement profiles differently from profilograph-based specifications. Inertial profilers, both high-speed and lightweight, have become the de-facto method for measurement of pavement profiles under IRI-based specifications. However, as with any "high-tech" device, profilers come in many shapes and sizes and use a variety of different sensors and data processing technologies. This synthesis documents some of the various technology advancements for collecting pavement profile data. In addition, the synthesis summarizes agency practices for certifying profilers and current efforts to assist agencies with certification.

5) Educational and training practices for agency and contractor personnel. The best specifications and test method requirements are of no use if it is not practical for contractors to achieve them and agency personnel to enforce them. A contractor who is not familiar with paving under an IRI-based specification will likely become frustrated and push back against new requirements if they are not properly acclimated to it first. Likewise, an agency project engineer or inspector who is not familiar with IRI-based specifications may not know how to properly analyze pavement profile data for the purposes of pay adjustments. As IRI-based specifications are deployed, there is a strong need for education of contractor and agency personnel. The synthesis summarizes some agency practices for educating and training agency and contractor personnel on the key aspects of paving, profile measurement, and enforcement of IRI-based specifications.

Methodology

The following methodology was used for developing this synthesis:

1) Literature Search. A literature search was conducted to identify more recent and ongoing research and implementation activities related to pavement smoothness. This includes research and literature on specification practices, pavement profile measurement, and best practices for construction.

2) American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Materials (SOM) Survey. A 12-question survey was developed and submitted to AASHTO Subcommittee on Materials representatives from all 50 states as well as Canadian provinces. The survey was used to help assess the current state-of-the practice for pavement smoothness requirements and to note any key issues agencies faced as they deployed IRI-based specifications.

3) Compilation of State Pavement Smoothness Specifications. Current pavement smoothness specifications from all 50 states were obtained and compiled to thoroughly summarize the current state-of-the practice for pavement smoothness specifications. Specifications for asphalt and concrete pavement were summarized separately and the various key aspects of smoothness specifications were compiled: IRI thresholds, pay adjustments, and localized roughness.

4) Compilation of Best Practices for Construction. At the end of the synthesis, a brief summary of best practices for asphalt and concrete pavement construction is provided.

Using this information a general assessment of current practices was provided along with gaps in current knowledge related to various issues.

CHAPTER 2. LITERATURE SEARCH

The first step in synthesizing the current state-of-the-practice was to identify recent and ongoing research and technology advances with respect to pavement smoothness. Key references compiled from the literature search are classified below by topic. This is by no means an exhaustive compilation of pavement smoothness literature, but it provides some of the more relevant information on these topics.

Equipment and Certification

Perhaps the most significant changes in recent years have occurred with the equipment that is used for measuring pavement profiles. Of particular importance are the specific requirements for inertial profiler devices, such as the sampling interval, resolution of the data, response to various roughness wavelengths, footprint for the sensors, etc. Certification is used to help ensure that data collected by different devices is portable, particularly for states which require contractor measurement of pavement profiles. As such, certification of inertial profilers used to measure pavement profiles for construction acceptance is a critical issue. Ensuring the fidelity of the data collected by these profilers is important to both the agency and contractor, as significant pay adjustments can be at stake. In addition to having a certification process in place, it’s also essential to ensure that the reference profilers that contractor and agency profilers are measured against are providing valid results. The following are selected references addressing advancements in equipment and issues with profiler certification.

Critical Profiler Accuracy Requirements ***[1].*** This report summarizes work conducted for the Transportation Pooled Fund Study TPF-5(063) “Improving the Quality of Pavement Profiler Performance” to define critical accuracy requirements for reference profiling devices that will be used to verify other profilers for construction quality control and network pavement monitoring. The report provides the objective criteria, such as the accuracy, repeatability, and sampling procedures required of a reference device. The report also defines a testing methodology needed to qualify candidate profilers for use as reference devices. These criteria provide a basis for specification and procurement of a device. In addition to the critical requirements, a major recommendation of this report is that a reference profiler should sense the pavement as similarly to a common automobile tire as possible since the tires themselves can effectively filter out certain roughness features (e.g., narrow cracks and small asperities in the pavement surface) that are picked up by laser sensors but do not affect ride quality.

The report recommends that “benchmark” tests be performed to determine the: (1) profile measurement accuracy, (2) profile repeatability, and (3) longitudinal distance measurement accuracy, when measured over a variety of pavement sections with diverse texture, pavement type, and roughness. Requirements for repeatability and accuracy are provided in the report for both the reference device and for devices (e.g., inertial profilers) which are measured against the reference device.

Evaluation of Potential Pavement Profile Reference Devices *[2].* This report documents the results from a recent round of formal evaluations of reference profilers against a Benchmark Profiler developed by the University of Michigan Transportation Research Institute (UMTRI). Tests on two reference profilers were conducted at the MnROAD research facility in Albertville, MN. Six pavement sections with a wide range of texture were first tested by the benchmark profiler, then subsequently tested by the two reference devices. This round of testing revealed that the two types of reference devices evaluated both had trouble achieving the short and medium waveband content requirements, with mixed results for the long waveband requirements. The experiment provided valuable information for use in assessing reference profilers during subsequent evaluations.

ACPA Profiler Repeatability Study *[3].* In 2005 the American Concrete Pavement Association (ACPA) conducted a study to evaluate the repeatability of various laser profilers over concrete pavement surfaces. This study was carried out in response to a 2002 study by the Michigan Concrete Paving Association and ACPA which found that the reproducibility, and in some cases repeatability, of the 12 profilers analyzed was not sufficient for concrete construction quality control applications. The original study found that profilers performed worst on test sections with coarse surface texture, and the problems were linked to the interaction of texture with the laser height sensor footprint of the candidate profilers. Profiler manufacturers have since developed or adopted new height sensor technologies with varying footprints to improve repeatability of profile measurements. In the 2005 study, five new profilers were tested for repeatability on four concrete test sections with diverse smoothness and texture: very smooth diamond ground concrete, moderately rough transversely tined concrete, smooth longitudinally tined concrete, and smooth concrete with a drag texture. The Ames Engineering lightweight profiler with a RoLine (line laser) height sensor demonstrated good or excellent repeatability on all four test sections. The Ames Engineering lightweight and high speed profilers using the TriODS (3 spot laser) system demonstrated good repeatability on the longitudinally tined section and excellent repeatability on the transversely tined and drag texture sections. The Dynatest Mark IV high-speed profiler (featuring a wide spot single laser) demonstrated excellent repeatability on the transversely tined section and good repeatability on the drag texture. The results of this study show that a majority of the profilers exhibited excellent repeatability on the transversely tined section and excellent or good repeatability on a light turf drag. Repeatability results on longitudinally tined and diamond ground pavement indicate that further development work is required by some profiler manufacturers.

Impact of Changes in Profile Measurement Technology *[4]*. A recent research project conducted by Texas Transportation Institute (TTI) for the Texas Department of Transportation (TxDOT) evaluated the impact of different inertial profiler laser sensors on TxDOT's current pavement smoothness specifications and measurement practices. This included an evaluation of the traditional single-point and newer wide-footprint (e.g., Roline and 19 mm) lasers over various pavement textures, including those from concrete, asphalt, and bituminous surface treatments. The study concluded that there is no sufficient basis to require Roline (line laser) sensors for testing conventional asphalt pavement sections. The study also found that Roline sensors in "bridge mode" significantly underestimated IRIs on porous friction course asphalt, and therefore should be operated in free mode only. For concrete pavement, the primary justification to switch to a wide footprint sensor is for testing concrete with longitudinal tining. The researchers also concluded that it is not prudent to recommend a 45 degree angle for Roline sensors testing non-continuously reinforced concrete pavements until more test data can be collected for a better assessment.

2012 Survey of Profiler Certification Methods. In 2012 Mr. David Huft with the South Dakota Department of Transportation conducted a survey of profiler certification methods as part of the "Improving the Quality of Pavement Profiler Measurement" pooled fund study. The intent of the survey was to gauge need and interest in profiler certification among agencies. Questions were asked to determine what agencies currently do for certification of their own and contractor profilers, and to identify the needs and/or obstacles for more centralized regional calibration centers. All 50 states were surveyed in addition to Puerto Rico, British Columbia, Quebec, Ontario, and FHWA (LTPP Program), and approximately 44 responses were received. Observations documented from this survey included:

1) Agencies own and certify a large number of devices.
2) Many agencies use their own procedures and facilities.
3) Most agencies do not accept other agencies' certification.
4) Some agencies apparently do not certify.
5) Perceived value of certification is credibility, technical validity.
6) There is perceived value for both network and project work.
7) Travel authorization, distance, and cost are potential barriers to regional certification facilities.

Specification Practices

A number of surveys of state practices for pavement smoothness have been conducted over the past 10-15 years. Current practices are documented later in this report. The following references provide valuable information for evaluating the progress and current state-of-the-practice for pavement smoothness specifications.

AASHTO Report on Comparative Performance Measurement for Pavement Smoothness *[5].* This report summarizes a study completed under National Cooperative Highway Research Program (NCHRP) Project 20-24(37B), which documents a comparative performance management study on pavement smoothness by the AASHTO Standing Committee on Quality, Performance Measurement and Benchmarking Subcommittee. The investigation summarized in this report analyzed two years' worth of smoothness data from the interstate system from 32 states, addressing differences in how states collect, report, and monitor performance in terms of pavement smoothness. While the report focuses on network-level data management, key information contained in this report are conclusions gained from studying "top performing" states in terms of pavement smoothness. States identified as top performing in this report included: Arizona, Missouri, New Mexico, Tennessee, Washington State, Georgia, Kansas, Michigan, Montana, North Dakota, Ohio, and Pennsylvania. This report documents a 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. Two key practices related to initial smoothness for new pavements were: (1) use of end-result ride specifications with financial incentives for good performance, and (2) establishment of close working relationships with the contractor community. Furthermore, five key agency practices that were identified for top-performing states included:

1) Strong Performance Management Orientation – establishing network-level pavement smoothness targets and deliberate investments, policies, and programs aligned with those targets.
2) Use End-Result Pavement Construction Specifications with Incentive Bonuses – specifications that 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.

3) Build Close Working Relationships with Paving Contractors – 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 for jointly identify opportunities to enhance smoothness.
4) Integrate Customer Input – involving the public in order to gauge acceptable levels of pavement roughness.
5) Pavement Management – emphasizing the importance of a sustained commitment to investment in strong pavement bases, preventive maintenance, and rehabilitation of pavements well before they become noticeably rough.

In addition to agency practices, four key contractor practices that were identified for top-performing states included:

1) Materials, Placement, and Finishing Techniques – use of polymer- or rubber-modified hot-mix asphalt (HMA) mixes, and minimizing mix segregation. For Portland cement concrete (PCC) pavements, techniques included minimizing hand finishing and timely application of the curing compound and joint sawing.
2) Equipment Deployment – 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.
3) Daily Testing and Adjustment – Daily testing of results using light-weight profilers can identify the need for immediate adjustments to improve smoothness.
4) Cultivating a “Quality Mindset” – emphasizing 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.

2009 AASHTO Subcommittee on Construction Survey of Pavement and Bridge Smoothness *[6]*. A 2009 survey of state highway agencies provided a snapshot of pavement smoothness specification practices at the time. The following are key outcomes from that survey:

- 27 of 41 (66 percent) responding agencies use IRI-based specifications for asphalt pavement, with the remaining 14 states using Profilograph Index (PrI)-based specifications.
- 9 of 42 (21 percent) responding agencies use IRI-based specifications for concrete pavement, 29 of 42 (69 percent) use PrI-based specifications, and the remaining four states do not have concrete pavement smoothness specifications.

- 32 of 41 (78 percent) responding agencies use 528 ft. section lengths for pavement smoothness measurement and pay adjustment.
- 11 of 40 (28 percent) responding agencies collect the profile data themselves, 17 of 40 (42 percent) require the contractor to collect profile data, and 12 of 40 (30 percent) have both agency and contractor data collection.
- 28 of 33 (85 percent) responding agencies have a verification process to evaluate contractor results.
- 26 of 43 (60 percent) responding agencies have a profiler certification program for state-owned profilers, and 20 of 39 (51 percent) responding states have a certification program for contractor-owned profilers.

Additional questions were asked regarding incentives and disincentive programs, but are not summarized here for brevity.

Other References

Certain characteristics of a pavement can significantly impact the profile data collected after construction. Curling and warping of concrete pavements is one of the key issues that has been identified, and the following references summarize this and associated issues.

Impact of Temperature Curling and Moisture Warping on Jointed Concrete Pavement Performance *[7].* This Tech Brief summarizes an extensive study of curling and warping of jointed concrete pavement over time and its effects on pavement performance. Under this study pavement profile and slab temperature data were collected on 38 jointed concrete pavement sites throughout the US over a 15-month period. Profile data were collected four times per day at each site in order to quantify diurnal curling, as well as four times per year at roughly half the sites to quantify seasonal changes in curling and warping. Although the study was not able to generate a direct correlation between curling and warping and pavement performance, it demonstrated a method for decomposing roughness into curvature- and non-curvature-related components. The study used the Second Generation Curvature Index (2GCI) to characterize slab curvature and correlate this curvature to roughness. The study found diurnal changes in roughness due to curling as high as 40 in/mi, with an average of 10 in/mi across all sites. This study highlights the importance of minimizing concrete pavement curling and warping through improved construction practices.

Curl and Warp Analysis of the Long-Term Pavement Performance (LTPP) SPS-2 Site in Arizona *[8].*This report documents the investigation of the roughness progression of an LTPP

SPS-2 (jointed concrete pavement) site in Arizona over the 16-year period after construction. The 21 sections evaluated varied in thickness, lane width, flexural strength, and base type. The analysis showed that curl and warp contributed to, and in some cases dominated, the roughness on many of the test sections. Curling was measured using profile data collected over the 16-year period and quantified on a slab-by-slab basis as a pseudo strain gradient (PSG) value. The PSG and changes in PSG over time were compared to changes in roughness to identify any correlations. The study was able to demonstrate the potential for isolating the effects of concrete pavement curling and warping from other sources of roughness (faulting, cracking, etc.) using the IRI-PSG relationship. The study also concluded that long-term increases in IRI may be caused by changes (i.e., progression) in curling and warping over time.

Relative Cost of Concrete Highway Features ***[9].*** This report documents a survey that was conducted by ACPA of concrete paving contractors to determine the relative cost of selected design features. Part of this survey included a component to estimate the cost of smoothness levels beyond the normal construction effort, taken as that to achieve a profilograph index of 7 in/mi with a 0.2-inch blanking band. Contractors were asked what additional efforts or tasks would be required to achieve smoother pavement. The study found that the cost to achieve lower and lower smoothness levels increases at an ever-increasing rate. In general, much of this increased cost was incurred by diamond grinding the pavement surface to achieve lower smoothness values.

NCHRP Project 10-93 - "Measuring, Characterizing, and Reporting Pavement Roughness of Low-Speed and Urban Roads" ***[10].***The stated objective of NCHRP Project 10-93 is "to identify/develop a means for measuring, characterizing, and reporting pavement roughness on low-speed and urban roads." Because the IRI is "tuned" to a speed of approximately 50 mph, there is question as to the applicability of the IRI for lower-speed roadways with unique roadway features (e.g., in urban areas). This study will be used to evaluate the feasibility and develop a model for better characterizing "urban IRI." In addition to this NCHRP study, the University of Michigan Transportation Research Institute is currently developing a prototype "urban profiler" that will be able to better measure pavement profiles under conditions unique to lower-speed urban roadways.

Intelligent Construction Technologies

Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction ***[11]***. One of the key technologies currently being deployed by a number of contractors is Real-Time Smoothness (RTS) technology for concrete pavements. This report documents the findings of Strategic Highway Research Program 2 Project R06E, which evaluated currently-available RTS technology on several concrete pavement projects in the US. RTS technology measures the pavement profile directly behind the paver, providing real-time feedback on pavement smoothness, allowing corrections to be made to the surface profile before the concrete has hardened. This report documents RTS as a tool for process control during paving, not as a substitute for profiling the pavement for acceptance after construction. The report documents a number of paving-process issues which can lead to significant roughness if not corrected, including stringline effects, concrete delivery effects, dowel basket effects, finishing effects, and other localized roughness caused by paver operation. Additional evaluations of RTS technology are currently underway through an FHWA equipment loan/demonstration program.

Other intelligent construction technologies that have the potential to improve smoothness of newly constructed pavements include:

Intelligent Compaction (IC). Although the impacts on pavement smoothness have not been thoroughly studied and documented, IC for soils and base materials is a tool to help ensure uniform compaction prior to placement of surface layers. Eliminating “soft” areas before the paver finds them can help eliminate roughness caused by an unstable paving platform. IC for asphalt pavement can help to ensure consistency of density and smoothness of the asphalt mat *[12]*.

Thermal Imaging. Thermal imaging is a technique for monitoring the mat temperature behind a hot-mix asphalt paver. Thermal imaging can help identify localized areas with significant variation in mat temperature that can lead to thermal segregation. Although it has not been thoroughly studied or documented in relation to initial pavement smoothness, there are some indications that mat temperature differences can lead to higher IRI values *[13]* and that segregated areas in the surface course can lead to noticeable roughness over time *[14]*.

Stringless Paving. Stringless paving also provides potential benefits for improving concrete pavement smoothness. Stringlines themselves can be a source of roughness imparted to the pavement surface by the paver if they are not set up correctly (particularly on crests, sags, or non-tangent sections) or carefully monitored during the paving operation. “Stringline sag” has been well documented as a cause of significant roughness *[15],[16]*. While stringless paving systems present challenges of their own, they can eliminate smoothness issues caused by stringlines *[17]*.

CHAPTER 3. SUBCOMMITTEE ON MATERIALS SURVEY

In order to help synthesize the current state-of-the-practice, the project team developed a survey for state highway agencies that was sent out to the various AASHTO SOM representatives from each state and Canadian province. In total, 36 survey responses were received, including one from the Province of Ontario.

While it was necessary to mine specifications from the states that did not submit a response, the survey provided additional information that cannot be gleaned from simply reviewing specifications. Information regarding challenges to deployment of new specifications, in particular, was helpful.

Survey Results

The following section documents the questions asked in the survey and provides a summary of key responses to each question. A summary of specification requirements (IRI thresholds, pay adjustments, etc.) is provided in a subsequent chapter since this required additional effort (in addition to the survey) to obtain that information.

Q1. What equipment is used for Measuring Smoothness?

- Equipment used for measuring smoothness, whether by the agency or contractor, is dictated by the specification requirements, with a few exceptions.
- Seven states (AR, DE, IA, KS, MI, NV, WA) with profilograph-based specifications for either asphalt or concrete allow a contractor to use profilograph simulation from inertial profiler data for computing PrI or for identifying bump/dip locations.
- Several states indicated that they own walking profilers, used primarily as reference profilers on their profiler certification sites, not for construction acceptance.
- Five states (CA, MT, NC, ND, SD) require wide-footprint (e.g., line laser) laser sensors on either agency or contractor-owned profilers, either for all pavements or at least concrete pavement.

Q2. What Smoothness Index are your pavement smoothness specifications based on?

- For concrete pavement, 50 percent of the states responding have IRI-based specifications, 44 percent have PrI-based specifications, and 6 percent have neither. For states with IRI-based specifications, 59 specify Mean Roughness Index (MRI) and 41 percent specify IRI (single wheelpath). For states with PrI-based specifications, 31 percent specify a null blanking band, 13 percent specify a 0.1-inch blanking band, and 56 percent specify a 0.2-inch blanking band.

- For asphalt pavement, 75 percent of the states responding have IRI-based specifications, 19 percent have PrI-based specifications, and 6 percent have Ride Number (RN)-based specifications. For states with IRI-based specifications, 45 percent specify MRI, 48 percent specify IRI, and 7 percent specify Half-car Roughness Index (HRI). For states with PrI-based specifications, 43 percent specify a null blanking band and 57 percent specify a 0.2” blanking band.

Q3. What is the basis for Pay Adjustments for pavement smoothness?

- For asphalt pavements, 89 percent of states have incentive/disincentive pay adjustments for smoothness, 3 percent have incentive/must-correct, 3 percent have disincentive only, and 5 percent have must correct only.
- For concrete pavements, 83 percent of states have incentive/disincentive pay adjustments for smoothness, 8 percent have incentive/must-correct, 3 percent have disincentive only, and 6 percent have must correct only.

Q4. What are criteria for Localized Roughness/Must Grinds?

- Virtually all states have some form of localized roughness provision in the form of a straightedge requirement.
- 39 percent of states indicated a profilograph-based localized roughness provision, 21 percent a continuous IRI localized roughness provision, 6 percent have a fixed-interval IRI localized roughness provision, 15 percent have only a straightedge requirement, and 18 percent either have none or did not respond.

Q5. Who conducts Pavement Smoothness Testing During and After Construction (for Quality Control and Quality Assurance)?

- 87 percent of responding states require the contractor to perform any quality control (QC) testing during construction, while the agency will conduct testing in 13 percent of the states.
- 56 percent of responding states conduct acceptance testing after construction while 44 percent require the contractor to perform acceptance testing.

Q6. What are data reporting requirements for contractor testing?

- 28 percent of states responding require both raw and processed/summary data to be submitted.
- 19 percent require only raw data to be submitted and 14 percent allow only processed data to be submitted.
- 17 percent do not permit contractor testing, and 22 percent did not respond.

Q7. What forms of corrective action are permitted?

- 92 percent of states responding allow diamond grinding as a form of correction and 89 percent allow removal and replacement. 81 percent of states permit both diamond grinding and removal and replacement as forms of correction.
- 30 percent of states which allow diamond grinding allow for incentive pay adjustment after correction and 38 percent of states allow for incentive pay adjustment after removal and replacement.

Q8. Profiler Certification Requirements

- 56 percent of states responding require certification at agency-owned facilities or agency-specified sites with known roughness.
- 22 percent of states responding require certification at a third-party certification site (e.g., TTI, National Center for Asphalt Technology, MnROAD).
- 11 percent of states responding rely upon vendor/manufacturer calibration in lieu of certification.
- 11 percent did not respond or do not have certification requirements.

Q9. Special Requirements

- None of the responding states have a time-of-day requirement for profiling concrete pavement.
- 22 percent of states responding have special requirements for open graded asphalt pavement, while 72 percent of states do not (6 percent did not respond).
- 61 percent of states responding have separate requirements for rehabilitation projects (e.g., mill and overlay, diamond grinding), while 31 percent do not (8 percent did not respond).
- 58 percent of states responding have different requirements based on facility type (e.g., controlled access vs. non-controlled, lower speed vs. higher speed facilities).

Q10. How were/are current specifications implemented?

- 58 percent of states implemented (or are currently implementing) smoothness specifications as special provisions/special specifications.
- 31 percent of states implemented (or currently have) smoothness specifications as full specs.

Q11. Was any training provided to contractors and agency project personnel?

- 75 percent of states provided formal training to contractors and agency personnel as specifications were deployed, while 6 percent did not. (19 percent did not respond.)
- Several states indicated that ProVAL Software training was provided to both agency and contractor personnel.

- Annual training of profiler operators for agencies and contractor personnel is required by several states.

Q12. What were obstacles to deploying specifications?

- 67 percent of states responding reported obstacles to specification deployment, with the various issues as listed below.
- Establishing acceptance thresholds, particularly when transitioning to IRI from PrI.
- Establishing appropriate pay adjustments (incentives/disincentives).
- Getting contractor/industry buy-in to the specification changes, sometimes requiring specification compromises.
- Resistance from agency personnel questioning why incentives are paid for smoothness.
- Making changes to the specification after it has been deployed (e.g., tightening requirements or adjusting pay factors).
- Having adequate data (e.g., existing smoothness numbers) to make decisions.
- Acquiring new equipment – affordability and deciding what to purchase.
- Convincing contractors and agency personnel that IRI is a better measure of ride quality.

CHAPTER 4. SUMMARY OF SPECIFICATION PRACTICES FOR CONSTRUCTION ACCEPTANCE

While the SOM survey provided valuable information regarding current practices, not all 50 states responded to the survey. Therefore, in order to compile pavement smoothness specifications from the remaining states, and to fill in information on current practices that was missing from some of the survey responses, additional mining of pavement smoothness specifications was completed.

The following summary encompasses the current state-of-the practice for IRI-based specifications for asphalt and concrete pavement. The scope is limited to new construction or full-depth reconstruction, with the understanding that most agencies have different requirements for rehabilitation projects encompassing overlays (and mill and overlays/inlays) for asphalt pavement and diamond grinding for concrete pavement. *Note that any state with an IRI-based specification, whether a full specification or special specification/special provision, is included in the summary*.

Smoothness Indices

Figure 1 and Figure 2 summarize the current distribution of smoothness specification types by state for asphalt and concrete pavements, respectively. Figure 3 and Figure 4 provide a further breakdown of the specific indices for the states with IRI-based specifications, for asphalt and concrete pavements, respectively. With respect to IRI-based specifications, the three smoothness indices used in US specifications are IRI (single wheelpath), MRI, and HRI. While many specifications call for the measurement of IRI in both wheelpaths, acceptance is most commonly based on the average IRI from the two wheelpaths, or MRI. Three states (CO, GA, TN) use HRI for asphalt pavement, and one of those states (CO) also uses HRI for concrete.

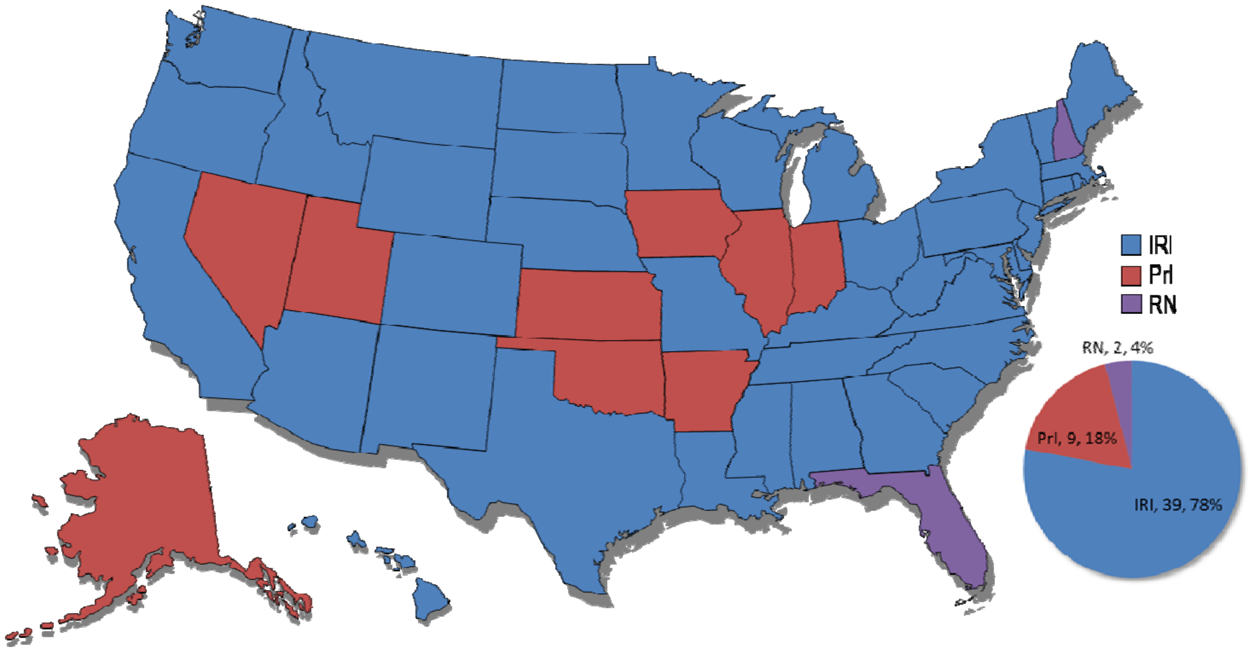

Figure 1
Smoothness specifications for asphalt pavements by state

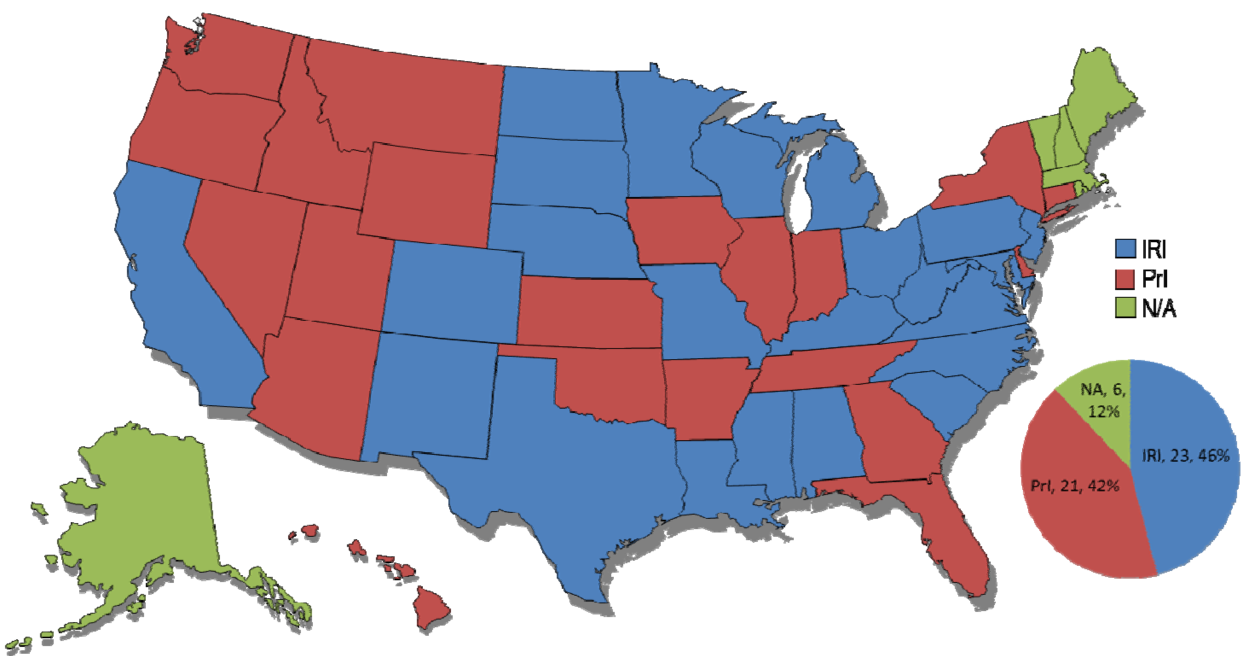

Figure 2
Smoothness specifications for concrete pavements by state

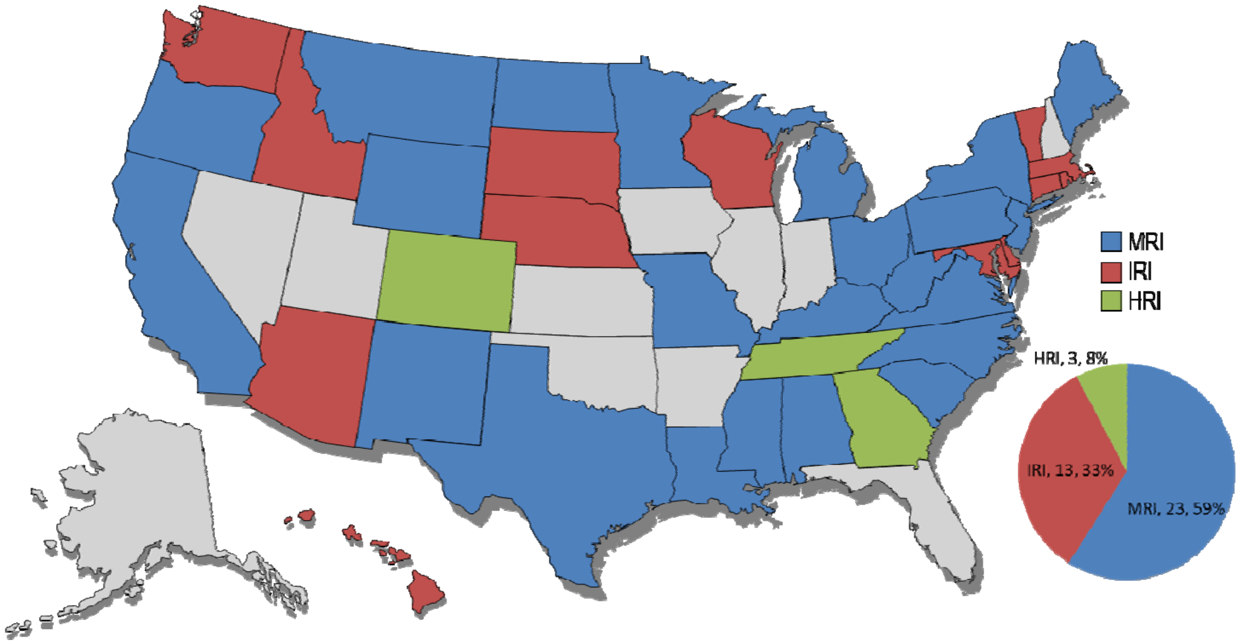

Figure 3
Specific IRI-based indices for asphalt pavements

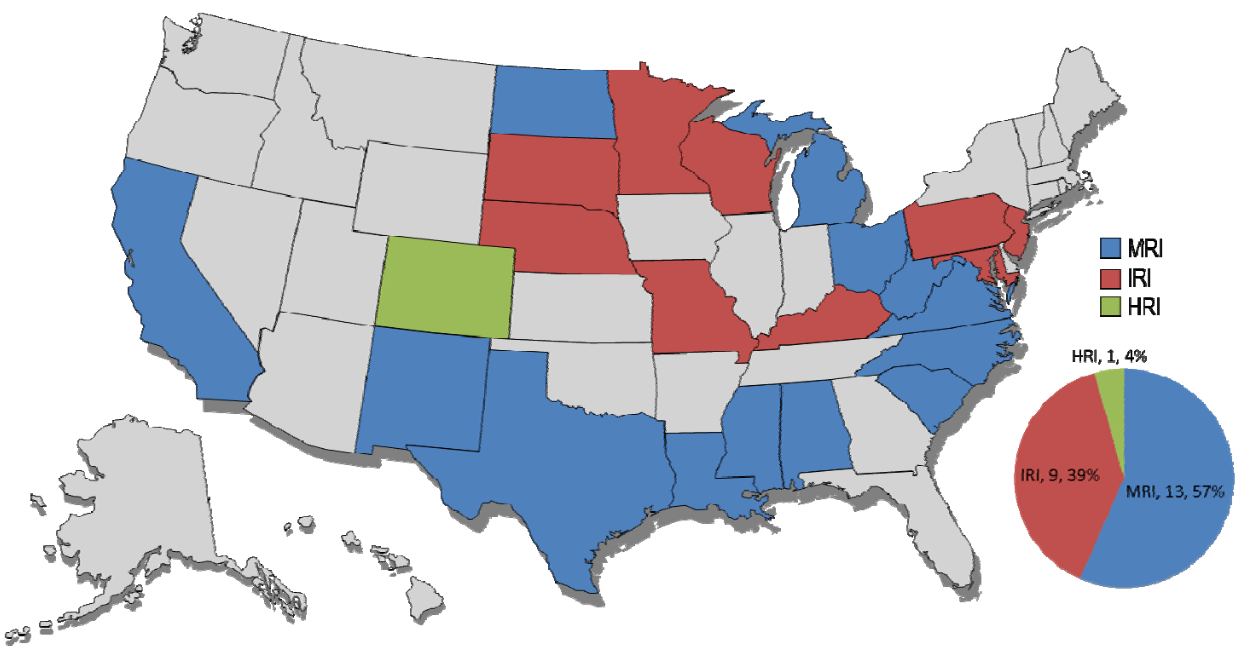

Figure 4
Specific IRI-based indices for concrete pavements

Smoothness Thresholds for IRI-Based Specifications

Table 1 summarizes the IRI/MRI/HRI thresholds for asphalt pavement and Table 2 summarizes the thresholds for concrete pavement. Thresholds are broken down by incentive pay adjustments, full pay, disincentive pay adjustments, and correction, as follows:

- The values for incentive pay adjustment represent the minimum, maximum, and average upper limits for when incentive payment would be given.
- The values for full pay are the minimum, maximum, and average values for both the lower and upper limits of full payment.
- The values for disincentive pay adjustment are the minimum, maximum, and average values for both the lower limit (i.e., value at which disincentives would be applied) and upper limit (i.e., value at which disincentive can still be applied rather than requiring correction) for disincentives.
- The values for correction are the minimum, maximum, and average values at which agencies require corrective action before acceptance.

Note that HRI is separate from IRI/MRI since the nature of the HRI index generally results in lower values than that which would be reported for the IRI or MRI. Additionally, it is important to note that not all states have both incentives and disincentives, and therefore the summarized values do not include all 39 (asphalt) or 23 (concrete) states. Figure 5 shows the comparison of IRI/MRI thresholds for asphalt and concrete pavement graphically.

Table 1
Summary of IRI-based specification thresholds for asphalt pavements

		Incentive Upper Limit	**Full Pay Lower Limit**	**Full Pay Upper Limit**	**Disincentive Lower Limit**	**Disincentive Upper Limit**	**Threshold for Correction**
MRI & IRI (36 states)	*min*	34.9	35.0	43.0	43.1	60.0	60.0
	max	79.9	80.0	100.0	100.1	149.0	150.0
	avg.	52.4	52.8	65.9	65.5	93.8	93.4
HRI (3 states)	*min*	34.0	35.0	45.0	46.0	70.0	48.0
	max	57.9	58.0	67.0	67.1	85.0	85.0
	avg.	46.0	46.5	53.2	56.6	77.5	67.7

Table 2
Summary of IRI-based specification thresholds for concrete pavements

		Incentive Upper Limit	Full Pay Lower Limit	Full Pay Upper Limit	Disincentive Lower Limit	Disincentive Upper Limit	Threshold for Correction
MRI & IRI (22 states)	*min*	39.9	40.0	54.0	54.1	67.5	60.0
	max	70.0	71.0	93.0	93.1	140.0	150.0
	avg.	56.2	56.5	71.7	72.5	95.3	96.9
HRI (CO only)		57.9	58.0	67.0	67.1	85.0	85.0

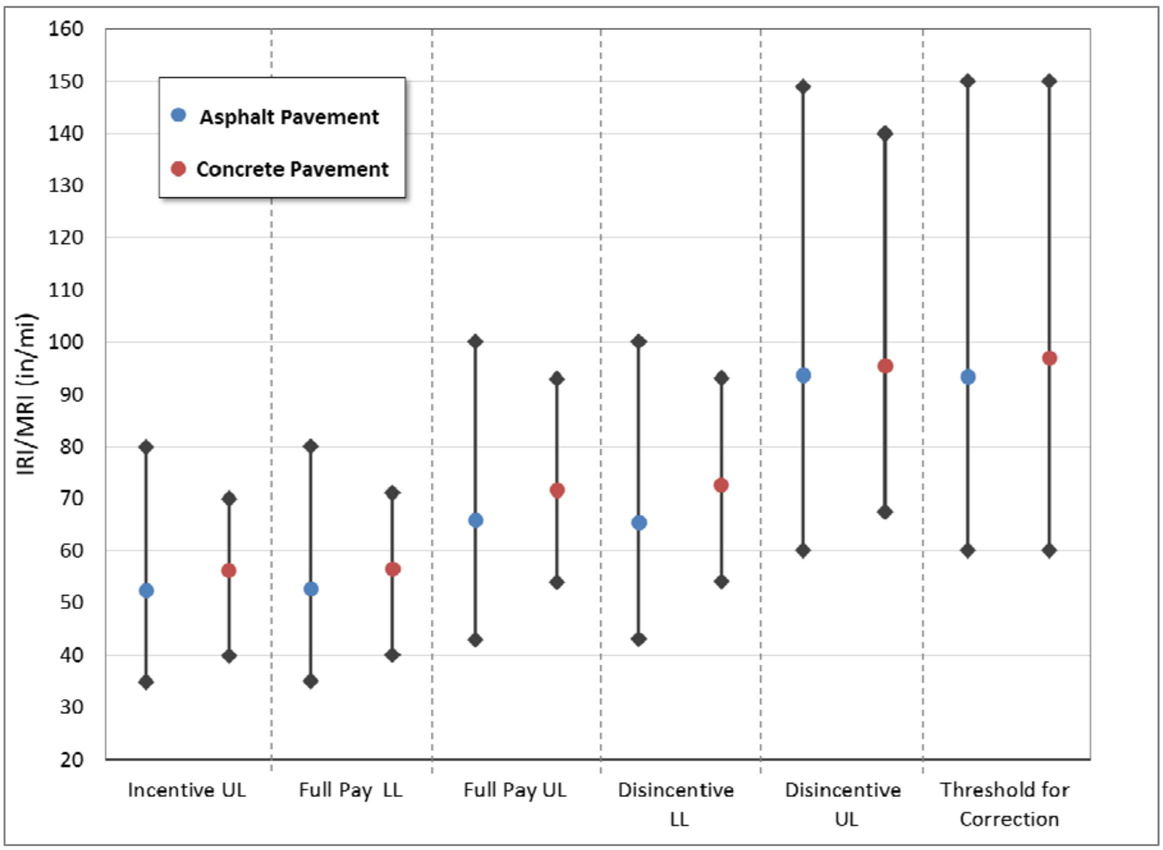

Figure 5
Comparison of specification thresholds for asphalt and concrete pavement for IRI/MRI

Reporting Segment Length

Although the vast majority of specifications are based on the IRI/MRI/HRI value for a 0.1-mile reporting segment, there are a variety of other reporting intervals found in current IRI-based specifications. It is important to note, however, that there does not appear to be any correlation between the IRI/MRI/HRI thresholds and reporting segment length. Table 3 summarizes the various reporting segment lengths found in the IRI-based specification summarized previously.

Table 3
Summary of reporting segment lengths for current IRI-based specifications

Reporting Segment Length	**Number of States**	
	Asphalt	***Concrete***
0.1-mile	28	18
1.0-mile	2	0
0.01-mile	2	2
500 ft	1	1
25 ft	1	1
Daily Placement	1	0
Project Length	2	1
3,000 ft	1	0
Variable: 0.01 to 0.1 mile	1	0

Pay Adjustments

Figure 6 and Figure 7 show the breakdown of pay adjustment schemes by state for asphalt pavement and concrete pavement, respectively. Note that only states with IRI-based specifications are shown. Pay adjustments for current specifications fall into four different categories:

1) Incentive and Disincentive – Both incentives and disincentives are applied based on ride quality values below (incentive) or above (disincentive) the full pay thresholds, discussed previously.
2) Disincentive Only – For ride quality values falling outside (above) the full-pay limits, disincentives are applied. (Most agencies will permit correction to avoid disincentives.)
3) Incentive/Must Correct – Incentives are applied for ride quality values below the full pay lower limit, but correction is required for anything above the full pay upper limit.
4) Must Correct Only – Neither disincentives nor incentives are applied. The contractor must correct ride quality to below the specified threshold.

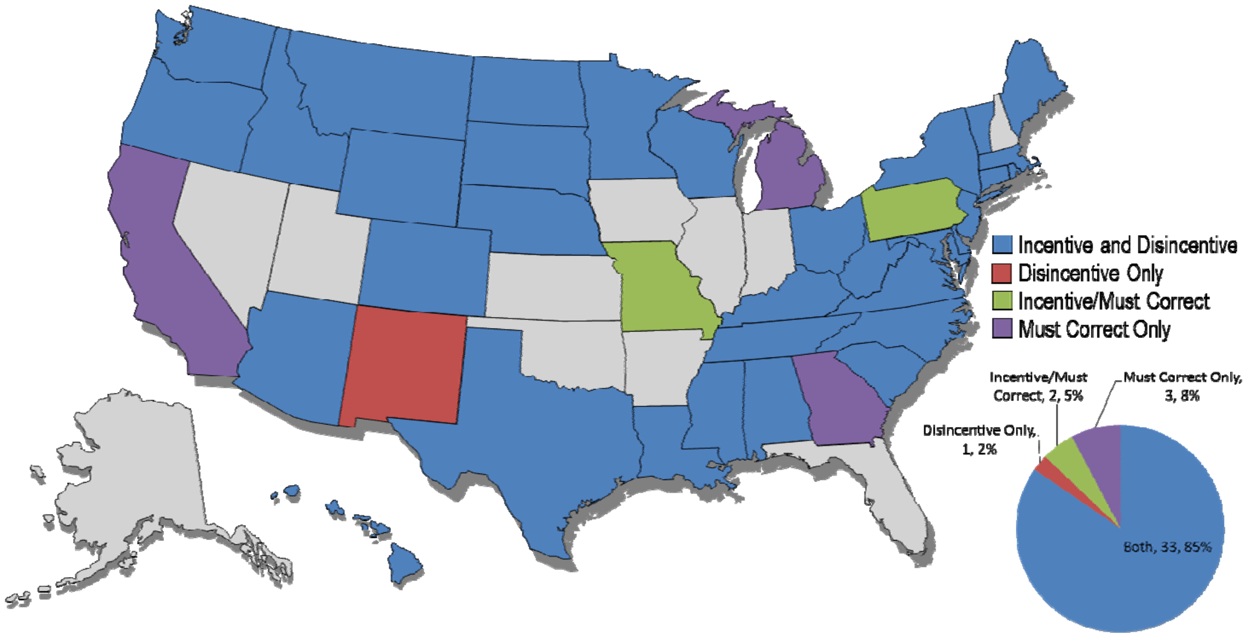

Figure 6
Summary of incentive/disincentive schemes for asphalt pavements

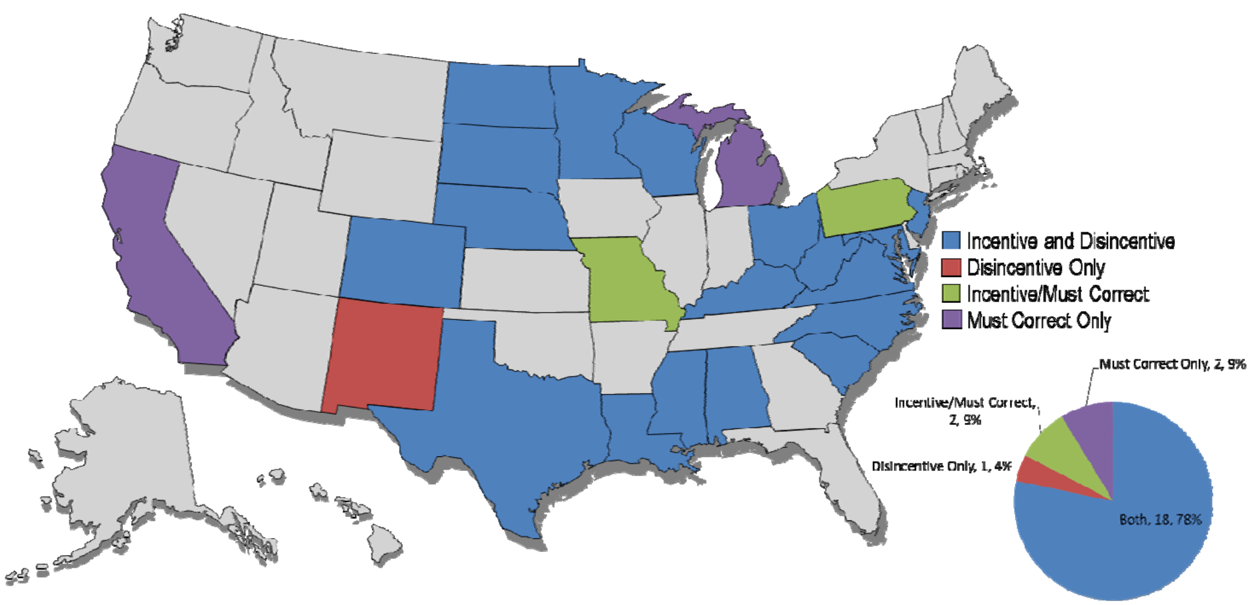

Figure 7
Summary of incentive/disincentive schemes for concrete pavements

For states with incentive and/or disincentive pay adjustment schemes, the actual pay adjustments are applied primarily by two different methods:

1) Fixed Dollar Value per Lot – A set dollar value is applied to each ride quality lot. For the majority of states, a lot is 0.1 lane-miles. However, some states use 1.0 lane-mile lots or actual square yardage of paved surface. At least one state uses 0.01-lane-mile lots and one state uses 500 lane-ft lots.
2) Percentage of Bid Item Price – The amount paid for the pavement bid item is adjusted by a certain percentage. For asphalt pavement, this adjustment is typically applied to the tonnage of asphalt placed, and for concrete pavement, this adjustment is typically applied to the quantity of concrete placed in square yards or cubic yards.

A few states use a Percent Within Limits (PWL) procedure for pay adjustments. However, the ride quality pay factor is combined with pay factors for other parameters (e.g., density, thickness, strength, etc.) and not as easily quantified as specifications in which ride quality adjustments are applied separately from other parameters. PWL-based specifications are not included in the summary tables provided below.

Maryland and New Jersey set pay adjustment thresholds based on each specific project. Wyoming’s asphalt specification uses an equation which factors in the average and standard deviation of multiple measurements along with the number of opportunities for smoothness (opportunities defined as milling, leveling, and lifts of pavement greater than 1.5 inches in thickness).

Table 4 summarizes the range of pay adjustments for current asphalt pavement specifications and Table 5 summarizes the range for current concrete pavement specifications for the various pay adjustment bases. Figure 8 provides a graphical comparison of these pay adjustments for concrete and asphalt pavement. In order to factor in the states using lots other than 0.1-miles, the pay adjustments for these states were interpolated to 0.1-mile lots and included in the average for the “Extended Pay Adjustment” shown in the table. The values for New Jersey were excluded from this extended pay adjustment as they tended to disproportionally skew the average.

Table 4
Summary of pay adjustments for IRI-based asphalt pavement specifications

Pay Adjustment Basis		Maximum Incentive	Maximum Disincentive
$ per lot (0.1 mi) ***14 states***	*min*	$200	-$250
	max	$1,098	-$1,750
	avg.	$602	-$660
$ per lot (SY) ***3 states***	*min*	$0.35	-$0.80
	max	$1.28	-$1.28
	avg.	$0.82	-$1.07
$ per lot (1.0 mi) ***2 states***	*min*	$7,350	-$7,350
	max	$8,481	-$10,177
	avg.	$7,916	-$8,764
$ per lot (0.01 mi) ***1 state***		$50	-$500
$ per lot (500 ft.) ***1 state***		$250	-$250
Extended Pay Adjustment $ per lot (0.1 mi) ***20 states (NJ excluded)***	*min*	$200	-$250
	max	$1,098	-$1,750
	avg.	$601	-$676
Percent Contract Price ***15 states***	*min*	102%	90%
	max	115%	45%
	avg.	108%	69%

Table 5
Summary of pay adjustments for IRI-based concrete pavement specifications

Pay Adjustment Basis		Maximum Incentive	Maximum Disincentive
$ per lot (0.1 mi) ***9 states***	*min*	$200	-$250
	max	$1,600	-$1,750
	avg.	$879	-$900
$ per lot (SY) ***2 states***	*min*	$1.40	-$1.12
	max	$1.40	-$1.40
	avg.	$1.40	-$1.26
$ per lot (1.0 mi) ***1 state***		$7,350	-$7,350
$ per lot (0.01 mi) ***1 state***		$50	-$500
$ per lot (500 ft.) ***1 state***		$250	-$250
Extended Pay Adjustment **$ per lot (0.1 mi)** ***13 states (NJ excluded)***	*min*	$200	-$250
	max	$1,600	-$1,750
	avg.	$825	-$831
Percent Contract Price ***7 states***	*min*	102%	90%
	max	108%	50%
	avg.	105%	75%

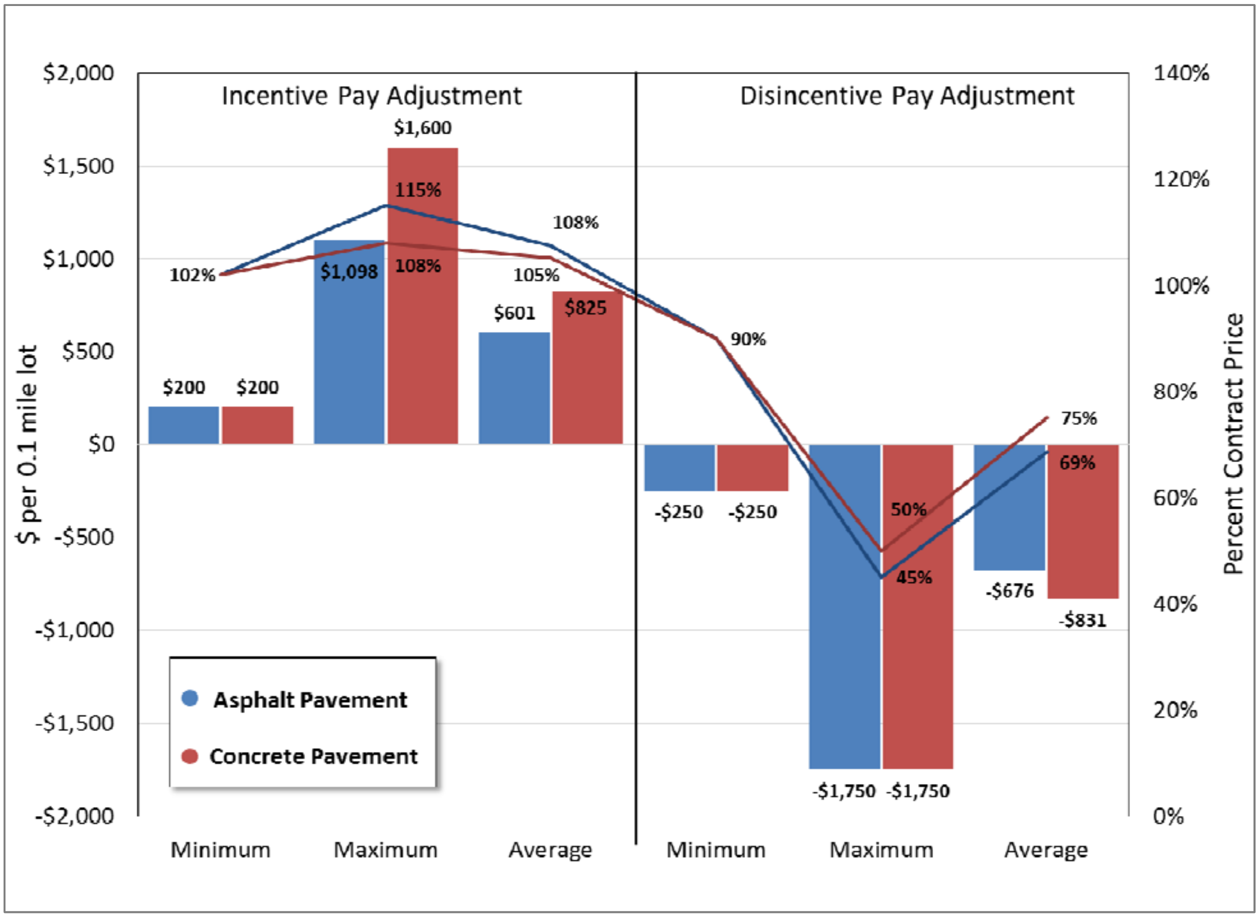

Figure 8
Comparison of asphalt and concrete incentives and disincentives for IRI-based specifications

Agency vs. Contractor Testing

Table 6 provides a summary of whether contractor or agency testing is used for acceptance of smoothness on a project. For agencies that permit contractor testing, the contractor's profiler must be certified at either a state-run or state-authorized calibration facility or at an authorized national calibration center. Most agencies which use contractor test results for acceptance will conduct verification testing on up to 10 percent of the project to ensure contractor results are comparable to agency results.

Table 6
Summary of contractor vs. agency testing requirements for IRI-based specifications

Pavement Type	**Agency Testing**	**Contractor Testing**
Asphalt (39 states)	17	22
Concrete (23 states)	7	16

Localized Roughness Provisions

Virtually all states have some form of localized roughness provision in the form of a straightedge requirement. This is typically specified as a deviation of no more than 1/8-inch to 1/4-inch over a 10 ft. or 16 ft. straightedge. While this requirement will help ensure obvious localized roughness issues (e.g., construction joints) are addressed during construction, it does not directly identify localized roughness that directly affects ride quality and smoothness indices after the fact. Most of the states with IRI-based specifications have localized roughness provisions that use the profile data collected by an inertial profiler to identify localized roughness. Roughly half of the asphalt IRI-based specifications have a localized roughness provision, while more than 85 percent of concrete pavement IRI-based specifications have a localized roughness provision. In general, these localized roughness provisions fall into one of four categories:

1) Continuous IRI – This method of localized roughness identification is outlined in more detail in AASHTO R 54-10 *[18]*. It involves using a short baselength continuous roughness (IRI/MRI/HRI) plot to identify areas that disproportionately contribute to overall roughness. The typical baselength is 25 ft. and the threshold varies from 80 in/mi to 200 in/mi (AASHTO R 54 range: 140-190 in/mi). While this method is very efficient in terms of identifying exactly where localized roughness is located in the roughness plots, issues with locating the localized roughness on the actual pavement have been reported *[19]*.
2) Fixed-Interval IRI – This method of localized roughness identification uses the IRI/MRI/HRI calculated for discrete segments of the pavement profile to identify segments where the roughness exceeds a designated threshold. Segment lengths are typically 25 ft. or 0.01 mi (52.8 ft.), and thresholds vary from 100 to 150 in/mi. One disadvantage of this method is that localized roughness may be split between two adjacent segments, effectively hiding a feature which may be significant.
3) Profile Moving Average – This method of localized roughness identification uses a moving average of the pavement profile (elevation data) to identify bumps and dips. The moving

average baselength is generally 25 ft., and the bump/dip threshold is generally 0.15 to 0.4 inches.

4) Profilograph Simulation – This method of localized roughness identification uses a software/computer based simulation of a profilograph trace based on the pavement profile to identify bumps and dips in a similar manner to that used under a conventional profilograph specification.

Table 7 summarizes ranges for various localized roughness provisions for IRI-based specifications, although these ranges should not necessarily be construed as the extreme cases for each type of provision. Several states permit a flat dollar amount pay deduction for areas of localized roughness in lieu of correction. The range for deductions is \$10 to \$500 per location, as summarized in Table 8.

Table 7
Summary of various localized roughness provisions for IRI-based specifications

Method	**Number of States**		**Range**	
	Asphalt	***Concrete***		
Continuous IRI (25 ft. baselength)	11	12	80 in/mi	200 in/mi
Fixed Interval IRI	4	4	25 ft. segment: 150-160 in/mi	0.01 mi (52.8 ft.) segment: 100-125 in/mi
Profile Moving Average (25 ft. baselength)	4	1	0.15 inches	0.4 inches
Profilograph Simulation (25 ft. baselength)	2	2	0.3 inches	0.4 inches
Straightedge Only	18	4	1/8-inch in 16 ft.	1/4-inch in 10 ft.

Table 8
Summary of pay deductions for localized roughness

	Asphalt Pavement *(8 States)*	**Concrete Pavement** *(3 states)*
Min	-$10	-$10
Max	-$500	-$250
Average	-$313	-$173

Equipment

As revealed from the SOM survey, most agencies with inertial profiler-based specifications will allow the use of lightweight profilers. Lightweight profilers offer two key advantages:

1) Because they weigh significantly less than a typical high speed profiler (mounted on a full size van or pickup truck), they can be used on new concrete pavement sooner, even before it has reached “open to traffic” strength.
2) Lightweight profilers have a lower operating speed, requiring less lead-in distance to get the profiler up to speed for testing. This makes these profilers better suited for operating in constrained conditions, such as behind barriers or between shorter sections of non-continuous pavement.

A key disadvantage to lightweight profilers is that most are set up to only measure one wheelpath. This requires at least two runs to obtain profile data for one lane (assuming an MRI or HRI specification), and requires careful coordination of the runs for each wheelpath to ensure they line up. As discussed above, a few states that require a profilograph simulation are using profile data in order to identify localized roughness.

Also as revealed from the SOM survey and specification query, several states require wide-footprint (e.g., line laser) sensors on either agency or contractor-owned profilers, either for all pavements or at least concrete pavement. A few states indicated that they would be moving towards a requirement for line lasers since the cost and availability of this technology has improved.

CHAPTER 5. ASSESSMENT OF THE CURRENT STATE-OF-THE-PRACTICE

This section will be used to provide a general assessment of the current state-of-the-practice for pavement smoothness specifications and requirements. The 2008 AASHTO Comparative Performance Management report for pavement smoothness discussed previously provides a good framework for evaluating the current state-of-the-practice *[5]*. The report presents a synthesis of practices of high-performing states for three different areas: construction specifications, construction practices, and agency practices. The current state-of-the practice is evaluated in light of these recommendations, along with identification of gaps in current knowledge for each area.

Construction Specifications

Use end-result specifications that include incentives and disincentives. As the summary of smoothness pay adjustments above shows, for states with IRI-based specifications, 92 percent currently have incentive and/or disincentive pay adjustments for asphalt pavement (Figure 6) and 91 percent have incentive and/or disincentive pay adjustments for concrete pavement (Figure 7). In this respect, the current state-of-the-practice for smoothness specifications is trending in the right direction, although there are still questions as to what levels of incentives and disincentives are appropriate.

With respect to end-result specifications, virtually all pavement smoothness specifications are end-result specifications. A few states still prescribe equipment that is believed to help achieve smoothness requirements (e.g., material transfer vehicles for asphalt paving), but it can be argued that those requirements benefit more than just smoothness (e.g., material transfer vehicles are known to help reduce temperature segregation in the mat). It can also be argued, however, that prescriptive specifications for materials and mixture designs can affect the smoothness values that the contractor is able to achieve. Design-build projects being used more commonly in many states provide insight as to what a contractor can achieve given more flexibility in selection of materials and methods for paving.

Involve industry in setting acceptable target values. Although it is difficult to assess from the information gathered for this synthesis how many states involve the paving industry in setting target values within pavement smoothness specifications, several states indicated a very intentional and thoughtful process for developing and deploying specifications. A number of states have very active industry association state chapters (ACPA, NAPA) which are regularly providing input for specification changes. There is an indication that most states deploy new or revised specifications gradually over several years, allowing them to evaluate the specification on select pilot projects initially. Some states indicated that they would remove incentive/disincentive pay adjustments from the specification during the pilot project phase so that specification could be evaluated at low risk to the contractor.

Use IRI for acceptance testing. If a profilograph is used, compute PrI with a zero blanking band. As the summary of specification practices above shows, 78 percent of states currently have an IRI-based specification for asphalt pavement (Figure 1) and 46 percent for concrete pavement (Figure 2), with 12 percent having no formal smoothness specification for concrete pavement. This is a significant improvement from the 2009 AASHTO SOC survey which reported 66 percent of states using IRI-based specifications for asphalt pavement and 21 percent for concrete pavement (recognizing that only 41 of 50 states responded for asphalt and 42 of 50 for concrete).

With regard to PrI-based specifications, only 4 of 21 states (19 percent) use a zero blanking band for concrete pavement, while 4 of 9 states (44 percent) use a zero blanking band for asphalt pavement. The majority of states (57 percent) use a 0.2-inch blanking band for concrete and roughly one-third use a 0.2-inch blanking band for asphalt. The remainder use a 0.1-inch blanking band.

Establish specifications with targets that can be achieved through good construction practices – without extensive grinding. No data is currently available to assess what specification targets will help ensure good practices while minimizing grinding. However, states with even the most stringent smoothness specifications (e.g., North Dakota DOT’s localized roughness provision for concrete) report that contractors who are very intentional about smoothness can routinely achieve IRI values in the 30-40 in/mi range. Specifications which either limit the amount of grinding allowed or at least restrict incentives only to non-ground pavement can help encourage better practices while minimizing the amount of grinding.

Gaps in Current Knowledge. With respect to the Construction Specifications recommendations and assessment presented above, the following summarizes gaps in current knowledge:

- How much flexibility should an agency give a contractor over materials and methods (for truly end-result specifications) in order to still ensure a long-lasting pavement?
- How much should an agency pay for smoother pavements?
- What are reasonable specification thresholds that will encourage good practices without begin overly punitive?
- What is the actual cost-benefit from incentive-based pavement smoothness specifications?

- At what point, if ever, should smoothness incentives be discontinued as industry practices continue to improve?
- Do the disincentives/pay reductions for smoothness deficiencies cover the potential long-term costs of maintaining those pavements?
- How much corrective action (e.g., grinding) should be allowed before removal and replacement is required?
- What are best practices for incorporating pavement industry input into the development or refinement of smoothness specifications?
- What are the costs vs. benefit of providing training to contractors?
- How often should an agency revisit smoothness specification thresholds and pay adjustments?
- What are the main obstacles to shifting to IRI-based specifications?
- What are best practices for timing of profile data collection on concrete pavement, considering the effects of slab curling?
- What is the best method for measuring, quantifying, and locating (for correction) areas of localized roughness?
- What are best practices for certifying contractor/consultant owned profilers locally?
- What effect does grinding have on pavement life and other surface characteristics such as frictional properties and tire-pavement noise?

Construction Practices

In terms of construction practices, the AASHTO report identifies at least three key practices:

Require project kick-off meetings at the start of each project. Planning and communication have been identified time and time again as essential elements of a successful paving project. A kick-off meeting and/or pre-paving meetings allow the contractor and inspectors to get all issues on the table before paving begins. The California Department of Transportation (Caltrans), for example, has a provision for "Just-In-Time-Training" that can be added to projects with new technology or specifications. While not the same as a kick-off meeting, the training is designed to get contractor personnel, inspectors, and other agency personnel together to discuss the project before construction begins, and to provide specialized training for unique aspects of the project.

Encourage the contractor's use of best practices. Incentives are one method for helping to encourage the contractor to use best practices, and as shown previously are incorporated into 90 percent of current asphalt pavement specifications (Figure 6) and 86 percent of current concrete pavement specifications (Figure 7). Incentives may encourage contractors to invest in equipment and intelligent construction technologies that will help them achieve smoothness incentives. They may also be used by contractors to help motivate their workforce through sharing of incentive payouts.

Another method for helping encourage contractors' use of best practices is through training for contractor personnel. Helping contractor personnel to understand aspects of the paving operation that affect pavement smoothness can only benefit the paving process. The New Mexico Department of Transportation (NMDOT) provides training to contractor and agency personnel through the New Mexico Technician Training and Certification Program (TTCP). TTCP is a collaborative effort with NMDOT, FHWA, and the Associated Contractors of New Mexico and provides a variety of training and certification modules, including training and certification for profiler operators. In 2011, NMDOT reported that contractors accounted for 13 percent of the TTCP trainees while private labs and consultants accounted for another 20 percent. The cost for most of the training classes is nominal (< $350) or free *[20]*. The Wisconsin Department of Transportation, likewise, facilitates a Highway Technician Certification Program (HTCP) through the University of Wisconsin-Platteville which includes, among a variety of other certifications, certification for profiler operators *[21]*. Finally, another method for helping encourage best practices is through some form of a Quality Management Program (QMP). A QMP, similar to that used by WisDOT, requires the contractor to maintain a very detailed quality control program for all testing during paving, including pavement smoothness testing.

Use quality materials in construction. The use of quality materials in construction is difficult to quantify from the information gathered. The AASHTO report noted that the use of polymer-modified or rubber-modified hot-mix asphalt mixtures are beneficial, as are techniques for minimizing mix segregation. Other indicators that states are encouraging contractors to pay special attention to materials that will help them achieve smoothness requirements include incentives for certain material or mixture properties. The Minnesota Department of Transportation (MnDOT), for example, provides a financial incentive for contractors to use an optimized aggregate gradation for concrete pavement. TxDOT and the Iowa Department of Transportation likewise have optimized aggregate gradation requirements for concrete pavement mixtures that will help improve constructability and long-term performance.

Gaps in Current Knowledge. With respect to the Construction Practices recommendations and assessment presented above, the following is a list of gaps in current knowledge:

- What is the cost vs. benefit of requiring kick-off, pre-construction, or pre-paving meetings?
- Are there any aspects of pavement smoothness specifications that can be relaxed if kick-off/pre-construction/pre-paving meetings are required?

- What are the most effective methods for encouraging contractor best practices?
- What is the cost vs. benefit for training and certification programs such as the NMDOT TTCP?
- What are prescriptive specification requirements for materials selection and mixture designs that can be relaxed to help contractors achieve smoothness requirements?

Agency Practices

In terms of agency practices, the AASHTO report identifies at least three key practices:

1) Performance management orientation, with alignment of practice to performance targets
2) Strong pavement management program
3) Establishing a cooperative relationship with the contracting community

The current state-of-the-practice with respect to these recommendations is difficult to assess based on information gathered for this synthesis. The first two practices are primarily related to network-level smoothness monitoring. However, there are aspects of construction specifications which are applicable to these. Decisions made at the point of construction can affect the long-term performance of a pavement. Pavements constructed smoother initially have been shown to stay smoother longer and last longer. However, the requirement for construction smoothness must be reasonable and achievable, accounting for specific project conditions.

What an agency is willing to pay for a smooth pavement is also affected by the agency's performance management philosophy. Providing agency personnel overseeing construction some flexibility in deviating from the design and construction plans, in order to give the contractor a better opportunity to achieve the smoothness requirements, is part of this philosophy. One example is providing contractors a material allowance to widen the pavement base to provide a stable trackline for a slipform concrete paver. Material allowances for any necessary "level up" can also be beneficial for helping the contractor achieve smoothness requirements.

In terms of pavement management programs, closely monitoring pavement condition can help ensure rehabilitation decisions are made in a timely manner, such that smoothness requirements for rehabilitation projects are still achievable. Monitoring pavement roughness progression over time through a pavement management program will also help agencies in setting smoothness targets for construction.

With respect to establishing a cooperative relationship with the contracting community, based on responses from the SOM survey and interviews with industry association representatives, it is apparent that most states understand the benefit of working closely with the contracting community when deploying new specifications or revising existing specifications. As new specifications are deployed, they are generally phased in on an evaluation basis before being applied to all projects. Many states provide training opportunities for contractors, along with agency personnel to smooth the transition to the new specification.

Agencies also provide tools for helping contractors meet the necessary training and certification requirements. Minnesota DOT, for example, has an online e-Learning course (and exam) that is provided free of charge for profiler operators to become certified, eliminating the need for classroom-based training and associated travel cost *[22]*.

Finally, recognizing good performance through awards or other recognition by the agency can help encourage the relationship with the contracting community.

Gaps in Current Knowledge

- What are key aspects of a Performance Management philosophy that will help promote good practices for pavement smoothness specifications?
- How can pavement smoothness values from construction be integrated into and used within a Pavement Management system?
- What are key aspects of a truly cooperative relationship with the contracting community as it relates to pavement smoothness?

CHAPTER 6. BEST PRACTICES FOR CONSTRUCTION

Paving, by its very nature, is a repetitive process in which roughness patterns emerge, caused by certain aspects of the paving operation (paving mixtures, material delivery, paver operation, finishing/rolling, etc.). Improper settings on a vibratory roller, for example, can result in "ripples" in the pavement, while stringline sag on a concrete paving operation can result in a 25-50 ft. "wave" in the finished pavement. In addition to these roughness patterns, single incidents during construction can result in isolated areas of localized roughness that contribute to the overall roughness disproportionately. These incidents can be as simple as a haul truck bumping the asphalt paver or a poorly constructed header joint.

IRI-based specifications present new considerations with respect to paving operations. Pavement profiles measured by inertial profilers can reveal roughness patterns and areas of localized roughness that may not have appeared in a profilograph trace. Therefore, certain aspects of the paving operation that may not have been as significant under a profilograph specification now become very important under an IRI-based specification.

With this in mind, this portion of the synthesis will help to summarize general best practices for construction. This is by no means a comprehensive summary of best practices, nor will following these practices ensure smoothness specification requirements are achieved.

Key Themes

Some overall key themes for any paving operation surfaced from the many sources of information on best practices. These overall themes include:

Planning and communication. Conscientious contractors spend a lot of time planning the entire paving job long before any asphalt or concrete is placed. It is critical to think through the whole operation, from the setup of the batch plant, material delivery, project location, traffic control, and paving sequence, among other items. Contingencies for equipment breakdowns, weather, and material issues should all be identified ahead of time.

Likewise, conscientious contractors communicate the entire plan to everybody involved in the project and do not have a "need to know" mentality. Pre-paving meetings with everyone involved, including DOT personnel and all levels of the paving crew, will help everyone understand what needs to be done to achieve the project requirements.

Quality materials and material handling. "What you put through the paver matters." Asphalt and concrete materials have a major impact on how the paver operates and the quality of the product behind the paver. Ensuring material consistency from batch to batch and ensuring a steady, uninterrupted supply of material is critical for both asphalt and concrete paving operations. Consistency of concrete materials will dictate how well a slipform paver is able to extrude the finished slab and how much hand finishing is required. Consistency of asphalt materials will dictate how well the paver can place the asphalt mat and influence the compaction operation. Materials should be monitored for segregation as they are delivered to the paver and adjustments made as necessary. Tools such as placer/spreaders for concrete and material transfer vehicles for asphalt can help ensure consistency of the material and placement in or in front of the paver. Carefully planning haul routes and haul times is also critical for ensuring steady supply of material.

What you pave on matters. Significant roughness in the paving platform (subgrade, prepared base, overlay surface, etc.) will reflect into the finished surface or make it much more difficult to place the pavement to the required smoothness tolerances. A stable, uniform platform for the paving operation is essential for maximizing smoothness of the finished surface.

Continually monitor your work. As discussed above, paving operations are very repetitive processes where each part of the operation is repeated over and over, which can lead to roughness patterns caused by some aspect of this repetitive process. These patterns can be corrected if identified early enough. Therefore it is essential for the contractor to continually monitor their work in order to identify these issues. Whenever practical, smoothness numbers should be checked on a daily basis so corrections can be made. This is easier for asphalt pavements which can be profiled shortly after final compaction, but lightweight profilers and real-time smoothness technology provide the same opportunities for concrete pavement.

FHWA's ProVAL software *[23]* is a very powerful tool for analyzing pavement profiles and diagnosing potential issues. Modules within ProVAL can help identify roughness patterns in order to trace them back to some phase of the paving operation, as well as areas of localized roughness for correction. Smoothness numbers should be checked every day and corrections made if necessary.

In 2002, FHWA produced two documents which highlight general best practices for asphalt and concrete pavements with pavement smoothness in mind *[*24*],[*25*]*. Key items from these documents, along with other best practices gleaned from various workshops and discussions with contractors by the project team, are summarized below *[16],[*26*]*.

Asphalt Pavement

Surface Preparation. Providing a stable platform for the paver, trimmed to grade, is essential for all pavements, but in particular for thinner-lift asphalt pavements. Smoothness of the base layer(s) should be monitored to ensure that as much roughness is eliminated from those layers as possible. It is understood, at least anecdotally, that roughness can be reduced by half (at best) with each pavement layer. This means that if the base course measures an IRI of 140 in/mi the smoothest the contractor will be able to get the surface course, theoretically, is 70 in/mi.

Paver Operation. For asphalt pavements, continuous paver movement is optimal, minimizing starts and stops. When the asphalt paver stops, the screed sinks into the mat, leaving a depression which could become an area of localized roughness. When it is absolutely necessary to stop the paver, quick but smooth starts and stops will help to minimize roughness associated with a paver stop.

Mix Production and Delivery. Mix temperature will affect how well the asphalt can be placed by the paver and compacted. Consistent mix temperature is key. Tools such as material transfer vehicles with remixing capability can help ensure consistent mix temperatures and alleviate thermal segregation. It is also good practice to avoid letting the hopper on the front of the paver run completely empty, ensuring a steady flow of material to the screed, with a constant head of material at the augers.

Delivery of asphalt material is also very important. Haul routes and times, with contingency plans, should be carefully planned out before paving begins. An adequate number of haul trucks should always be available to eliminate the need for stopping the paver to wait on material. When material is dumped directly into the paver, ensure that the haul truck does not bump the paver. The paver should be allowed to make the initial contact with the haul truck. Some contractors will dedicate one person on the paving crew to monitoring and guiding the haul trucks. It is also very important to remove any residual asphalt material that falls in front of the paver as the haul truck pulls away, particularly any material that falls in line with the paver tracks.

Grade Control. Best practice for grade control is to use grade control for every layer possible, including milling, binder courses, and surface courses. Ensuring the smoothest surface possible prior to placing the surface course will maximize the smoothness of the finished surface. Although stringlines can be used, mobile reference devices, such as skis, floating beams, or joint matching shoes are generally common practice for grade control.

Compaction. Compaction can play a major role in the smoothness of the finished surface. The correct combination of rollers (steel drum, pneumatic, and finish) should be used based on the asphalt mix, and test strips will help to determine the proper combination and rolling pattern for a given project. Drums and pneumatic wheels should always be kept clean to prevent indentations or deleterious materials from being rolled into the surface. Roller operation should be slow, always moving, with smooth changes in direction, matching roller patterns to production, and not straddling new and older pavement. The roller should always be turned toward the center of the mat at a 45 degree angle, and the roller should never be stopped or parked on a hot mat for any reason.

Joint Construction. Transverse joints can be a very common source of localized roughness. Butt joints or tapered joints are most commonly used, depending on whether the new mat needs to be opened to traffic. When resuming paving at a transverse joint, best practice is to place starting blocks under screed, build up a normal head of material in the paver before pulling off the blocks, and bring the paver up to normal speed as quickly as possible. The joint should be carefully checked with a straightedge, and hand work at joints should be minimized.

Special Circumstances. Special circumstances, such as paving around leave-outs, paving against curb and gutter, or around drainage structures can present unique challenges for achieving smoothness requirements. Most state specifications exclude many of these areas from smoothness requirements, but there is generally still a straightedge requirement. As a general best practice, hand placement should be limited to only as much as absolutely necessary in these areas.

Concrete Pavement

The following best practices are adapted from the "Great Eight Best Practices for Constructing Smooth PCC Pavements" developed by the Kansas Department of Transportation when transitioning from a 0.2-inch blanking band to 0-inch blanking band profilograph specification.

Build From the Ground Up. Similar to asphalt pavement construction, a stable paving platform is essential for concrete pavement construction. Rough or soft tracklines can have a significant impact on the smoothness of the finished surface and the amount of correction required by the paver and/or finishers to achieve it. Best practice is to extend the base (or stabilized subgrade) an additional 2-3 feet beyond the edge of pavement to provide a stable platform for the paver tracks.

Precise Grade Reference. Maintaining precise grade reference is critical for slipform pavers. Automated grade controls using stringlines are the most common method used in current practice, with dual stringlines preferable over a single stringline. Regardless of the setup, stringlines must be continually monitored during the paving operation to ensure they are not disturbed. Stringline sensors, likewise, must be continually checked for functionality and sensitivity.

Stringless paving is becoming much more common and eliminates the issues associated with stringlines. However, stringless paving systems have a unique set of factors that must be continually checked and maintained.

Watch Paving Speed and Delivery Rate. Similar to asphalt pavement construction, a consistent, steady supply of material is necessary for keeping the paver moving. Haul routes and times, with contingency plans, should be carefully planned out before paving begins, and an adequate number of haul trucks should always be available. It is preferable to slow the paver for delays in material delivery, rather than to stop and restart, as paver stops can leave areas of localized roughness.

Control Concrete Head. The saying that "a slipform paver is a finisher, not a dozer" speaks to the control of material placement in front of the paver. The job of a slipform paver is to consolidate and extrude the concrete material through the pan, not to push a mound of fresh concrete. A constant head of concrete material, uniformly distributed across the width of the paver, should be maintained in front of the strike-off bar. Too much material will cause the paver to ride up on the concrete and not enough material will require hand placement of concrete to fill in the low areas. Fresh concrete should be deposited in front of the paver in such a manner that minimal effort by the auger or plow is required to maintain a constant, uniform head of material. Belt placer/spreaders can be very effective for placing a uniform amount of material in front of the paver and may be necessary if dowel baskets are staked to the ground in front of the paver.

Strive for Mix Consistency. Concrete mixture consistency is essential for keeping the paving operation moving and ensuring a uniform concrete slab behind the paver. Inconsistency between batches of concrete can cause the paver to react differently from batch to batch, potentially leaving to areas of localized roughness in the slab.

Mixture segregation can also affect the operation of the paver and quality of the slab extruded by the paver. Segregation should be carefully monitored for mixes delivered by non-agitating (dump) trucks, and when placer/spreaders are used.

Minimal Hand Finishing. The role of a slipform paver is to consolidate, mold, and extrude the fresh concrete into a smooth and uniform concrete slab. Ideally, the only finishing that should be required behind the paver is edging and sealing the surface with a float. Hand finishing can be beneficial or harmful, depending on the experience of the finishers. Finishing can correct localized roughness areas or it can create them, but should be minimized as much as possible. Oscillating automated floats/auto screeds have been known to impart short wavelength roughness into the pavement surface, and should be carefully monitored if used. “Finishing water” should not be added to the pavement surface unless absolutely necessary to help seal the surface.

Texture should be done in a timely manner and should not significantly disturb the pavement, pulling smaller aggregate out of the surface. Curing should also be applied in a timely manner to minimize moisture loss from the surface of the pavement. Delayed application of curing can lead to plastic shrinkage cracking or excessive moisture loss from the surface. Excessive moisture loss can lead to curling and warping due to the moisture gradient in the slab.

Special attention should be paid to header joints as these are common areas of localized roughness. Pave-through headers allow the paver to continue paving through the joint and provide a clean vertical surface for beginning the next placement. Straightedges should be used to check for localized roughness at header joints while the concrete is still moldable.

Use Good Equipment. Slipform paving trains, haul trucks, batch plants, forms, and other equipment are large investments that should be well taken care of. Equipment should be continually cleaned and maintained so that it performs as intended. Even if ready-mix plants are locally available, it may be necessary for a contractor to provide their own batch plant to ensure consistency of the mix and keep pace with the paving operation. Likewise, dedicated (contractor-owned) haul equipment may be necessary to ensure material can be delivered at the required rate.

Motivate Workforce. The paving crew is a key component to ensuring quality in any paving project. This includes those overseeing the operation and the crews working on the paving train, the batch plant, and haul trucks. Instilling a “quality mindset” at all levels of the company is essential for achieving smoothness requirements. Giving paving crews ownership of the project by celebrating results or sharing financial incentives is a key to motivating the workforce.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

Overall, the state-of-the-practice is moving towards IRI-based specifications for construction acceptance nationwide. Roughly 78 percent (up from 66 percent in 2009) of asphalt pavement specifications are IRI-based and 46 percent (up from 21 percent in 2009) of concrete pavement specifications are IRI-based. States continue to realize the importance of collecting data that is more representative of actual ride quality and recognize the importance of collecting smoothness data for construction in the same manner as network-level data. As inertial profiler technology has evolved, the cost of profilers has come down and issues that may have been obstacles in the past, such as sensor footprint, have been largely addressed.

Although the majority of current IRI-based specifications have incentive and/or disincentive provisions, this synthesis revealed that there is no general consensus as to the most appropriate threshold at which incentives should be paid or disincentives applied. There is still a fairly wide range of IRI/MRI thresholds for incentives, disincentives, full pay, and correction. There is also a wide range of pay adjustments that are applied. This is not unexpected, and speaks to the fact that states are carefully analyzing the needs for their particular state and "locally calibrating" IRI thresholds rather than just borrowing the specification thresholds from other states.

Where coherence amongst state specifications is apparent is in the way specifications are structured with respect to testing and reporting requirements. Most specifications seem to be structured in a similar manner in terms of how profile data is collected and summarized. The majority of states us 0.1-mile lots and apply pay adjustments to each lot or based on the bid unit price for pavement. Many state specifications and test procedures are modeled after the AASHTO standards (M 328, R 54, R 56, and R 57), and those states that do not have their own test procedures refer directly to AASHTO standards *[18, 27-29]*.

This being said, there are still a number of gaps in current knowledge and are recommended for further investigation:

Timing of profile data collection on concrete pavements. As noted in the literature search, the differences in IRI over the course of a day can range anywhere from 10 to 40 in/mi. While the severity may not be as great immediately after construction, the effects of concrete pavement slab curling and warping on roughness are well documented. No smoothness specification currently addresses this issue, mainly because there are still a lot of unknowns on the issue.

Establishing clear guidance for localized roughness. Methods for identifying, quantifying, and locating (for correction) areas of localized roughness are still quite varied. Even some states that have IRI-based specifications require a profilograph simulation or even a straightedge to identify localized roughness. Although AASHTO R 54 provides a recommended practice for using continuous IRI roughness profiles to identify localized roughness, not all states are currently using this, and some have reported issues with actually locating these areas on the pavement after they have been identified *[18]*.

Profiler certification practices. Most states which require the contractor to perform smoothness testing have developed some form of certification program for ensuring the fidelity of the data collected by the contractor, typically using some centralized facility in the state. AASHTO R 56 provides guidance for certification of profilers, but additional guidance on how to set up local certification sites and what equipment (e.g., reference profilers) to use would be useful. Current efforts by FHWA to evaluate the various reference profilers that are commercially available against the FHWA/University of Michigan Benchmark Profiler will help provide answers for equipment selection *[28]*.

Specifications for low-speed and urban roadways. The specifications summarized herein are those from each state for high-speed and generally controlled access facilities. Most states have separate specification thresholds for lower speed facilities, but there is a sense that additional guidance for setting those thresholds would be very helpful. Fortunately, this issue is currently being addressed by NCHRP Study 10-93 and an FHWA study to develop an "urban profiler," discussed previously. The results of these efforts, however, may require complete revision of existing specifications for urban/low-speed facilities.

Evaluation of the "Return on Investment" for smoothness. The question of how long agencies should continue paying financial incentives for smoothness, and whether or not the additional investment is paying off in terms of user satisfaction and pavement performance is continually asked. A related question is if disincentives/pay reductions for subpar smoothness actually cover the potential costs of increased maintenance on the pavement during its lifespan. The issue of appropriate IRI thresholds is currently being studied by the North Carolina Department of Transportation through a research study by the University of North Carolina-Charlotte *[27]*. The issue of the relationship between pay adjustments and return-on-investment still requires investigation.

LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
HRI	Half-car Roughness Index
IRI	International Roughness Index
LTPP	Long-Term Pavement Performance Program
MRI	Mean Roughness Index
NCHRP	National Cooperative Highway Research Program
PrI	Profilograph Index
RN	Ride Number
SOM	Subcommittee on Materials (AASHTO subcommittee)
SHRP2	Strategic Highway Research Program 2

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