

SHRP 2 Renewal Project R07

Implementation Guidelines Volume II

Developing and Drafting Effective Performance Specifications: A Guide for Specification Writers

PREPUBLICATION DRAFT • NOT EDITED

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Implementation Guidelines
Volume II

**Developing and Drafting Effective Performance Specifications:
A Guide for Specification Writers**

SHRP 2 RENEWAL RESEARCH

Performance Specifications for Rapid Highway Renewal



TRANSPORTATION RESEARCH BOARD
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PERFORMANCE SPECIFICATIONS FOR RAPID HIGHWAY RENEWAL

IMPLEMENTATION GUIDELINES

VOLUME II

Developing and Drafting Effective Performance Specifications: A Guide for Specification Writers

Prepared for
Strategic Highway Research Program 2
Transportation Research Board
of
The National Academies

Sidney Scott III, P.E., Hill International, Inc., Philadelphia, Pennsylvania
Linda Konrath, Hill International, Inc., Philadelphia, Pennsylvania
Ted Ferragut, P.E., TDC Partners, Ltd., Lewes, Delaware

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- Stuart Anderson, Ph.D., Ivan Damjanovic, Ph.D., Ali Nejat, and Meena Nagreeb of Texas A&M University
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PREFACE

Transportation agencies are under increasing pressure to improve mobility while maintaining existing facilities with limited resources. In response to this pressure, agencies have begun experimenting with ways to accelerate construction and minimize disruption while improving mobility, safety, and long-term performance. To help advance such initiatives, Congress established the second Strategic Highway Research Program (SHRP 2) in 2006 to pursue research in four focus areas: safety, reliability, renewal, and capacity.

The renewal area looks at improving the aging and increasingly congested transportation infrastructure through design and construction methods that will accelerate construction, cause minimal disruption to road users and the community, and produce long-lasting facilities. Recognizing that traditional method specifications can act as a barrier to the innovation often needed to achieve these objectives, SHRP 2 Project R07 was tasked with developing performance specifications that could be used to motivate and empower the contracting industry to provide creative solutions to save time, minimize disruption, and enhance durability.

As an outgrowth of the SHRP 2 R07 research effort, the following guidance document has been prepared to assist specifiers with the development and drafting of performance specifications. The guide presents a flexible framework that specifiers may use to assess whether performance specifying represents a viable option for a particular project or project element, and if so, how performance specifications may then be developed and used to achieve project-specific goals and satisfy user needs. The guidance is intended to be accessible to both experienced and novice members of a project team, as well as adaptable to any project element and delivery method.

To demonstrate how this conceptual framework could be applied to different project elements and delivery approaches, a series of guide performance specifications were also developed under Project R07. Given the difficulty in anticipating every rapid renewal need, the guide specifications are limited to the following application areas that demonstrated either the greatest need or potential for performance specifying:

- Asphalt pavement
- Concrete pavement
- Concrete bridge deck
- Earthworks construction and other geotechnical features
- Work zone traffic management

While it is perhaps most instructive to review these guide specifications in the context of the best practices identified in this overall manual, each could also serve as a standalone reference or template for developing a project-specific performance specification for the particular topic area addressed therein.

CHAPTER 1

Introduction to Performance Specifications

1.1 OVERVIEW AND ORGANIZATION OF THIS MANUAL

1.2 HOW DO PERFORMANCE AND METHOD SPECIFICATIONS DIFFER?

Method Specifications

Performance Specifications

Specification Continuum

1.3 DECIDING BETWEEN METHOD AND PERFORMANCE SPECIFICATIONS

Chapter Objectives

This chapter addresses the following questions:

- How do performance specifications differ from traditional method specifications?
- What are the advantages and disadvantages of using performance specifications?
- Under what conditions would one use performance specifications instead of traditional method specifications?

1. Introduction to Performance Specifications

“Just tell me what to do; I want to build it and move on.”

The statement above embodies the conventional approach to highway construction that places the burden on owners to design, specify, and control the work. Contractors are hired based on lowest price with the expectation that they will execute the work in accordance with the prescriptive requirements provided in the plans and specifications. The risk? Mostly on the owner. The innovation? Again, mostly on the owner.

Societal changes and economic conditions suggest that this traditional approach may no longer be sufficient to keep pace with the growing demands placed upon our national highway system to move people and goods safely and efficiently. Recent infrastructure report cards indicate that the system is deteriorating and facing increasing congestion. At the same time, agencies are facing shrinking budgets and dramatic reductions in both the numbers and experience levels of inspectors and engineers. The complexity of high-speed construction, nighttime construction, and rehabilitation work under traffic—all of which the public demands—further stretches available agency resources.

In response to this widening gap between investment needs and available resources, several transportation agencies have begun experimenting with alternative specifications and contracting strategies that place more responsibility for performance on the private sector. The traditional way of doing business, using prescriptive requirements that tell the contractor how to perform the work, does not motivate the contractor to provide more than the prescribed minimum. The addition of performance specifications to an agency’s toolbox would provide the means to motivate and empower contractors to find creative solutions to save time, minimize disruption, and/or enhance safety and quality in the interest of rapid renewal.

1.1 Overview and Organization of this Manual

As an outgrowth of the SHRP 2 R07 research effort, the following guidance document has been prepared to assist specifiers with the development and drafting of performance specifications. The guide presents a flexible framework that specifiers may use to assess whether performance specifying represents a viable option for a particular project or project element, and if so, how performance specifications may then be developed and used to achieve project-specific goals and satisfy user needs.

This introductory chapter serves to address the following general questions related to performance specifications:

- How do performance specifications differ from traditional method specifications?
- What are the perceived advantages (and disadvantages) associated with performance specifications?
- What project types are most suitable for performance specifications?

Chapter 2 then presents a step-by-step “how-to” guide for developing performance specifications that specifiers may apply to any project element or delivery method. Recognizing that particular performance requirements and specification language could be highly dependent on subject matter, the framework provided in Chapter 2 is intentionally conceptual in nature.

With the fundamentals thus established, the focus of Chapter 3 shifts to the practical application of this conceptual framework to the likely features of a rapid renewal project. Given the difficulty in anticipating every rapid renewal need, the discussion is limited to the following application areas that demonstrated either the greatest need or potential for performance specifying:

- Portland cement concrete (PCC) pavement
- Asphalt pavement
- Concrete bridge deck
- Earthworks construction and other geotechnical features
- Work zone traffic management

To introduce and complement the set of guide specifications prepared under the R07 project, Chapter 3 highlights the specific considerations, gaps, and trends unique to performance specifying each of these project elements. While it is perhaps most instructive to review the guide specifications in the context of the best practices identified in this overall manual, each could also serve as a standalone reference or template for developing a project-specific performance specification for the particular topic area addressed therein.

While critical to a project’s success, a well-drafted performance specification will not in and of itself ensure that an agency’s performance goals will be met. A companion volume to this document, *Strategies for Implementing Performance Specifications: A Guide for Executives and Project Managers*, provides a more high-level overview of the cultural and organizational changes necessary to support the implementation of performance specifications across a wide spectrum of work and projects.

1.2 How do Performance and Method Specifications Differ?

The primary function of a specification, whether method or performance-oriented, is to communicate a project's requirements and the criteria by which the owner will verify conformance with these requirements. In this respect, performance specifications are similar to conventional method specifications. Where they differ is in how they define performance and how much latitude they extend to contractors to meet project requirements.

1.2.1 Method Specifications

Method specifications (also called *prescriptive* or *recipe* specifications) require contractors to use specific materials, equipment, and methods to complete the work. The prescribed requirements are typically based on materials and methods that have historically produced satisfactory results for the agency, thereby eliminating risk associated with newer, less proven methods and risk associated with varying contractor performance. Contractors are provided few, if any, opportunities to deviate from the specified requirements, allowing the agency to retain significant control over the work.

Under this traditional approach, the agency will base acceptance on the "reasonable conformance" or "substantial compliance" of the work with the specified requirements. If test results are used as a component of the acceptance determination, usually only individual or representative field samples are taken. These individual results may fail to recognize the inherent variability in the material itself, potentially leading to disputes between the contractor and agency over acceptance decisions. Moreover, because method specifications do not establish a range of quality levels, they generally do not include procedures for pay adjustments. The contractor therefore typically receives 100% payment for the work completed as long as it strictly adheres to the specified requirements. Table 1.1 further summarizes the advantages and disadvantages of using method specifications.

Table 1.1: Advantages and Disadvantages of Method Specifications

<i>Advantages</i>	<i>Disadvantages</i>
<ul style="list-style-type: none">• Method specifications are well-established, easily understood, and applicable to a wide range of topic areas.• Agency can exert significant control over the work (however, this may come at the expense of increased agency inspection efforts).• Requirements are based on materials and methods that have worked in the past, minimizing risk associated with newer or less proven methods or varying contractor performance.	<ul style="list-style-type: none">• The contractor has little opportunity to deviate from the specifications, and, provided that the specifications are met, is not responsible for performance deficiencies of the end product (i.e., the agency retains performance risk).• Method specifications lack built-in incentives for contractors to provide enhanced performance (e.g., cost, time, quality, etc.).• The prescribed procedures may prevent or discourage the contractor from using the most cost-effective or innovative procedures and equipment to perform the work.• Contractor payment is not tied to the performance or quality of the work.• Acceptance decisions based on test results of individual field samples can increase the potential for disputes.

Reference: FHWA Technical Advisory, Development and Review of Specifications, March 24, 2010

1.2.2 Performance Specifications

In place of the explicit materials and construction requirements found in traditional method specifications, performance specifications contain statements of required results that focus on the desired quality level or performance of the finished work.

To the extent that the agency is willing to relinquish control over some aspects of the work, this approach has the potential to foster contractor innovation and thereby improve the quality or economy, or both, of the end-product. Additional advantages and disadvantages of performance specifications are identified in Table 1.2.

Table 1.2: Advantages and Disadvantages of Performance Specifications

<i>Advantages</i>	<i>Disadvantages</i>
<ul style="list-style-type: none">• Performance specifications promote contractor innovation.• The contractor assumes more performance risk.• Contractors have the flexibility to select materials, techniques, and procedures to improve the quality or economy, or both, of the end product.• A performance specification can provide a more rational mechanism for adjusting payment based on the quality or performance of the as-constructed facility.	<ul style="list-style-type: none">• The agency can exert less control over the work.• Opportunities for smaller, local construction firms may be reduced.• It can be challenging to identify all of the parameters critical to performance and establish related thresholds.• Roles and responsibilities of the contractor and agency can become blurred if not adequately defined in the specifications or contract documents.

Reference: FHWA Technical Advisory, Development and Review of Specifications, March 24, 2010

1.2.3 Specification Continuum

As used in this guidance document, the expression “performance specifications” serves as an umbrella term, encompassing various non-traditional specification types used or proposed for use in the highway construction industry, including end result specifications, quality assurance (QA) specifications, performance-related specifications (PRS), performance-based specifications (PBS), and warranty and long-term maintenance provisions (see Box 1.1).

Box 1.1: Classification of Performance Specifications

End-result specifications require the contractor to take entire responsibility for supplying a product or an item of construction in exchange for receiving flexibility in the selection of materials, techniques, and procedures. The agency's responsibility is to either accept or reject the final product or to apply a pay adjustment to account for the degree of compliance with the specified performance criteria, as established through sampling and testing of the final in-place product.

Quality assurance (QA) specifications require contractor quality management and agency acceptance activities throughout the production and placement of a product. Final acceptance of the product is usually based on a random, statistical sampling of the measured quality level on a lot-by-lot basis for key quality characteristics. Price adjustments are generally determined based on a mathematical assessment of the measured variability of the product.

Performance-Related Specifications (PRS) are QA specifications that:

- Base acceptance on key materials and construction quality characteristics that have been found to correlate with fundamental engineering properties that can be used to predict subsequent product performance
- Use mathematical models to quantify the relationship between key materials and construction characteristics that lend themselves to acceptance testing at the time of construction
- Provide rational pay adjustments based on the difference between the as-designed and as-constructed life-cycle cost

Thus far, PRS have only been piloted for concrete pavement.

Performance-Based Specifications (PBS) are QA specifications that describe the desired levels of fundamental engineering properties (e.g., resilient modulus, creep properties, and fatigue properties) that are predictors of performance and appear in primary prediction relationships (i.e., models that can be used to predict stress, distress, or performance from combinations of predictors that represent traffic, environmental, roadbed, and structural conditions). PBS differ from PRS in that they specify the desired levels of actual fundamental engineering properties (as opposed to key quality characteristics) as predictors of performance. Further development and validation of predictive models and performance-based test methods would be needed to advance PBS, which have thus far not been implemented on highway construction projects.

Warranties hold the contractor responsible for product performance over a prescribed post-construction period, thereby protecting the agency against defective work and premature failure. Warranty provisions incorporate performance indicators and thresholds that are used to monitor actual performance or condition of the product over time (e.g., performance indicators for an asphalt pavement may include rutting and cracking). While the scope of warranted work and performance indicators may not capture all of the factors contributing to performance, they provide a tool to transfer responsibility for performance to the private sector and ensure that the products of construction will meet targeted performance thresholds for part of the life-cycle of that product or component. Although it is possible to develop a warranty provision of sufficient duration to address long-term performance, bonding issues may limit the practicality of implementing such a specification.

Performance-based maintenance provisions incorporate performance indicators and thresholds similar to those found in warranties. However, unlike typical short-term warranties, post-construction operational and maintenance provisions that extend for at least the design-life of the facility [i.e., as found on design-build-operate-maintain (DBOM) or public-private partnership (PPP) projects], provide the means to transfer whole-life performance risk to the contractor by providing maximum flexibility with regard to design, construction means and methods, and the repair and rehabilitation measures that will be necessary over the contract term.

In general, these specification types represent a progression towards increased use of functional acceptance parameters that are more indicative of how the finished product will perform over time. To varying degrees, they all attempt to shift more performance risk to the contractor in exchange for limiting prescriptive requirements related to the selection of materials, techniques, and procedures.

Figure 1.1 places these specification types along a continuum of increasing contractor responsibility for performance. At one end of this continuum are the traditional method specifications through which the agency will retain primary responsibility for end-product performance. Moving along the continuum, performance specifications that allow for quality adjustments based on end-result testing or predictive models begin to shift more performance risk to the contractor. At the other extreme are post-construction performance provisions that are designed to monitor and hold the contractor accountable for *actual performance over time*.

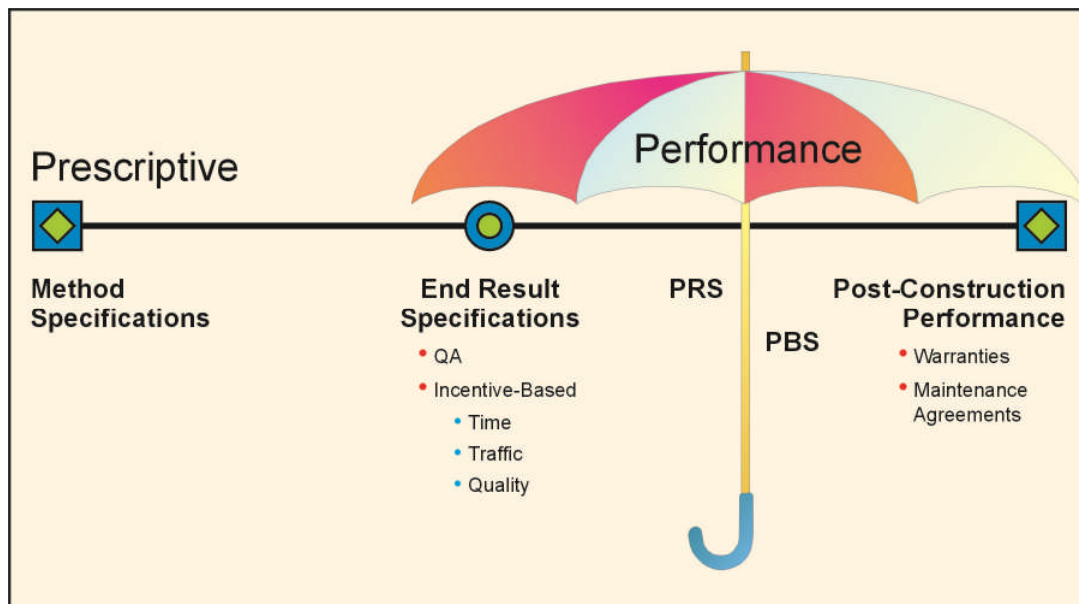


Figure 1.1: Continuum of Highway Specifications

It is not an objective of this manual to advocate the use of one of these specification types over another. The guidance is instead intended to be flexible enough to accommodate any specification strategy chosen for a project. However, after proceeding through the step-by-step process outlined in Chapter 2, one method may ultimately prove to be more appropriate for a given project or agency than another.

1.3 Deciding between Method and Performance Specifications

As discussed above, both method and performance specifications hold unique advantages and disadvantages that should be carefully weighed when considering how best to specify requirements for a particular project or project element.

While the motivation for using performance specifications will likely vary from agency to agency and from project to project, the literature and input from practitioners suggests that implementing performance specifications has the potential to improve quality and long-term durability, encourage innovation, accelerate construction, and reduce an owner's quality assurance burden during construction (particularly if the contractor has post-construction responsibilities).

The likelihood of realizing such benefits tends to correlate with project complexity. Performance specifications are typically most advantageous when the nature of the project provides ample opportunity for the industry to innovate and influence performance outcomes, as is often the case on complex projects involving major reconstruction or new capacity, multi-phased work zone management, major or non-standard structures, and high traffic volumes requiring accelerated design and construction.

In contrast, non-complex projects involving minor resurfacing or restoration of the pavement surface, or use of standard structural components to match existing facilities, tend to be the least likely project types to benefit from using a performance specification unless the agency allows significant latitude through the selection of alternate designs, materials, or construction methods.

Table 1.3 summarizes the typical conditions under which method and performance specifications can be best applied.

Primary Objectives for Using Performance Specifications

- ✓ Transfer performance risk to the contractor
- ✓ Motivate contractors to be more quality-conscious
- ✓ Improve long-term durability
- ✓ Accelerate construction
- ✓ Encourage innovation
- ✓ Reduce agency-inspection costs during construction

Table 1.3: Appropriate Conditions for Using Method vs. Performance Specifications

<i>Method Specifications</i>	<i>Performance Specifications</i>
<ul style="list-style-type: none">• End product performance cannot be easily defined.• End product performance cannot be easily or economically measured and verified.• Limited methods exist that would satisfy the agency's minimum requirements.• The agency must retain performance risk because of permit requirements, maintenance considerations, need to tie into existing or adjacent construction, and similar issues.• Removing and replacing defective work would be impractical.• Pre-existing conditions would compromise the transfer of performance risk to the contractor.	<ul style="list-style-type: none">• End product performance can be defined in terms of desired outcomes or user needs.• Key performance parameters can be measured and tested, and the test methods are rapid, reliable, and economical.• There are multiple approaches to achieve the desired results.• Industry is willing to assume performance risk.• Agency is willing to relinquish control over some aspects of the work.

As a practical matter, it is important to note that the decision to use method or performance specifications is often a matter of degree (how much and at what level). Different approaches to specifying may be appropriate to particular project elements. It is therefore possible, if not likely, for a project to include both method and performance requirements.

As described further in Chapter 2, the appropriate mix of requirements is generally driven by a project's scope and objectives, as well as the project delivery approach and risk allocation strategy. In practice, this means that the decision to use performance specifications should be supported by an in-depth evaluation (as described in Chapter 2) of the type and level of performance requirements appropriate for the project characteristics and delivery approach.

CHAPTER 2

Developing Performance Specifications

- 2.1 CONCEPTUAL FRAMEWORK: THE PYRAMID OF PERFORMANCE**
- 2.2 STEP 1: IDENTIFY USER AND SOCIETAL NEEDS AND GOALS**
- 2.3 STEP 2: TRANSLATE USER NEEDS AND GOALS TO FUNCTIONAL PERFORMANCE PARAMETERS**
- 2.4 STEP 3: CONSIDER PROJECT DELIVERY APPROACH**
- 2.5 STEP 4: DETERMINE THE APPROPRIATE MEASUREMENT STRATEGY**
- 2.6 STEP 5: STRUCTURE INCENTIVE STRATEGIES AND PAYMENT MECHANISMS**
- 2.7 STEP 6: IDENTIFY GAPS**
- 2.8 STEP 7: IDENTIFY AND EVALUATE RISKS RELATED TO PERFORMANCE REQUIREMENTS**
- 2.9 STEP 8: DEVELOP SPECIFICATION LANGUAGE**

Chapter Objectives

This chapter addresses:

- How performance specifications can be developed to achieve a project's needs and goals
- How to establish a performance measurement strategy, including:
 - The role project delivery can play in selecting performance parameters
 - Changes in roles and responsibilities related to quality management
 - Potential gaps and risk mitigation
 - How to structure a payment mechanism to motivate contractor performance

2. Developing Performance Specifications

Performance specifications emphasize desired outcomes and results, challenging specifiers to think in terms of user needs and to recognize that more than one solution may achieve the project objectives. Incorporating such concepts into a specification represents a distinct departure from today's "build-to-print" culture and demands a new approach to specification writing. Gone are the explicit materials and construction requirements that have historically helped agencies ensure satisfactory results. In their place are performance parameters, measurement and verification strategies, and payment/incentive mechanisms designed to encourage contractor innovation and performance excellence.

To assist specifiers with the development of performance specifications, this chapter presents a simple, step-by-step framework that may be used alone or in conjunction with the guide specifications prepared under the SHRP 2 R07 research effort to develop project-specific performance requirements. Whereas past efforts at performance specifying (particularly in the pavement area) primarily focused on the development and use of predictive models to define performance needs, this framework offers a pragmatic approach that balances user needs and project goals against available technology and resources and industry's appetite for assuming performance risk. The result is a flexible process intended to be accessible to both experienced and novice members of a project team, as well as adaptable to any project element and delivery method.

2.1 Conceptual Framework: The Pyramid of Performance

The primary function of a specification, whether prescriptive or performance-oriented, is to communicate a project's requirements and the criteria by which the owner will verify conformance with these requirements. In this respect, performance specifications are similar to conventional method specifications. Where they differ is the level at which performance can be defined. For example, Figure 2.1 illustrates the possible requirement levels for a hypothetical pavement project. Taken as a whole, the pyramid depicted in the figure is intended to represent the entirety of knowledge and experience related to pavement design and construction. Taking and evaluating each level individually, one can create a specification that is entirely prescriptive, if based solely on the material and workmanship properties defined on the lowest levels, to one that is more performance-oriented, if based on the user needs and functional requirements identified on the higher levels.

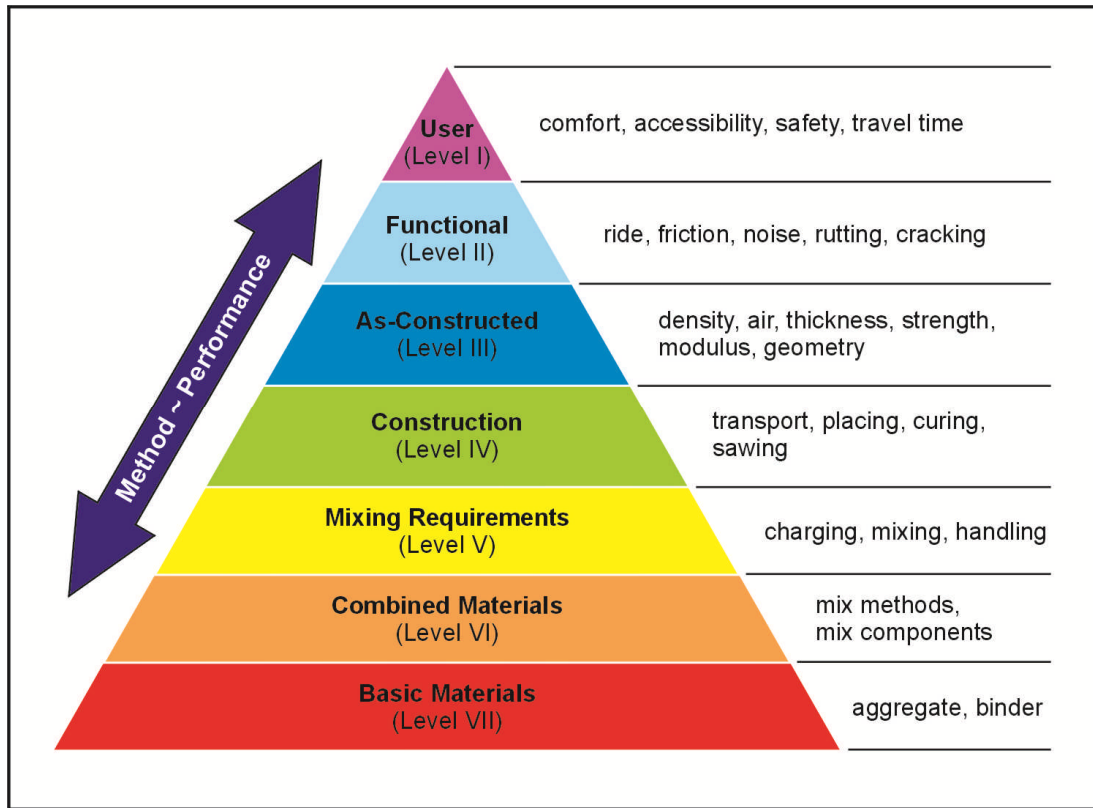


Figure 2.1: Pyramid of Performance

Adapted from: Netherlands Ministry of Transport, Public Works, and Water Management (van der Zwan 2003)

For a particular project, the appropriate mix of performance requirements is driven by the project's scope and objectives and the chosen project delivery approach and risk allocation strategy. In practice, this means that specifications will typically include elements from several of the levels shown. Determining the appropriate balance between prescriptive and performance-oriented requirements is one of the main objectives of the 8-step specification development process described in this chapter and illustrated Figure 2.2.

The guidance that follows describes this specification development framework in greater detail, systematically leading the specifier through each step in the process. However, as suggested by a review of the guide specifications themselves, some steps are more critical to certain topic areas than to others. For example, although project delivery approach (Step 3) plays a large role in shaping the development of a performance specification for pavements and bridges, it has less influence on establishing performance requirements for work zone traffic control and geotechnical features.

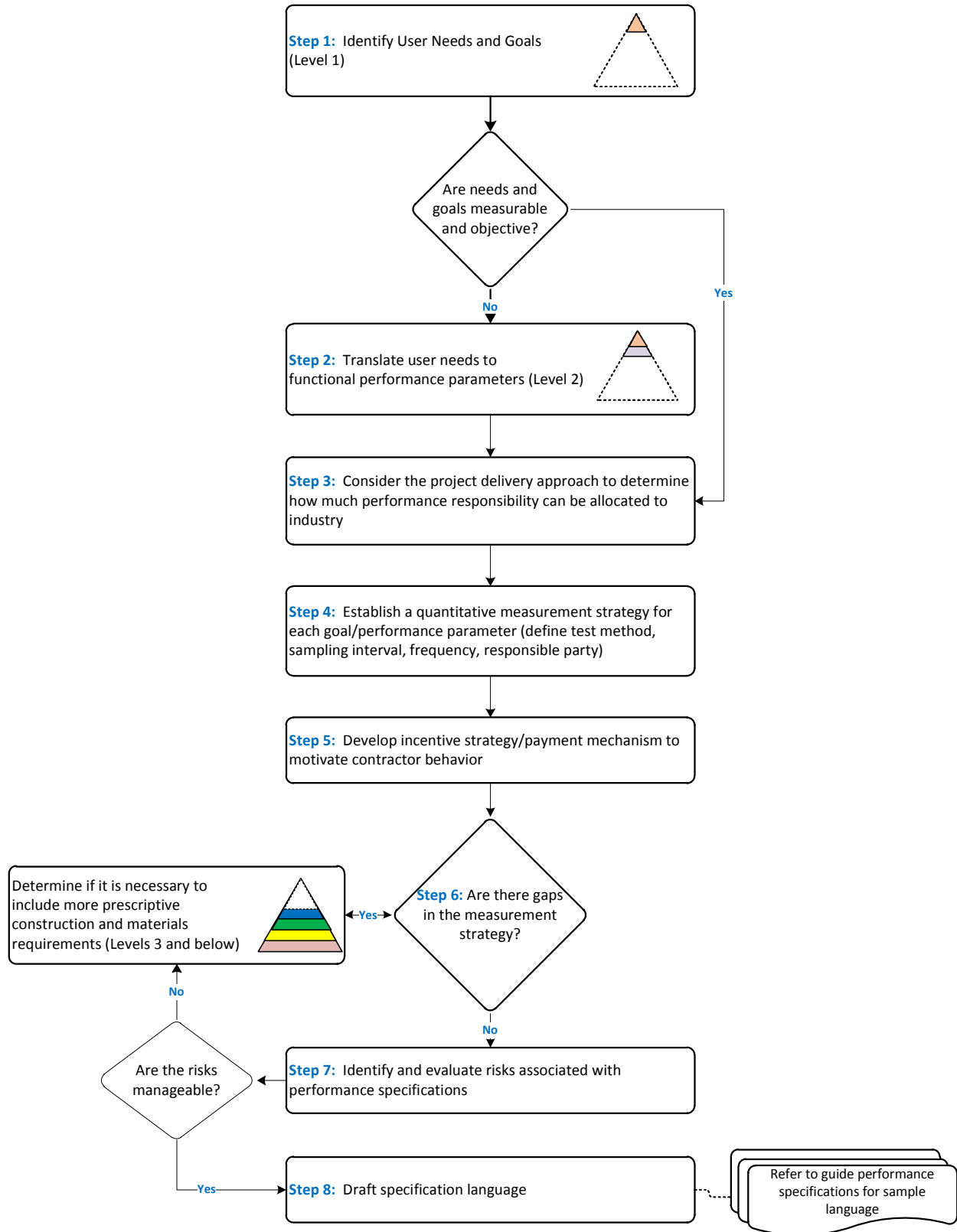


Figure 2.2: Performance Specification Development Process

2.2 Step 1: Identify User and Societal Needs and Goals

When facilities are described using prescriptive terms, the needs of the end users – from vehicle drivers to the community at large – rarely figure prominently in the resulting specifications or contract documents. This is because method or prescriptive specifications are built from the bottom of the pyramid up, as specification writers respond to the question – *How is this work to be accomplished?* – by defining the facility in terms of its basic material components and the methods by which it is to be constructed.

In contrast, performance specifications are built from the top of the pyramid down, to shift the emphasis from materials and methods to desired project outcomes. The process of developing an effective performance specification therefore begins by considering – *What goals and needs are we trying to satisfy?* – a question that inherently has the customer or end-user in mind.

For example, road users and communities may want an accessible road that offers a safe, comfortable, and quiet ride with minimal delays and inconvenience due to construction. Performance specifications can be used to motivate the contractor to develop solutions capable of meeting these expectations.

2.3 Step 2: Translate User Needs and Goals to Functional Performance Parameters

Ideally, a performance specification should operate on the user needs level (Level 1). In practice, however, user needs, such as safety, mobility, and comfort, tend to be too abstract to ensure consistent interpretation and enforcement. The next step in the specification development process therefore entails translating the needs identified in Step 1 into measurable performance parameters that are known to relate

to the desired project outcomes. For example, in Figure 2.3, the user need of safety aligns with the functional performance parameter of friction.

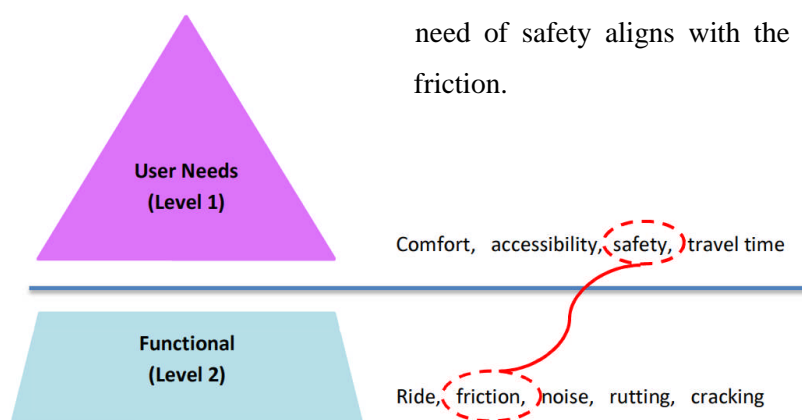


Figure 2.3: Translating User Needs to Functional Parameters

Determining the appropriate functional parameters to include in a specification requires an understanding of both the users' needs and the technical characteristics of the products that might meet these needs.

Characteristics of Effective Performance Parameters

- ✓ Significant or relevant to users
- ✓ Quantitative rather than qualitative
- ✓ Verifiable through analysis, tests, or demonstrations
- ✓ Attributable to actions within the contractor's control
- ✓ Material and process independent
- ✓ Indicative of poor or improper workmanship

To the extent possible, functional parameters should be material and process independent (to provide contractors with sufficient flexibility in determining solutions), yet also measurable and verifiable through the use of accurate and reliable evaluation methods. In addition, to minimize excessive risk pricing, the parameters should relate to actions within the contractor's control (e.g., if a paving contractor is not responsible for subgrade conditions, inclusion of certain parameters, such as structural deflection, may be inappropriate).

In some cases, more than one functional parameter may be necessary to satisfy a particular user need. Returning to the earlier example of safety, the friction parameter could be coupled with one addressing the number of crashes. A single parameter could also align with more than one goal, which could increase its overall effectiveness as a key performance parameter.

When initially identifying functional performance parameters, consider all factors that could potentially affect the project's needs and goals, regardless of measurement difficulties and other issues or concerns that could prevent a parameter's immediate application on a project. Such inclusiveness with regard to the candidate performance parameters will help ensure that all factors affecting performance are identified.

One of the objectives of subsequent steps is to then determine whether or not these parameters will work within the larger context of an agency's program, the chosen project delivery and risk allocation approach, readily available technology, and the goals of rapid renewal. This analysis may result in eliminating certain parameters, that while valid and measurable, do not offer sufficient insight into the performance of the facility to justify the time and expense needed to verify or audit contractor compliance. In such cases, it may be more desirable to use prescriptive requirements.

2.4 Step 3: Consider Project Delivery Approach

The delivery approach selected for a project will largely drive the extent to which an agency can allocate responsibility for performance to the contractor. Consider, for example, a design-bid-build (DBB) project that presents few opportunities for the contractor to provide input on design or constructability issues. As illustrated in Figure 2.4, under such circumstances the contractor's responsibility for the project's performance would not extend beyond the end of construction or possibly a limited (1-year) materials and workmanship warranty. In contrast, the nature of a design-build-operate-maintain (DBOM) contract will inherently expose the contractor to more performance risk as it assumes responsibility for design, construction, and the repair and rehabilitation measures that will be required over the contract's operation and maintenance period (usually one life-cycle or longer). The degree of performance risk allocated to the contractor under design-build (DB) and warranty projects would fall between these two extremes.



Figure 2.4: Risk Allocation & Project Delivery

When developing a performance specification, one must therefore consider how a particular delivery approach and its inherent conventions regarding design, quality management, and post-construction maintenance could affect the selection of performance parameters and the setting of limits or thresholds commensurate with the degree of performance risk assumed by the contractor. For example, as summarized in Figure 2.5 and discussed further below, specifying high-level performance requirements on a DBB project would be inappropriate as it would require the contractor to assume risk for items for which it has minimal control or influence. At the other end of the project delivery spectrum, a DBOM project would primarily favor the selection of performance parameters from the top levels of the pyramid depicted in Figure 2.1, as materials and construction requirements would represent unnecessary constraints on a contractor required to assume whole-life performance risk.

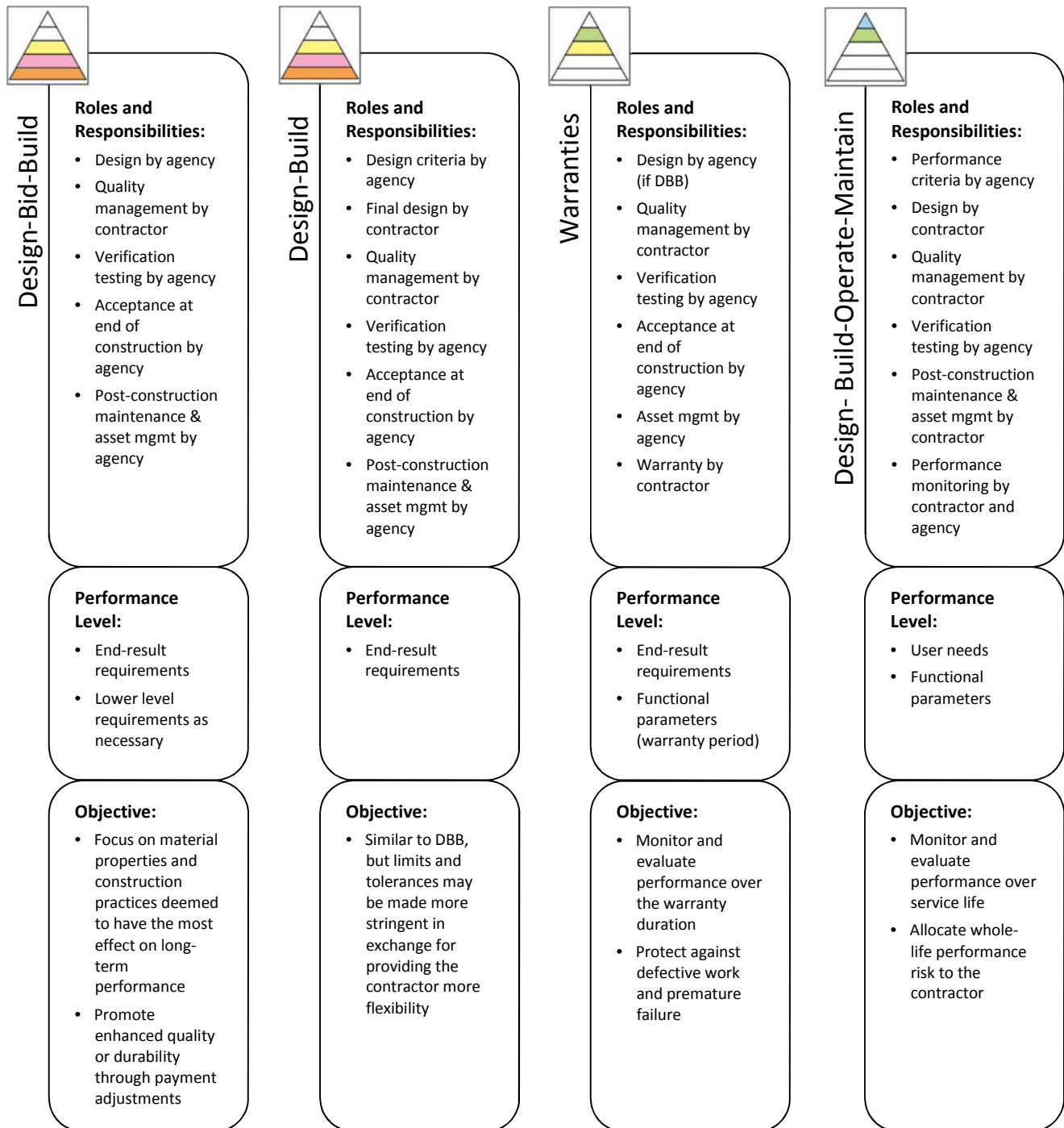


Figure 2.5: Using Performance Specifications under Various Contract Delivery Approaches

Other variants of the four delivery approaches shown above (e.g., design-build-finance-operate and maintenance contracts) are not specifically addressed in these guidelines or in the guide specifications. However, the parameters used to monitor and evaluate the contractor's performance in

maintaining the asset over time would be comparable to those found in the DBOM case. Another project delivery approach receiving considerable attention as of late is Construction Manager at Risk (CMR). In the case of CMR, although the contractor may be able to provide some early input on design and constructability issues, the performance specifications would not be fundamentally different from those implemented under DBB.

Design-Bid-Build (DBB) is the traditional project delivery system through which an agency will contract with separate entities for design and construction services. Given this separation of services, a DBB project would present few opportunities for a contractor to provide input on design and constructability issues. Specifying high-level performance parameters under this approach would therefore be inappropriate, as it would require the contractor to assume risk for items for which it has minimal to no control. A performance specification implemented under the DBB approach would therefore primarily include materials and construction requirements taken from the lower levels of the pyramid shown in Figure 2.1, coupled with any end-result parameters needed to address specific project goals (e.g. use of a smoothness requirement on a pavement project).

Under this scenario, if a performance specification is defined as one that describes “how the finished product should perform over time” (TRB 2009), one could argue that, absent a warranty provision, use of the DBB approach limits the extent to which a contractor could be held responsible for performance *over time*. The goal, therefore, of a performance specification developed for the DBB delivery approach is not to monitor and evaluate a product’s performance over time (as may be the case for a performance warranty or a specified operations and maintenance period) but to:

- Focus on material properties and construction practices deemed to have the most effect on long-term performance, and to
- Incorporate financial incentives/disincentives to promote enhanced quality or durability.

Design-Build (DB) is a delivery system in which the agency retains a single entity to design and construct a project. In contrast to DBB delivery, a DB project would provide more opportunities for a contractor to provide input on design and constructability issues, especially if innovation is an agency goal. Several of the lower-level materials and construction requirements that would be included in a DBB specification could therefore be eliminated or relaxed under DB to extend more flexibility to the contractor. However, by relieving the contractor of further responsibility for facility performance at the end of construction (beyond the standard materials and workmanship warranty), the agency would still be limited to an acceptance plan based primarily on end-result properties similar to those included under the DBB approach.

In exchange for providing more design freedom and for reducing its typical inspection and testing activities to accommodate an accelerated construction schedule, the agency may tighten up the acceptable tolerances under DB to help ensure that schedule or cost considerations do not compromise quality.

Performance warranties are used to guarantee the integrity of a product and the contractor's responsibility to repair or replace defects for a defined post-construction period (e.g., 5 to 10 years). Warranties may be applied to both DBB and DB projects to similar effect, assuming that the agency provides sufficient latitude to the contractor with respect to the design and construction of the warranted project element(s).

A warranty will allow the agency to expand the performance measurement strategy used under DBB or DB to include functional parameters that monitor and evaluate the *actual* performance or condition of the project *over time*. The protection against defective work and premature failure offered by the warranty will allow the agency to eliminate or relax some of its standard materials and construction requirements if doing so could help save time and/or minimize disruption in the interest of rapid renewal.

Given their limited duration, short-term performance warranties primarily only protect the agency against premature failures. Although it is possible to develop a warranty provision of sufficient duration to address long-term performance, bonding issues may limit the practicality of implementing such a specification.

Note that warranties often do not include all of the factors that contribute to performance, particularly if the contractor is not responsible for design or if the risk related to pre-existing conditions cannot be allocated to the contractor in an equitable manner. In such cases, the warranty provision should explicitly identify exclusions relieving the contractor of responsibility for performance problems stemming from issues over which it has limited control. For example, warranty provisions for pavements often exclude subbase, drainage, and embankment features or other factors related to pavement design, as well as underlying deficiencies that may affect performance.

Under **Design-Build-Operate-Maintain (DBOM)**, a single entity designs, constructs, and operates and maintains a project for a specified duration (usually the life-cycle of the project element or longer). Note that the DBOM approach could be extended to include private sector financing as well.

The assignment of post-construction maintenance responsibility and, with that, allocation of whole-life performance risk, to the contractor allows the agency to shift its emphasis from the end-result and performance-related acceptance properties relied upon under the DBB and DB methods to post-

construction measurement strategies that evaluate the actual performance or condition of the facility over time.

Given the degree of performance risk assumed by the contractor, the specification should provide maximum flexibility with regard to design, construction means and methods, and the repair and rehabilitation measures that will be required over the contract period. Few, if any, lower-level materials and construction requirements should be included in the measurement strategy to avoid undermining the effectiveness of the risk transfer to the contractor.

Note that in order to motivate the contractor to provide high quality construction and to perform preventative maintenance in a timely and efficient manner, the contract term should be of sufficient duration to expose the contractor to the consequences of its actions (i.e., allow the contractor to enjoy the profits that may stem from high quality work and to suffer losses due to poor workmanship and planning). Ideally, this concept will lead not only to significant efficiency gains, but also to technological innovation.

2.5 Step 4: Determine the Appropriate Measurement Strategy

Perhaps the most complex aspect of performance specifying entails developing a quantitative measurement strategy to evaluate the contractor's performance against the goals and parameters identified in Steps 1 and 2. To be complete and effective, the measurement methodology should identify:

- what gets measured (i.e., parameters and performance measures);
- the manner through which compliance will be determined (e.g., tests, inspections, audits);
- sampling plan (sample size, lot size, sample location, frequency, etc.);
- how the test results will be used (e.g., process control, screening test, pay determination);
- who will perform the testing (agency or contractor);
- allowable deviation from the performance standard; and
- consequences for failing to meet the required performance level.

Such decisions require a thorough understanding and evaluation of each parameter being considered for inclusion in a performance specification. Ideally, historical data obtained from the agency's asset management system would provide a reliable source of information to support the decision process. If analysis indicates that a parameter would not be appropriate to include in an acceptance determination, the agency may still wish to consider including it for screening purposes or as part of the contractor's quality control (QC) plan, rather than eliminating it completely.

A summary of the various decision steps and considerations that will drive the development of a measurement strategy for a given project is provided in Figure 2.6. The narrative that follows then provides a more detailed explanation of each step in this process.

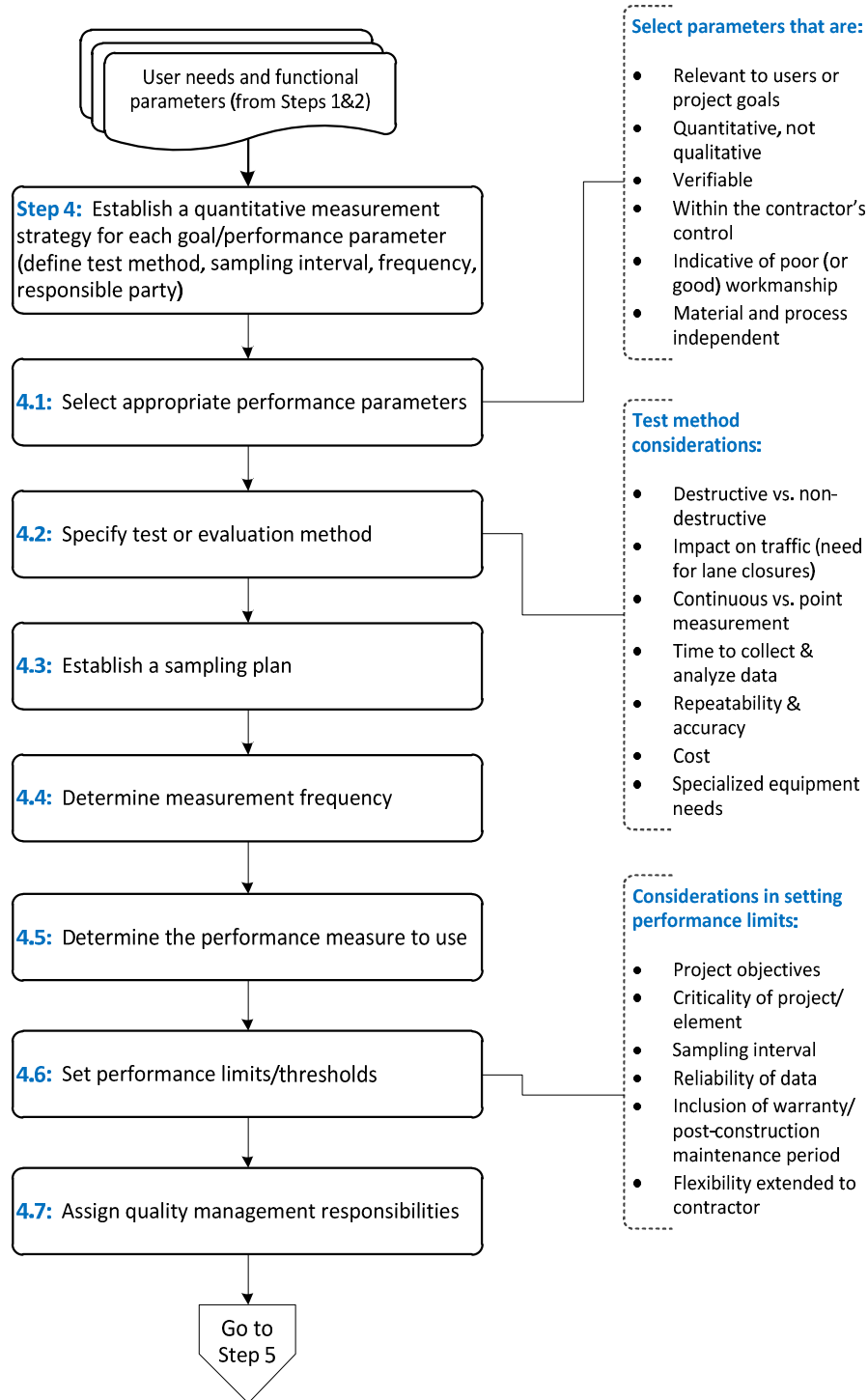


Figure 2.6: Development of a Performance Measurement Strategy

2.5.1 Step 4.1 – Finalize Selection of Performance Parameters

Identifying the appropriate performance parameters to ensure an acceptable product can be challenging. Nonessential requirements can hinder contractor innovation, add unnecessary complexity to the measurement strategy, require additional testing resources, conflict with the project delivery approach, or otherwise force the agency to continue to retain the bulk of the performance risk.

Although any number of the parameters identified and refined in earlier steps could be incorporated into a specification, best practice suggests limiting acceptance parameters to those that:

- focus on key project or program objectives,
- relate to actions within the contractor's control, and
- are indicative of poor or improper workmanship and/or long-term durability.

Furthermore, any items that are already routinely measured or monitored as part of the agency's asset management program would also make for ideal performance parameters, particularly if the agency has a solid historical baseline of data from which to establish the associated performance limits or thresholds. Likewise, an agency may wish to include parameters (e.g., modulus values) that will correlate field data to design assumptions.

2.5.2 Step 4.2 – Specify Test/Evaluation Method

For a measurement strategy to be successful, it is essential for both the agency and contractor to perceive the specified test or evaluation method as being objective and capable of yielding accurate and repeatable results. For this reason, methods that produce quantitative results are generally preferred to those that provide only qualitative indications of performance, which are more difficult to verify or audit. Likewise, measurement procedures based on published industry or agency standards may be more desirable than newer, less proven methods, particularly if technicians are unfamiliar with the associated calibration, testing, or analysis procedures. With regard to data collection efforts, automated or computer-aided methods (assuming minimal equipment downtime) may also be considered by some to be more objective than manual, labor-intensive methods for measuring certain parameters, such as traffic flow through a work zone.

In specifying testing and evaluation methods, consideration should also be given to the goals of rapid renewal. For example, non-destructive testing (NDT) techniques may be able to reduce some of the delay associated with quality assurance and acceptance activities, especially if results are available in real-time or within a matter of days. Similarly, techniques that could minimize traffic disruption (e.g., by

ensuring timely opening of roadways after a construction project or by eliminating the need for lane restrictions during warranty or maintenance periods) would be preferable to those that would impair mobility. Requiring trial placements or sections may also be beneficial from a rapid renewal context to provide insight into the construction process before the actual work begins. The experience gained through the trial placement would allow the contractor to modify its approach as necessary before the quality of the project, in whole or in part, suffers. The trial placement, if located outside of the traveled way, would also provide the opportunity to make adjustments and optimize procedures with minimal disruption to traffic.

Rapid Renewal Considerations:

- Can measurement and testing be done in a manner that has minimal impact on traffic and lane closure?
- Can the data be collected and processed in a timely manner?
- Are non-destructive testing techniques available?

Certain requirements, such as those involving aesthetics, may still involve the agency's judgment. For such subjective items, the agency and contractor should mutually develop and agree to an acceptance standard for that parameter. For example, a visual standard can be established by inspecting a representative sample early in the project.

2.5.3 Step 4.3 – Establish a Sampling Plan

The sampling plan for a rapid renewal project should reflect a balance between efficiency and risk reduction. Obviously, the more robust and comprehensive the sampling strategy, the less risk to the contractor and agency; however, project costs, as well as road-user costs, may increase as a result of excessive sampling and testing. The optimal sampling plan will therefore be driven by the criticality of the parameter to be tested, the agency's resources, and the uniformity of the materials in question.

Project goals and contract delivery approach will also influence sampling strategies. For example, an agency's objective in using a performance specification may be to reduce sampling and testing needs during construction, particularly if a warranty or maintenance agreement is provided. On the other hand, use of predictive models may require more sampling and testing than traditionally performed. In this case, testing technologies that provide continuous coverage (100% sampling) would be preferable to those that provide point measurements. For example, although still a nascent technology in need of further calibration and development prior to use as an acceptance test, intelligent compaction may ultimately provide a means to obtain more comprehensive information regarding uniformity of ground conditions and compaction results than more conventional point testing methods (e.g., density gauges).

In addition to sample size, lot size (or, in the case of pavement monitoring, segment length) can be another key consideration when developing any sampling plan. For example, pavement surface distresses (e.g., cracks, rutting) are typically measured and evaluated as a function of the average distress per segment length. If evaluation segments are too long, a localized area of poor performance may go undetected. However, segments must be long enough to allow for a practical and efficient means of data processing. Typical segment lengths used in the U.S. range from approximately 300 to 500 feet (100 meters to 0.1 miles). Note, however, that these segment lengths may differ from those used to process network data under an agency's standard pavement management system.

2.5.4 Step 4.4 – Determine Measurement Frequency

In establishing and defining the overall measurement strategy, the specification should identify how often the measurements will be taken. For example, performance could be measured: at specific project milestones, continuously, or periodically (e.g., hourly, daily, monthly, annually).

The frequency selected will depend largely on the specific performance parameter in question. For example, data related to travel time through a work zone could be collected continuously for the entire duration of the traffic restriction, continuously for peak travel times only, or on some other periodic basis determined to be practical and cost-effective for a given project's conditions and goals. On the other hand, parameters such as pavement smoothness would be measured at the end of construction as an acceptance property. If the contract also includes a warranty or an operations and maintenance phase, smoothness and other distress parameters would also be measured periodically during the post-construction phase of the contract. The specification should also allow the agency to conduct unscheduled or random inspections.

2.5.5 Step 4.5 – Decide What Performance Measure to Use

For each parameter that will factor into the agency's acceptance determination, it is necessary to decide what quality or performance measure to use. In the past, statistical averaging was often used as a basis for acceptance; however, use of the average alone fails to address product variability, which can also serve as an important indicator of performance.

To the extent possible, more statistically valid measures of quality, such as percent within limits (PWL), should be used instead of the average or average deviation from a target value. Unlike other measures, PWL (or, alternatively, percent defective) captures both the mean and standard deviation (center and spread) in one measure, encouraging uniformity while minimizing opportunities for process

manipulation. The PWL approach is endorsed by FHWA, has been adopted by many transportation agencies, and is largely understood and accepted by industry.

PWL can be defined as the percentage of a lot falling above a lower specification limit (LSL), beneath an upper specification limit (USL), or between the upper and lower limits (see Figure 2.7). Percent defective (PD) is an equivalent measure that can be equated to PWL through the equation: $PWL = 100 - PD$. Most agencies, however, prefer to

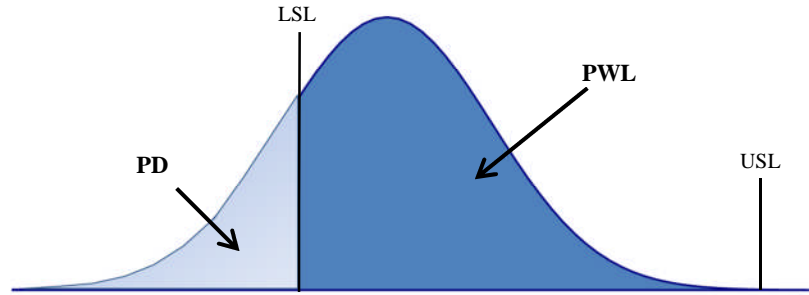


Figure 2.7: Percent Within Limits

address quality in terms of how much of the material meets the requirements (i.e., PWL), rather than how much of it fails to do so (i.e., PD). Box 2.1 provides a brief summary of the PWL method. For further information on the PWL method, refer to FHWA-RD-02-095 and NCHRP 10-79 (Burati et al. 2003; Hughes et al. 2011); in addition, the guide specifications prepared under SHRP 2 R07 provide examples of how the PWL concept can be incorporated into a specification's acceptance and payment provisions.

Box 2.1: Calculating Percent Within Limits (PWL)

The following general procedure can be used to statistically analyze the subplot test result values for a given lot to determine the total estimated PWL. In essence, the PWL method is based on the normal distribution, but instead of using the Z-value to measure the area under the normal curve, a similar statistic – the quality index (Q) – is used with a PWL table to estimate the PWL for a given lot. For further details, refer to FHWA-RD-02-095 and NCHRP 10-79.

1. Determine the lot sample average value, \bar{X} , by calculating the average of all subplot test values.
2. Calculate the Q-statistic using Equations 1, 2, and 3:

$$S_n = \sqrt{\frac{\sum(x_i - \bar{X})^2}{n-1}} \quad (1)$$

$$Q_L = \frac{\bar{X} - LQL}{S_n} \quad (2)$$

$$Q_U = \frac{UQL - \bar{X}}{S_n} \quad (3)$$

Where:

- S_n = standard deviation of the subplot test values
- \bar{X} = average of subplot test values
- x_i = individual subplot test values
- n = number of sublots
- Q_L = quality index for the lower quality limit
- Q_U = quality index for the upper quality limit
- LQL = lower quality limit
- UQL = upper quality limit

Box 2.1: Calculating Percent Within Limits (PWL) (con't)

- Determine the percentage of material above the lower tolerance limit, P_L , and the percentage of material below the upper tolerance limit, P_U , by entering a PWL table (e.g., see sample table below) with Q_L and/or Q_U using the column appropriate to the total number of sublots, n , and reading the appropriate number under the column heading "PWL". This table estimates PWL by rounding up to the nearest whole number, as necessary. For example, the PWL to be used for $n = 4$ and a Q_U of 1.4200 would be 98.

PWL	n=3	n=4	n=5	n=6	n=7	n=8
100	1.1600	1.5000	1.7900	2.0300	2.2300	2.3900
99	1.1541	1.4700	1.6714	1.8008	1.8888	1.9520
98	1.1524	1.4400	$Q_U = 1.42$	1.6982	1.7612	1.8053
97	1.1496	1.4100		1.6181	1.6661	1.6993
96	1.1456	1.3800		1.5497	1.5871	1.6127
95	1.1405	1.3500	1.4897	1.4887	1.5181	1.5381
94	1.1342	1.3200	1.3946	1.4329	1.4561	1.4716
93	1.1269	1.2900	1.3508	1.3810	1.3991	1.4112
92	1.1184	1.2600	1.3088	1.3323	1.3461	1.3554
91	1.1089	1.2300	1.2683	1.2860	1.2964	1.3032
90	1.0982	1.2000	1.2290	1.2419	1.2492	1.2541
89	1.0864	1.1700	1.1909	1.1995	1.2043	1.2075
88	1.0736	1.1400	1.1537	1.1587	1.1613	1.1630
87	1.0597	1.1100	1.1173	1.1191	1.1199	1.1204

- For quality characteristics with only an Upper Quality Limit, PWL equals P_U . For characteristics with only a Lower Quality Limit, PWL equals P_L . For properties with both Upper and Lower Quality Limits, first calculate Q_U and Q_L . Then determine PWL using Equation 4:

$$PWL = (P_U + P_L) - 100 \quad (4)$$

2.5.6 Step 4.6 – Set Performance Limits/Thresholds

Limits or threshold values must be established for each performance parameter, which entails making engineering decisions regarding acceptable and unacceptable (or rejectable) material. Setting specification limits should be done in conjunction with selecting the performance measure and acceptable and unacceptable performance levels. For example, if PWL is used as the performance measure, the acceptable quality level could be defined as 90 PWL. Table 2.1 summarizes key factors to consider when setting and structuring performance limits.

Table 2.1: Considerations for Establishing Performance Limits

<i>Factor</i>	<i>Considerations</i>
Project objectives	<ul style="list-style-type: none"> Decide what the optimum performance should be and whether it is essential to set the required standard at this level. If project conditions indicate that the 100% performance standard is not essential or achievable, having a zero-tolerance threshold (i.e., noncompliance triggers a need for immediate remedial action) may be excessive. In this case, a range of thresholds, based on varying levels of noncompliance and corresponding remedial actions, may provide the best value. If raising the bar on quality is a project goal, set the performance limits above the expected baseline (note, however, that limits should still be realistic and achievable to prevent unnecessary contractor risk pricing). If performance specifications are new to both the agency and the local contracting community, consider initially establishing limits that are relatively easy to achieve to familiarize all parties with the new process and procedures. Once the parties have gained sufficient experience, the limits may be made more demanding.
Criticality of project/element	<ul style="list-style-type: none"> Acceptable performance limits may vary based on the criticality of the project (e.g., high vs. low profile projects) or the project element (e.g., rough grade, finish grade, temporary pavement, etc.).
Contract duration	<ul style="list-style-type: none"> The inclusion of a warranty or post-construction maintenance period may require development of multiple sets of performance limits if the agency wishes to address conditions at different time periods (e.g., new construction vs. during the maintenance/operations period vs. at handback to the agency).
Sampling interval	<ul style="list-style-type: none"> The evaluation interval or section may affect how the limits are set. For example, in the case of pavement rideability, the shorter the interval, the more likely the IRI will be affected by local extremes.
Flexibility extended to the contractor	<ul style="list-style-type: none"> The more freedom given to the contractor, the tighter the performance limits should be. To a large extent, this flexibility is driven by the project delivery approach (DBB vs. DB and its variants) and project type (new construction vs. renewal vs. contract maintenance, etc.). A DB project would typically offer more opportunities for contractor input and innovation than a comparable DBB project, just as new construction would provide more opportunities than a resurfacing or maintenance project. In both cases, the selected parameters could be made more demanding than on a conventional DBB project.
Reliability of data	<ul style="list-style-type: none"> Consider the reliability of the information used to establish performance limits to avoid setting unrealistic or unnecessarily tight tolerances that will result in excessive risk pricing. If the performance limits are based on predictive models, consider if the model has been tested and confirmed to produce reliable results and if the model needs to be calibrated to reflect regional conditions.

What constitutes acceptable material is generally based on what has performed well for the agency in the past. A key resource for determining the appropriate values is therefore historical data

gathered through past projects and the agency’s asset management system. If historical data is consistent and reliable, an agency can establish a baseline of performance through a statistical analysis of data from similar projects (see Box 2.2, “Setting Limits Using Historical Data”). Absent such historical data, performance limits could also be developed through:

- research and review of common industry standards and measures from other agencies,
- collaboration with industry and subject matter experts,
- use of demonstration projects or test strips/pads at the project level, and
- engineering judgment and analysis (predictive models).

Box 2.2: Setting Limits Using Historical Data

As an example of how to establish performance limits using statistical analysis of historical data, consider the case of an agency wishing to develop a baseline IRI threshold for an HMA pavement warranty.

Step 1. As a first step, the agency should obtain an understanding of how local pavements perform over time by reviewing the data collected through its pavement management system (PMS). For this example, PMS data is taken from an Indiana DOT 10-year HMA pavement using a high speed inertial profiler and rut bar based on 1.0-mile segment lengths.

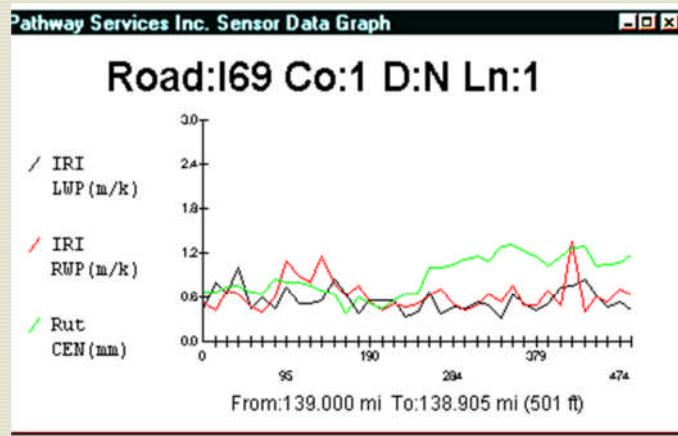
Road/Surface Condition Information

File	Edit	Options	Image	Samples	Distress	Sensor	Map	Signs/Inv	Help											
Num	Road	From(mi)	To(mi)	Dir	Len(ft)	SvyLen	P	Set	StartImage	EndImage	SurveyDateTime	IRI L e	IRI R e	RutAvg(in)						
26	169	139.000	138.000	D	5280.0	5440.2	A	101	01:33:07.15	01:34:10.17	05/05/98 11:40	34	41	0.04						
27	169	138.000	137.000	D	5280.0	5275.4	A	101	01:34:10.21	01:35:09.08	05/05/98 11:41	41	51	0.04						
28	169	137.000	136.000	D	5280.0	5304.2	A	101	01:35:09.08	01:36:05.21	05/05/98 11:42	35	44	0.05						
29	169	136.000	135.000	D	5280.0	5278.1	A	101	01:36:05.21	01:37:02.09	05/05/98 11:43	37	45	0.04						
30	169	135.000	134.000	D	5280.0	5267.6	A	101	01:37:02.09	01:38:09.04	05/05/98 11:44	56	59	0.03						
31	169	134.000	133.000	D	5280.0	5268.1	A	101	01:38:09.04	01:39:10.12	05/05/98 11:45	65	65	0.03						
32	169	133.000	132.000	D	5280.0	5275.6	A	101	01:39:10.12	01:40:06.26	05/05/98 11:46	40	46	0.03						
33	169	132.000	131.000	D	5280.0	5304.5	A	101	01:40:06.26	01:41:03.26	05/05/98 11:47	39	44	0.02						
34	169	131.000	130.000	D	5280.0	5280.9	A	101	01:41:03.26	01:42:00.17	05/05/98 11:48	42	65	0.11						
35	165	75.000	76.000	I	5280.0	5295.1	A	101	00:49:55:28	00:50:52:16	05/04/98 19:23	55	58	0.12						
36	165	76.000	77.000	I	5280.0	5257.1	A	101	00:50:52:16	00:51:48:20	05/04/98 19:24	48	51	0.11						
37	165	77.000	78.000	I	5280.0	5503.9	A	101	00:51:48:20	00:52:47:14	05/04/98 19:25	29	36	0.11						
38	165	78.000	79.000	I	5280.0	5137.1	A	101	00:52:47:14	00:53:42:10	05/04/98 19:26	30	38	0.17						
39	165	79.000	80.000	I	5280.0	5281.1	A	101	00:53:42:10	00:54:38:26	05/04/98 19:26	32	40	0.14						
40	165	80.000	81.000	I	5280.0	5265.1	A	101	00:54:38:26	00:55:35:02	05/04/98 19:27	42	48	0.10						

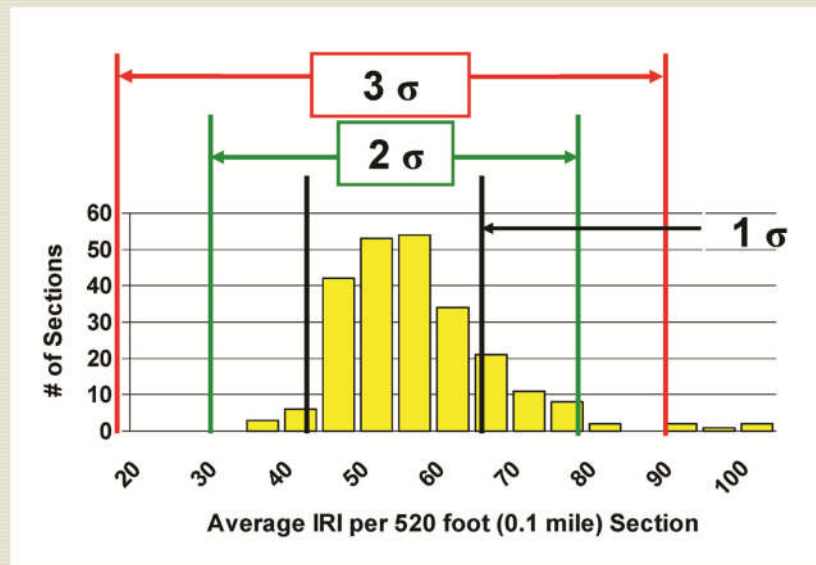
Step 2. The 1.0-mile PMS segments are typically too long to accurately evaluate warranted pavement condition for shorter warranty segments. To develop IRI thresholds for shorter warranty segment lengths (typically 0.1 mile), the existing PMS data should be reprocessed using the shorter section length. Data from areas with expected localized extremes caused by bridge approaches or other transitions in the pavement should also be eliminated.

Box 2.2: Setting Limits Using Historical Data (con't)

Step 3. For an evaluation length of 0.1 mile (520 feet), use the re-processed PMS data to compile the IRI data for 520-foot (0.1 mile) sections.



Step 4. Calculate the standard deviation (σ) of IRI as shown below to determine the statistical distribution of the data.



Assuming a normal distribution, approximately 68% of the data would fall within 1 σ and 95% of the population would fall within 2 σ . As a starting point, the DOT may set the threshold at 2 σ (where only 5% of measured sections would exceed the threshold) to reduce the risk to the contractor for the warranted pavement. As industry gains experience with warranties, the agency may decide to tighten the threshold (to between 1 σ and 2 σ) or to extend the warranty.

2.5.7 Step 4.7 – Assign Quality Management Responsibilities

Performance specifications provide the opportunity to expand the contractor's role in construction quality management beyond conventional process control activities to include several of the quality assurance tasks traditionally performed by agency personnel. Although this approach may represent a departure from the traditional manner in which agencies allocate responsibility for quality management, it is consistent with the degree of risk assumed by the contractor for performance of the work. Too much oversight by agency personnel could shift significant risk back to the agency, as well as add time and inefficiency to the project in contradiction to the goals of rapid renewal; too little could compromise safety and performance.

In accordance with Title 23, Code of Federal Regulations, Part 637 (23 CFR 637), a comprehensive construction quality assurance program should consist of the following core elements: quality control, acceptance, independent assurance, dispute resolution, personnel qualification, and laboratory accreditation/qualification. Use of a performance specification does not diminish the need to perform any of these functions; however, the party performing them may differ from an agency's standard practices. Possible options include the agency, an independent evaluator, the contractor (with agency verification sampling and testing), or some combination thereof. Given the importance of quality management to the outcome of a project and the likelihood that some of the traditional quality roles will change, performance specifications should explicitly define the quality-related responsibilities of all parties to the contract.

Contractor Testing. The guide specifications prepared in conjunction with this manual place much of the quality management responsibilities on the contractor, with the agency performing oversight through verification sampling and testing. (Other approaches, in which the agency retains a more traditional quality assurance role, are also possible to fit the needs of a particular project or program.)

An integral component of the guide specifications is therefore the contractor's preparation of a comprehensive quality management plan (QMP) describing the sampling, testing, inspection, and related activities the contractor will perform to assure quality. The QMP requirement allows the agency to reduce several prescriptive requirements in exchange for the contractor's development and adherence to a detailed plan of how it intends to complete the work, assure quality, and meet the specified performance requirements. The QMP should contain the necessary detail and project-specific information to assure the agency that the contractor understands how its own actions (e.g., in the ordering, transporting, handling, and placing of materials) will impact the in-place properties and performance of the work.

If contractor test data will be used in the agency's acceptance decision, the contractor's sampling and testing personnel must be qualified in accordance with 23 CFR 637.209. Similarly, all laboratories performing contractor testing included in the acceptance determination must also be qualified per 23 CFR 637.209. The contract documents should set forth the minimum requirements to ensure that bidders and contractors are aware of the agency's qualification and accreditation process.

Agency Responsibilities. Even though the contractor may assume a larger role for testing and inspection under a performance specification, responsibility for acceptance will continue to reside with the agency.

Verification Sampling and Testing. If contractor test data will be used in the agency's acceptance decision, the agency, or its designated agent (i.e., consultant under direct contract with the agency), must perform some level of *independent* verification sampling and testing to meet the intent of 23 CFR 637. Use of a third-party testing and inspection firm hired by the contractor does not relieve the agency of its responsibility for verification. Likewise, splits of contractor-obtained samples cannot be used for verification purposes.

Not all properties and parameters being monitored through the contractor's quality management program need to be verified by the agency, only those that will form the basis of the agency's acceptance decision. The frequency of the agency's verification sampling and testing may also be lower than that of the contractor.

Ideally, the agency should perform enough verification sampling and testing to be able to identify statistically valid differences between its results and those of the contractor. [The F-test (comparison of variances) and t-test (comparison of means) are commonly used together to validate contractor test data]. In practice, however, available resources and budget constraints will likely play a larger role in determining sampling and testing frequencies. While there is no universally accepted standard, a minimum rate of 10 percent of the contractor's testing rate has been suggested as a rule of thumb. In the case of small quantities, where the number of contractor tests

23 CFR 637.207

Quality control sampling and testing results may be used as part of the acceptance decision provided that:

- A. *The sampling and testing has been performed by qualified laboratories and qualified sampling and testing personnel.*
- B. *The quality of the material has been validated by the verification sampling and testing. The verification testing shall be performed on samples that are taken independently of the quality control samples.*
- C. *The quality control sampling and testing is evaluated by an IA program.*

and agency verification tests is too limited to perform a statistical comparison, it may be advisable to base acceptance on only the agency's test data.

In addition, if including contractor test data in the acceptance determination, agencies are required to have a dispute resolution system in place to resolve possible discrepancies between the contractor's QC and the agency's verification data.

Inspection. The agency's acceptance program should also contain a reasonable level of visual inspection to ensure quality and workmanship meet the specified requirements.

Independent Assurance. Independent assurance (IA) is unbiased testing the agency performs in accordance with 23 CFR 637 to ensure that sampling and testing activities are being performed by qualified personnel using proper procedures and properly functioning and calibrated equipment. The objective of IA is to assure the reliability of all data used in the agency's acceptance decision – including both the agency's verification test results and the contractor's QC testing.

For agencies that do not routinely include contractor's test results in its acceptance decision, as well as for contractors that may be unfamiliar with IA requirements, extension of the IA program to contractor's personnel and equipment creates new demands. Particularly on fast-paced renewal projects, it can be challenging to keep track of ongoing contractor QC and agency verification testing to schedule the requisite IA activities. To help ensure cooperation, the contract requirements should require the contractor to keep the agency's IA personnel apprised of upcoming QC testing activities so that IA activities can be scheduled. For large projects, using the system approach to IA (in which IA frequency is based on covering all active testers and equipment over a period of time, independent of the number of QC and verification tests completed on a particular project), can also be an effective strategy.

Design-Build and Warranties. It is important to note that use of DB delivery does not eliminate the need for the agency to perform acceptance activities. Although the regulation does allow agencies some discretion to modify their standard QA program to fit the needs of a DB project, an independent verification check of the contractor's results is still necessary for acceptance purposes (23 CFR 637.207(b)).

Similarly, even if the work is subject to a warranty, some level of agency acceptance is still required (23 CFR 635.413). For projects with short-term warranties, where the warranty will not cover the anticipated life of the warranted product, the agency will generally perform some level of initial

acceptance testing at the end of construction. The agency will then be responsible for routine evaluations and monitoring of performance criteria during the warranty period.

Post-Construction Performance Monitoring. For contracts with longer-term warranties or post-construction operation and maintenance periods covering the product's design life or longer, it is typically the contractor's responsibility to monitor performance, document results, and report issues of non-compliance to the agency, with the agency reserving its right to audit quality data and perform its own testing and inspection. To minimize the potential for future disagreements, such long-term performance specifications should clearly describe this reporting process. For example:

- What reports are required (e.g. monthly reports, annual reports, non-conformity reports, corrective action reports, accident reports, etc.)? How frequently must they be submitted?
- What is the required content of each report?
- How soon after a monitoring period are the reports to be submitted?
- How often are meetings required between the agency and contractor?
- Does a lack of compliance with monitoring and reporting requirements trigger payment deductions?

Long-term contracts also require the development of procedures related to the handback of the asset to the agency. Based on the international experience with DBOM contracts, this process typically entails a series of specific inspections conducted prior to handback (e.g., starting 5 years prior to contract expiration), during which the parties are to work to jointly agree on the capital investments to be made by the contractor before the maintenance term expires.

2.6 Step 5: Structure Incentive Strategies and Payment Mechanisms

To be most effective, a performance measurement strategy should not only assist an agency in monitoring the contractor's compliance with the specified performance goals, but should also motivate the contractor to strive for excellence in performance (which for a rapid renewal project would likely entail optimizing construction efficiency and providing quality workmanship, with minimal traffic disruption). Achieving this objective often requires developing and structuring a payment mechanism that will encourage and reward superior performance with regard to the key performance parameters, while assessing penalties for noncompliance.

In developing a payment mechanism, a balance must be struck between value for money and effective motivation of the contractor to prevent and/or correct substandard performance. To achieve this

balance, the cost of incentives must be weighed against the benefits of enhanced performance and the risks of a possible failure to the agency.

2.6.1 Pay Adjustment Factors

In case measurements indicate that the facility does not comply with the performance requirements, the specification should describe the reconstructive work or remedial action that the contractor must perform to meet the performance requirements. If, however, the nonconformance falls within an allowable tolerance, the specification may provide the contractor the option of foregoing the repairs in return for accepting reduced payment. The required remedial action, or, alternatively, the pay adjustment, should reflect the severity of the nonconformance.

Application of quality- or performance-related pay adjustment systems is generally more evolved and prevalent for pavements than for other highway discipline areas, such as bridges and earthwork. Nevertheless, even for pavements, no universally accepted method for calculating quality-related pay factors has been established. As discussed further below, one approach proposed for use in highway construction entails development of performance-related specifications (PRS) in which mathematical models are used to perform a life-cycle cost (LCC) analysis of the as-constructed facility. More common, however, are statistically-based sampling and testing plans that consider the measured variability of the product to determine pay factors.

Considerations Regarding Pay Adjustment Strategies:

- How much is the agency willing to pay to achieve a level of performance beyond the minimum prescribed?
- Which performance parameters, if any, should be tied to incentives/disincentives?
- Does the incentive strategy align with the payment conventions associated with the chosen project delivery method?
- Have the pay adjustments been designed in a manner that will discourage distortions or behavior that run contrary to the agency's ultimate objectives?
- Are there alternatives to monetary incentives (e.g., extension of a O&M term)?

Performance-Related Specifications. Ideally, price adjustments for quality should be based on a LCC analysis. Negative pay adjustments or disincentives should cover the cost of future maintenance and rehabilitation due to the construction not meeting the designed level of quality, whereas a positive adjustment would reflect the savings in maintenance and rehabilitation due to the higher level of initial quality. In reality, however, it can be challenging to develop and implement the performance simulation models needed to tie design assumptions to actual field data and acceptance tests.

Perhaps the most progress in this regard has occurred in the development of a PRS and associated simulation software (PaveSpec) for PCC pavement (Hoerner and Darter 1999a; Hoerner et al. 2000a;

Hoerner et al. 2000b). PRS methodology for PCC allows users to develop a composite pay factor adjustment based on the difference between the estimated LCC of the as-designed pavement and the estimated LCC of the as-constructed pavement. This provides for a more rational approach for adjusting payment, but one that still does not get away from engineering judgment entirely. For example, some judgment may still be needed to develop a reasonable estimate of user costs and to establish rehabilitation criteria and a discount rate for the LCC analysis.

Although implementation of PRS has been somewhat limited to date, technological advancement, particularly in the area of non-destructive testing (NDT) techniques, and incorporation of more robust mechanistic-empirical models, such as those developed for and used in the Mechanistic-Empirical Pavement Design Guide (MEPDG), could ultimately help advance the use of acceptance parameters and payment strategies that better reflect the future performance and design life of the facility.

Statistically-Based Pay Adjustment Systems. In contrast to PRS, statistically-based acceptance plans and pay adjustment systems have been widely applied on highway construction projects and remain a key component of today's quality assurance (QA) specifications, particularly for pavement construction. Although these adjustment systems are largely driven by engineering judgment and are not tied to any specific economic analysis (unlike PRS), they nevertheless provide a streamlined and practical approach for relating payment to the degree of quality received that is statistically accurate and fair to both the contractor and agency.

The literature provides ample discussion and analysis of the theory behind, and implementation of, a statistically-based acceptance program. It is not the objective of this manual to provide a detailed examination of these procedures, only to present an overview of the general concept and various decision points that would enter into the development of a pay adjustment system. Specifiers interested in obtaining a more comprehensive understanding of how to develop and combine individual pay factors in a statistically valid manner should consult FHWA-RD-020-095, *Optimal Procedures for Quality Assurance Specifications* (Burati et al. 2003), and NCHRP Project 10-79, *Guidelines for Quality-Related Pay Adjustments Factors for Pavements* (Hughes et al. 2011). Additional guidance may be found in AASHTO R-9, *Acceptance Sampling Plans for Highway Construction*, and AASHTO R-42, *Development of a Quality Assurance Plan for Hot Mix Asphalt*.

Types of Payment Schedules. Pay factors and pay adjustment schedules can take several forms; however, it is widely agreed that a fair acceptance program should pay 100 percent (or 1.00) of the contract price, on average, when the work is performed at the level specified as being

acceptable in the contract documents. Given the inherent variability associated with any statistical estimation procedure, for the *average* pay to be 1.00 at the target performance level, it is necessary to apply a positive incentive to work that exceeds the performance target to prevent a downward bias due to the random nature of the sampling process. A recent survey conducted as part of NCHRP 10-79 revealed that 31 transportation agencies (out of 37 responding) use incentives ranging from 1 to 15 percent, with 18 agencies capping the incentive at 5 percent (Hughes et al. 2011). (Typically, the higher incentives are restricted to ride quality, reflecting the importance of this parameter to customer satisfaction.)

The earliest pay adjustments were based on tables or stepped schedules, which often led to disputes over rounding errors and measurement precision when the quality level of the work happened to fall just on one side or the other of a large step in the schedule. To avoid this problem, many agencies now use continuous (equation-type) payment schedules that provide a smooth progression of payment as the quality level varies (see Figure 2.8).

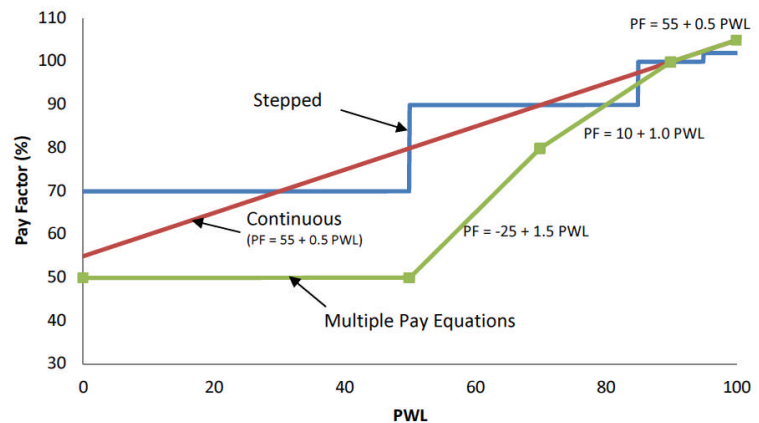


Figure 2.8: Examples of Stepped and Continuous Pay Schedules
(From NCHRP 10-79)

A commonly used continuous pay equation is that recommended in AASHTO R-9:

$$PF = 55 + 0.5 (PWL)$$

Where:

PF = pay factor as a percent of contract price
PWL = estimated percent within limits

Other forms of pay equations are also possible. For example, if the agency would like to emphasize the incentive or disincentive, a series of straight-line pay equations having differing slopes could be used, as shown in Figure 2.8.

Composite Pay Factors. It is rare that a single performance parameter will adequately address all of a project's goals. More likely, project conditions will dictate that pay factors be assigned to multiple acceptance properties. This leads to the problem of how to combine multiple individual pay factors into single composite factor that can be used to characterize the quality of a lot.

Ideally, as discussed earlier, performance prediction models would consider the interaction among various acceptance parameters to determine a composite pay factor based on the predicted performance of the in-place work. Unfortunately, such models are either unavailable or have failed to gain widespread acceptance. Other methods for determining a composite pay factor are therefore necessary. AASHTO R-9 recommends an additive approach using weighted pay factors:

$$CPF = W_1(PF_1) + W_2(PF_2) + \dots + W_n(PF_n)$$

Where:

CPF = composite pay factor
 W_i = weighting factor for AQC “i”
 PF_i = pay factor for AQC “i”
n = number of AQCs

Composite pay equations of this form provide agencies the flexibility of adjusting weights to reflect past experience and to meet the needs of a particular project. The weightings, however, will be subjective in nature and possibly difficult to defend.

Operating Characteristic and Expected Pay Curves. After establishing an acceptance plan and pay adjustment schedule, best practice calls for evaluating if this plan will perform as intended under project conditions. If structured properly, the plan will result in paying an appropriate amount (on average, 100 percent of the contract price) for work that is at or near the target performance level, and similarly, rejecting or paying a reduced amount for work that is at or below the rejectable quality level.

These conditions suggest that two risks are associated with acceptance and payment plans: the seller’s risk (α) (i.e., the risk to the contractor of having acceptable quality level material or workmanship rejected) and the buyer’s risk (β) (i.e., the risk to the agency of accepting rejectable quality level material or workmanship). While these risks cannot be eliminated entirely, they can be minimized by structuring a well-balanced pay system that does not impose inordinate risk on either the agency or the contractor.

Computer simulation tools, such as FHWA’s SpecRisk software, are available to help specifiers evaluate the expected behavior of multi-characteristic acceptance plans and pay adjustment schedules by calculating and displaying the Operating Characteristic (OC) and Expected Pay (EP) curves over a range of possible quality levels. These curves can then be used to analyze and balance risks to ensure that the acceptance program will not yield unanticipated results.

2.6.2 Pay Adjustments and Contract Delivery

The payment conventions and risk allocation inherent to various project delivery approaches will also have a large bearing on the structure of any incentive strategies used to influence contractor behavior. For example, the unit-price basis of DBB contracts makes them particularly well-suited to pay factor adjustments of the type described above to address end-of-construction quality. Conversely, the post-construction responsibilities included in a DBOM contract should largely eliminate the need to apply such adjustments at the end of the initial construction phase. However, such contracts may include complex penalty/reward systems to address the post-construction operation and maintenance of the facility.

DBB and DB. DBB projects are generally bid and measured on a unit-price basis, which makes the application of pay factors, developed using either predictive models or statistically-based acceptance procedures, relatively straightforward.

In contrast, DB contracts are typically awarded on a lump-sum basis, making them less amenable to pay factor adjustments tied to quantities and unit prices. Therefore, to apply a similar pay adjustment process to a DB contract, the agency should require in the solicitation documents that proposers submit a breakdown of quantities and unit prices for each work item subject to pay adjustment. During the construction phase, the agency should then also monitor and measure the associated material quantities, just as they would on a DBB project.

Warranties. It is generally unnecessary for warranty projects to include quality-based pay adjustments or incentives for certain construction acceptance criteria, such as initial pavement smoothness, if the agency will be monitoring these criteria during the warranty period. However, an agency may decide to apply pay factors to end-of-construction acceptance properties that would not otherwise be addressed as part of the warranty evaluations.

DBOM. The payment terms found in DBOM agreements tend to be more complex than other contract types, particularly if the contractor finances certain front-end costs of the project (e.g., planning, design, construction, etc.), which are to be recouped as part of toll revenue or periodic payments received from the agency during the operation and maintenance phase of the agreement. However, even without a private financing component, the payment mechanism used under DBOM is critical to the successful transfer of whole-life performance risk to the contractor.

To ensure the contractor's motivations remain aligned with the project goals, the performance requirements and associated payment mechanisms should be structured in a manner that will provide clear economic incentive to the contractor to perform to the required standards and prevent and correct service

failures. This can be accomplished through a system of monetary deductions for non-compliance (or bonuses for superior performance) and assessment of lane rental fees (or similar) for taking lanes out of service.

For example, during the operation and maintenance phase of a DBOM project, the contractor will typically receive a periodic payment (sometimes referred to as an *availability* payment) on a monthly or some other basis related to its maintenance obligations. In order to be entitled to the full payment, the contractor must ensure that the facility complies with the specified performance requirements. The payment will remain the same as long as the required performance levels are met. It is therefore possible that during some months the contractor will have to carry out a large amount of physical works in order to meet the required performance levels and very little work during other months. If the agency's goal is receive high initial construction quality, the pay adjustment system could be used to make it cost-prohibitive for the contractor to provide poor initial quality at the risk of incurring penalties and lane rental fees to correct service failures during operation.

Perhaps the simplest way to account for performance deficiencies is to apply a straight monetary deduction to the contractor's periodic payment. Alternatively, a two-step process could be used, in which the contractor would incur a specified number of penalty points for each failure, with the accrued points then translated to a monetary deduction. In this case, deductions may not start until a threshold number of points are exceeded. Under either approach, if performance deteriorates below a certain level, other non-financial means can be implemented to compel the contractor to improve performance, ranging from increased oversight to termination for breach of contract.

To establish an appropriate magnitude for the payment adjustments (and/or penalty points), consider the following factors:

- Importance of a particular parameter to the agency
- Extent to which the safety of the public is compromised
- Incidence and persistence of a particular non-compliance item

In addition to not meeting quality-based performance targets, adjustments may be made for the contractor's failure to respond to performance deficiencies in the prescribed timeframe. Positive adjustments could also be made to account for greater than expected usage of the facility by heavy vehicles, given their disproportionate effect on service life.

Similar to warranties, the contractor's post-construction responsibilities should eliminate the need for quality-based pay adjustments at the end of the initial construction phase. However, if timely construction completion is an issue, the agency may choose to apply incentives or disincentives to the completion of the initial construction phase of the contract. Alternatively, the structure of the payment terms for the maintenance phase of contract may also be used to inherently reward or penalize the contractor for early or late completion. By not beginning the scheduled periodic payments until after issuance of a construction completion certificate, and not adjusting the overall contract period (i.e., construction plus maintenance phase) as a result of the early or late completion of the initial construction phase, the contract would in effect impose a penalty for late completion and a corresponding bonus for early completion.

2.7 Step 6: Identify Gaps

Developing and refining a performance measurement strategy will likely entail an iterative process. Once a draft set of performance parameters and associated measures has been established, it is good practice to review and ensure that all factors affecting performance have been covered, either through measurable performance parameters or prescriptive requirements, if necessary.

In addition, when reviewing a measurement strategy, consideration should be given to the likelihood of its success in the field. It is possible for a performance measure to be technically sound, but difficult to implement due to a need for specialized or costly equipment, an inability to yield timely results, or some other impracticality. Such issues can be characterized as “gaps” in the performance measurement strategy.

The existence of gaps can limit the extent to which an agency can develop a performance measurement strategy based solely on user needs or functional parameters (Levels 1 and 2 of Figure 2.1). For this reason, performance specifications must often incorporate some materials and construction-related properties from lower levels of the pyramid to act as surrogates. For example, density and moisture content are commonly used as surrogate properties in acceptance plans and payment schedules for soils even though they do not provide as direct an indication of future performance as would a modulus value. Although some existing technologies, such as falling weight deflectometer testing, can already be used to estimate modulus, and it appears that intelligent compaction technology may ultimately be able to do so as well, agencies would have to expend additional effort to validate and calibrate their design models, as well as obtain sufficient contractor buy-in, before a modulus value could be used as an acceptance parameter without the risk of increased bid prices and payment disputes. In the near term, this means that some traditional indirect measurements will likely remain as useful surrogates.

In the absence of surrogate measures, a gap may also have the wider effect of eliminating the use of a performance requirement as a means to achieve a project goal. For example, if noise reduction on PCC pavement is a goal, it would be possible to develop a functional parameter based on the noise generated in decibels from pavement-tire interaction. However, if the typical contractor is uncertain about how to modify its standard means and methods to meet a certain decibel level, it may be more cost-effective and palatable to industry to simply use a prescriptive texturing specification to accomplish the same objective.

Advancements in the area of nondestructive testing (NDT) technology may ultimately eliminate some of the current gaps related to collecting, processing, and analyzing desired performance data in a timely manner. Recent research efforts, such as the SHRP 2 R06 project and NCHRP Report 626 on NDT Technology for Quality Assurance of HMA Pavement Construction (Von Quintus et al. 2009), suggest that interest in this area is high. It may take some time, however, before such technologies can be used routinely. In the interim, it is therefore important to consider gaps during the development of performance specifications to ensure that the elimination of prescriptive requirements and the implementation of new measurement strategies will not compromise final quality and performance, or create the potential for disputes.

To help identify possible gaps associated with performance specifying, consider the questions in Table 2.2 below.

Table 2.2: Potential Gaps Associated with Performance Specifications

<i>Gap</i>	<i>Considerations</i>
Technology gap	<ul style="list-style-type: none"> • Can a particular parameter be measured and evaluated using existing technology? • Are standardized tests available? • Do the tests provide repeatable results? • Will both the agency and contractor have confidence in the ability of the measurement strategy to yield reliable results? • Are “referee” tests available if the agency or contractor disputes the results of the initial testing? • Is the approach quantitative? If not, is it possible to minimize the subjectivity of qualitative measures by requiring the parties to reach agreement as to what constitutes acceptable performance prior to construction (e.g., through the use of trial sections)?

<i>Gap</i>	<i>Considerations</i>
Sampling & testing gap	<ul style="list-style-type: none"> • Can the data be collected, processed, and analyzed in a timely manner to influence and improve contractor operations? • Can sampling and testing be conducted in a manner that has minimal impact on traffic and lane closure? • In comparison to other testing techniques (or use of method specifications), is the measurement and testing economical? Is a major capital investment required? • Do the measurement techniques require a high skill level from technicians? Are special certifications necessary? • Is specialized equipment necessary? If so, should the contractor provide this equipment or should the agency? • Does sampling provide continuous coverage?
Knowledge gap	<ul style="list-style-type: none"> • Are the main factors affecting performance for a particular parameter known and understood? • Would a typical contractor know how to control its materials and processes to meet a particular performance standard? • Is there sufficient experience or historic data to properly calibrate design or predictive models?

Issues related to the use of bonds to ensure performance during long-term warranties and maintenance periods may also be characterized as a gap. In practice, sureties have been reluctant to offer the required coverage at reasonable rates, contributing to reduced competition for warranty projects. As discussed in further detail in Volume I, Chapter 3 of these Implementation Guidelines, alternatives to bonding, such as the use of letters of credit or other forms of security in the event of default or nonperformance, may provide a means to fill this gap.

Another gap unique to longer-term contracts is the potential for advancements in technology to significantly alter the state-of-the-practice with respect to measurement technology and construction means and methods over the course of the contract. The specification should therefore allow for the modification of performance requirements (by mutual agreement) if future advancements suggest that doing so would improve the management and performance of the asset.

2.8 Step 7: Identify and Evaluate Risks Related to Performance Requirements

As discussed in Step 3 (see Section 2.4), the project delivery approach will significantly affect how much risk for performance can be placed upon the private sector, factoring in both possible changes to traditional roles and responsibilities with respect to design, quality management, and post-construction maintenance, and the level at which performance parameters may be set.

Returning to the Pyramid of Performance depicted in Figure 2.1, current technology and experience are generally adequate to design, specify, and construct facilities that will meet the materials and construction-related properties appearing on the lower levels of the pyramid. These properties form the foundation of today's prescriptive specifications, which typically operate on the principle that if the specified materials and methods worked in the past, then the finished product will likely perform well in service as long as the contractor strictly adheres to the prescribed requirements. Such requirements thereby eliminate risk associated with newer, less proven methods and risk associated with varying contractor performance. The tradeoff, however, is that method requirements generally fail to foster innovation, and performance risk will continue to reside with the agency provided the contractor complies with the specifications.

Certain projects would benefit from shifting more risk and responsibility to the contractor through the inclusion of performance requirements from the higher levels of the pyramid. For example, to manage uncertainties regarding work zone traffic, an agency may determine that contractors are in the best position to develop traffic management plans that will minimize disruption. Performance specifications that include travel time, queue length, or similar requirements could be developed to allocate this responsibility to the contractor.

Specifying at the functional or user needs level, however, can introduce its own set of risks to a project. Staying with the work zone example, what would happen if automated equipment used to record or monitor travel time suffered a breakdown? What if such equipment failed to provide a statistically significant sampling of the vehicles passing through the work zone? Such possibilities suggest that performance specifications will inherently present some risk to both the agency and the contractor, as there will always be a small probability that the agency may be paying for rejectable work or that the contractor may not be receiving due compensation for acceptable work.

The objective of this step is to therefore (1) identify any risks unique to performance specifications that would require further consideration during the specification development process, and (2) based on the available information and expert opinion, determine an appropriate strategy for managing these risks.

Like the gaps identified in Step 6 (see Section 2.7), the presence of possible risks may affect the level at which performance parameters are set. For example, Figure 2.9 expands upon the question initially posed in Figure 2.3 of how best to meet the user need of safety. As shown, skid resistance or friction is a critical functional performance parameter that can be used to directly address the need of safety.

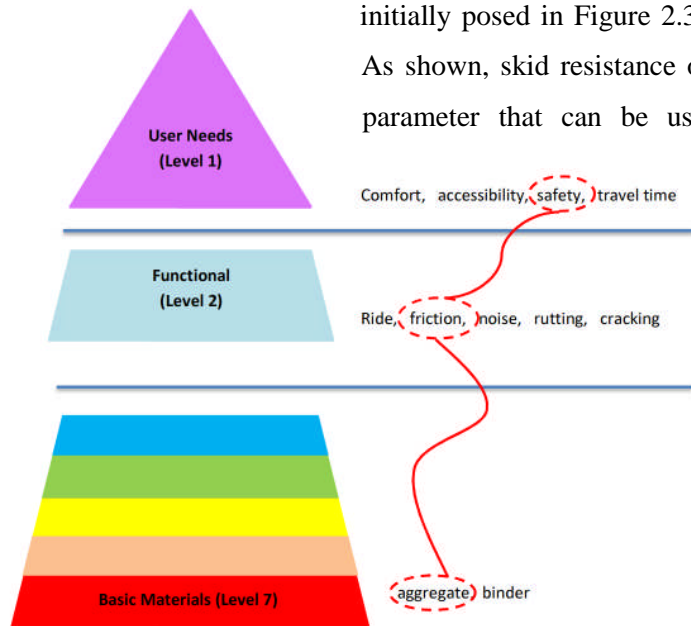


Figure 2.9: Translating User Needs to Materials Requirements

However, given the political sensitivity regarding safety and crash data, it may be more appropriate for the agency to retain control and address friction by specifying lower-level material and mixture properties (e.g., polished stone testing of aggregate used in HMA pavements) instead of establishing a skid resistance target for end-of-construction acceptance.

Prior to finalizing a measurement strategy, it is therefore important to understand and consider how risks (or conversely, opportunities) could adversely (or positively) affect project goals. Figure 2.10 presents a five-step process that specifiers may use to identify and manage the risks associated with applying performance specifications to a rapid renewal project. Additional clarification regarding each step in the process is then provided in the narrative that follows.

For a more in-depth discussion of risk management, specifiers should consult the SHRP 2 Guide for the Process of Managing Risk on Rapid Renewal Projects (Golder Associates et al. 2013).

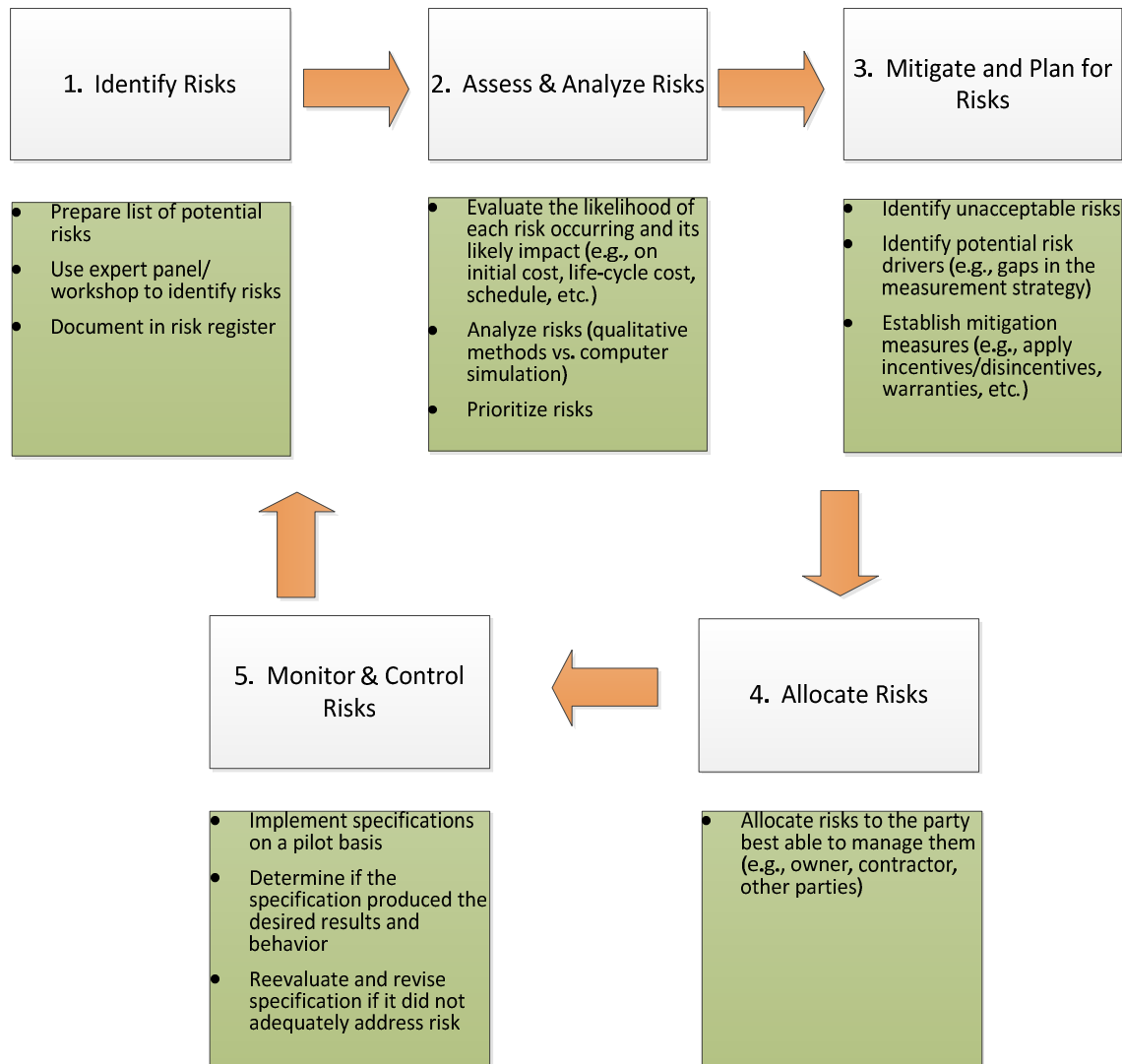


Figure 2.10: Risk Management Process

Risk Identification. To evaluate risks, the first step involves identifying and documenting the risks and opportunities that could significantly affect project performance. The identification process could range from an informal brainstorming exercise to a more structured and facilitated work session in which project team members and independent subject matter experts are solicited for information and issues of concern.

As a starting point, Table 2.3 summarizes some general risk areas that may be used to facilitate the identification of risks related to performance specifications.

Table 2.3: General Risk Areas Associated with Performance Specifications

<i>Risk Area</i>	<i>Description</i>
Gaps related to measurement and testing technology	<ul style="list-style-type: none"> Gaps related to the accuracy and reliability of measurement and testing technology can limit the extent to which measured values reflect reality. A related risk is that while the measurement may be objective, the sampling is inconsistent or not sufficiently representative of actual conditions.
Limitations of performance prediction models (and a lack of understanding of long-term material behavior)	<ul style="list-style-type: none"> Questions remain regarding the ability of predictive models to correlate engineering properties or other parameters measured at the end of construction to performance over the design life. Basing final acceptance and payment on such predictions poses a risk to both the contractor and the agency, as actual performance over time may differ substantially from the predictions. A related risk is that contractors may attempt to manipulate engineering properties to increase pay measures. Models based on empirical knowledge may also be ineffective if innovative products and techniques fall outside the bounds of the empirical basis.
Contractor reluctance to assume risk	<ul style="list-style-type: none"> If the required performance level is poorly defined or if contractors do not understand how their actions affect performance, contractors may be reluctant to bid on projects using performance specifications, resulting in reduced competition or excessive risk pricing.
Agency and contractor reluctance to adapt to performance contracting environment	<ul style="list-style-type: none"> Existing contract administrative procedures are based on traditional method specifications. Resistance by agency and contractor personnel to assume the new roles and responsibilities associated with performance specifications could reduce the effectiveness of the performance requirements and risk transfer (e.g., contractor reliance on the agency's standard specifications and design manuals; agency unwillingness to relinquish control).
Making an incorrect acceptance decision and/or assigning the wrong pay adjustment	<ul style="list-style-type: none"> Two risks exist: the seller's risk (α) (i.e., the risk to the contractor of having acceptable material or workmanship rejected) and the buyer's risk (β) (i.e., the risk to the agency of accepting rejectable quality level (RQL) material or workmanship). Such risks cannot be eliminated entirely but they can be minimized and balanced through a well-written acceptance plan and pay adjustment schedule. Inclusion of highly correlated performance parameters for acceptance and payment purposes could also compromise the intended payment strategy as an increase (or decrease) in one parameter would result in the same response in the other.
Conflicting performance and method requirements	<ul style="list-style-type: none"> The inclusion of unnecessary prescriptive requirements could restrict innovation or require contractors to assume responsibility for items over which they have limited control.

Risk Assessment and Analysis. After identifying risks, it is necessary to understand the attributes of each, such as who assumes the risk (agency or contractor), the frequency or likelihood of its occurrence, and the likely impact of the risk should it occur (i.e., the consequence severity). It is also important to consider how each risk will likely manifest itself. In other words, risk to what (e.g., service, schedule, safety, capital cost, maintenance cost)?

The evaluation of risks related to performance specifications can be integrated into any risk management approach the agency may otherwise be using to manage project-related risks. This could range from rigorous analytical methods to more subjective and qualitative methods for prioritizing risks based on the combined effect of their frequency and severity. The selected method will ultimately involve a tradeoff between sophistication (and hence, defensibility) and the method's ease of use. Refer to the SHRP 2 Guide for the Process of Managing Risk on Rapid Renewal Projects for complete guidance on performing a risk analysis (Golder Associates et al. 2013).

Planning and Mitigation. Once risks are identified and evaluated, the next step would be to determine if such risks can be:

- a) **accepted** on the basis that the risk and its consequences are minimal in comparison to the expected benefits of implementing the performance requirement;
- b) **transferred** to the contractor in a manner that is equitable and consistent with the project goals;
- c) **mitigated** through the use of specification language, incentive/disincentive strategies, or project delivery methods (e.g., warranties) that provide ample protection to the agency while also offering sufficient motivation to the contractor to meet performance expectations; or
- d) **avoided** by including additional prescriptive requirements to either supplement or replace the performance requirement in question.

To best manage risks (or exploit opportunities), it may be necessary to draft additional specification requirements, include lower level performance parameters, or structure a payment mechanism in a manner that will effectively motivate the contractor to prevent and/or correct substandard performance. For example, an agency could mitigate risks related to automated recording equipment by assessing penalties for equipment downtime or insufficient data collection (or, alternatively, awarding bonuses for continuous data collection efforts). From an agency's perspective, broader risks related to limitations of performance prediction models could be mitigated by awarding long-term contracts for design, construction, and maintenance that transfer more performance responsibility to the industry.

Allocation. Performance specifications provide a vehicle for allocating risks to the party best able to manage them. When risks are understood, decisions can be made to allocate them in a manner that minimizes costs, promotes project goals, and ultimately aligns the motivations of the agency and the contractor with the needs of the traveling public.

As addressed in Step 3 (see Section 2.4), the project delivery approach will have a significant bearing on how much risk the industry would be willing to assume, given the roles and responsibilities related to design, quality management, and post-construction maintenance inherent to each method. After identifying and evaluating risks, it may therefore be necessary to revisit the chosen delivery method to ensure consistency with the risk allocation strategy.

Monitoring. Risk management is an iterative process. Field implementation provides the opportunity to assess whether the performance specification adequately addressed risk or if changes should be made prior to subsequent use. For example, inconsistent performance/quality or routine processing of downward pay adjustments could suggest that the specification did not properly mitigate or equitably allocate risks.

A specification's risk profile may also change over time. Technological advancements could eliminate some previously identified risks, allowing for tighter tolerances or elimination of quality-based incentives.

2.9 Step 8: Develop Specification Language

To adequately communicate a project's needs and goals, a performance specification should address the following questions:

- What is the required level of performance?
- How will the agency evaluate and/or monitor the contractor's compliance against the required performance level?
- What are the consequences for failing to meet the required performance levels and/or the possible rewards for exceeding minimum standards?

The seven previous steps were designed to help specifiers develop measurement and risk allocation strategies to satisfy these questions. The final step involves drafting specification language to convey this information to interested parties.

The information to include in a specification will vary with both project delivery approach and subject matter. Some general specification sections common to all project elements and delivery approaches include the following:

- Scope of Work
- Material Requirements
- Construction Requirements
- Quality Management
- Acceptance Criteria
- Measurement and Payment

Some of these sections will figure more prominently under certain delivery methods than others. Materials and construction requirements are more important, for example, under DBB than DBOM or even DB delivery. Other requirements would be unique to specific delivery methods. For example, a warranty provision should address bonding requirements, distress evaluations, and required remedial actions during the warranty period. Likewise, a DBOM specification should emphasize handback (or residual life) criteria at the end of the operation and maintenance phase of the contract.

Subject matter will also have a large bearing on content considerations and specification language. For this reason, the guidance presented in this manual has remained primarily conceptual in nature thus far, to first provide specifiers with the fundamentals of performance specifying. Chapter 3 then applies this conceptual framework to different project elements and delivery methods. The companion set of guide specifications prepared in conjunction with this manual contains specific recommendations regarding performance requirements for different project scenarios. These guide specifications may be used by engineers and specifiers as a template from which to develop project-specific performance specifications.

CHAPTER 3

Overview of Guide Performance Specifications

- 3.1 CONCRETE PAVEMENT**
- 3.2 ASPHALT PAVEMENT**
- 3.3 BRIDGE**
- 3.4 EARTHWORKS**
- 3.5 WORK ZONE TRAFFIC CONTROL**
- 3.6 QUALITY MANAGEMENT**

Chapter Objectives

This chapter:

- Introduces the guide specifications developed under the SHRP 2 R07 research project
- Identifies how the guide specifications attempt to advance the state of practice and promote rapid renewal
- Discusses what additional developments would be necessary to further advance performance specifications

3. Guide Performance Specifications

The step-by-step process described in Chapter 2 provides specifiers with the foundation needed to develop a performance specification for virtually any project scenario. With the fundamentals thus established, the focus of this chapter can shift to the practical application of this conceptual framework to the likely features of a rapid renewal project. Given the difficulty in anticipating every rapid renewal need, the discussion is limited to the following application areas that demonstrated either the greatest need or potential for performance specifying:

- Portland cement concrete (PCC) pavement
- Asphalt pavement
- Concrete bridge deck
- Earthworks construction and other geotechnical features
- Work zone traffic management

The sections below highlight the specific considerations, gaps, and trends unique to performance specifying each of these project elements. The guide specifications prepared in conjunction with this manual then illustrate how one could develop a project-specific performance specification suited to these topic areas.

3.1 Concrete Pavement

3.1.1 State of the Practice in Performance Specifications

Much of the research and debate related to performance specifying concrete pavement has focused on the application of quality- or performance-related pay adjustment systems. As noted in Section 2.6, two general approaches have emerged. One, as promoted in today's QA specifications, involves statistically-based sampling and testing plans that consider the measured variability of the product to determine pay factors. The other entails the use of predictive models to assign more rational pay adjustments based on the difference between the as-designed and as-constructed life-cycle cost of the pavement.

Statistically-Based Specifications. Statistically-based acceptance plans and pay adjustment systems have been widely applied to concrete pavement construction. However, many of the properties emphasized in today's specifications do not necessarily reflect performance. Properties related to concrete durability (e.g., air quality, permeability, unit weight, steel placement, thickness, and mix uniformity) can be more critical to pavement performance than strength, yet are often excluded from acceptance plans.

Commonly used acceptance quality characteristics (AQC's) include compressive strength, thickness, and smoothness. (Agencies concerned with freeze-thaw resistance also often use air content as a screening test prior to concrete placement, but not as a pay factor.)

Agencies differ on the methods and weights used to combine pay factors, with most relying upon experience and engineering judgment to establish a composite pay factor equation. The following equation from NCHRP 10-79 synthesizes the various pay equations reportedly being used by DOTs across the country (Hughes et al. 2011):

$$CPF = 0.25(PF_{\text{strength}}) + 0.35(PF_{\text{thickness}}) + 0.40(PF_{\text{smoothness}})$$

Performance Related Specifications. Much of the more performance-oriented research in the concrete pavement area has focused on the development of performance-related specifications (PRS) that use mathematical models to predict future performance based on select quality characteristics measured at the end of construction. PRS are often referred to as the next generation of QA specifications, as they attempt to use predictive models to assign rational pay adjustments based on the difference between the as-designed and as-constructed life-cycle cost of the pavement.

The basic premise behind PRS methodology is that lower or more variable quality levels will result in reduced pavement performance, requiring an agency to incur future maintenance and rehabilitation expenditures earlier and more frequently than would otherwise be the case. By using bonuses or penalties to pass the expected consequences of particularly good or bad construction quality onto the contractor, a more rational acceptance and payment methodology can be achieved (Hoerner and Darter 1999a).

PRS have been fully implemented on select projects in Indiana, Florida, California, Tennessee, and Wisconsin (Hoerner and Darter 1999b; Evans et al. 2005; Rao et al. 2007; Evans et al. 2008). Other states, including Iowa, New Mexico, and Kansas, have demonstrated PRS as a “shadow” specification (i.e., results did not affect contractor pay).

The PRS for these projects were developed using PaveSpec 3.0 software, which supports pay adjustments for the following AQC's (Hoerner et al. 2000a, 2000b):

- concrete strength (either compressive or flexural, depending on normal State practice),
- slab thickness,
- initial smoothness, and

- entrained air content.

(The software also allows use of Percent Consolidation Around Dowels as an acceptance parameter, but this has not been used in any PCC pavement PRS to date, presumably due to the difficulty of measuring this property in the field.)

One of the key features of the PaveSpec software is that it allows users to adjust calibration factors/coefficients to reflect the agency's actual experience. While this methodology and software provide a sound process for developing PRS, the software does have some limitations, including:

- The software only considers Jointed Plain Concrete Pavement (JPCP) and not Continuously Reinforced Concrete Pavement (CRCP) or Jointed Reinforced Concrete Pavement (JRCP).
- Performance prediction models consider only transverse joint faulting, transverse fatigue cracking, transverse spalling, and roughness progression/IRI.

Work is underway to finalize and pilot PaveSpec version 4.0 software, which will incorporate the latest MEPDG JPCP models and support a more comprehensive set of AQC's. However, some of the limitations seen with the current software will still remain:

- Pay factors are independent (i.e., interaction between AQC's is not explicitly considered in the simulation).
- Models do not address durability, longitudinal cracking, and other long-term distresses.

Ideally, PRS will evolve to incorporate *all* of the important AQC's of PCC pavement that not only affect performance but that are also under the contractor's control. Incorporation of more robust mechanistic-empirical models, such as those developed for and used in mechanistic-empirical design procedures, may enhance the current PRS methodology, but will not eliminate the challenge of how to tie design assumptions to actual field data and acceptance tests.

To achieve the ideal PRS will require advances in non-destructive sampling and testing and improved understanding of long-term material behavior. FHWA-RD-98-155 defines the various stages of PRS implementation as follows (Hoerner and Darter 1999a):

- Level 1 or "Simplified" PRS use standard agency monitoring and testing practices as much as possible. Independent pay factors are developed for each AQC, and these are then combined manually through a composite pay factor equation. The PRS that have been implemented to date are considered Level 1 PRS.
- Level 2 or "Transitional" PRS seek to better quantify future performance by comparing as-designed and as-constructed LCC's. The Level 2 PRS encourage use of more in situ and non-

destructive sampling and testing. The pay schedules developed under a Level 2 PRS consider the interaction of the various AQCs to directly compute a pay factor through computer simulation.

- Level 3 or “Ideal” PRS will consider as many AQCs as possible in the LCC evaluation, and will utilize only non-destructive in-situ testing to measure these AQCs. Many issues need to be addressed before Level 3 PRS can be achieved, such as development of new test methods and identification of all critical AQCs.

Warranty Provisions. Moving beyond QA and PRS specifications, warranty provisions have also been applied to PCC pavements to address actual performance over time. One of the advantages of a warranty specification is the ability to cover certain types of distresses and functional characteristics that would be difficult to address using predictive models. For example, corner cracking, deterioration cracking/material-related distress, popouts, texture loss, scaling, and sealant damage/loss are some of the distresses commonly found in warranty provisions for PCC pavement. Warranties can also address certain functional characteristics that would be difficult to predict using mathematical models, such as texture/texture loss and skid resistance.

Warranties have not been as widely applied to PCC pavement as they have to HMA. Although warranties can be successful in protecting against *premature* failure (i.e., ensuring that distresses due to materials and workmanship such as plastic shrinkage cracking and surface deterioration/scaling are corrected), they do not serve as effective guarantees of *long-term* performance. This is because concrete pavements tend to fail in a non-linear fashion, with deterioration occurring rapidly starting at some threshold point in the pavement life, which is generally well beyond the 5-year duration of most short-term warranties. To successfully ensure long-term performance, the warranty period would have to be long enough to allow indicators of long-term performance issues to appear within the warranty period such that future problems could be averted through corrective action. Unfortunately, difficulties in obtaining bonds have generally precluded long-term warranties.

Higher-level performance parameters directly addressing user needs (e.g., comfort, safety, accessibility, etc.) have primarily only been implemented for pavements under longer-term DBOM contracts. The more progressive of these specifications are attempting to view the pavement and underlying soil layers as an integrated system, more akin to how the traveling public views a roadway. Such a specification would promote a paradigm shift in how pavements are designed and constructed (e.g., by allowing developers to adjust their pavement design based on the as-constructed subgrade conditions).

3.1.2 Guide Specifications

Cast-in-Place Concrete Pavement. A family of guide performance specifications for concrete pavement was developed under the SHRP 2 R07 research study. These specifications were developed with a specific delivery approach in mind; that is, the recommended performance parameters and materials and construction requirements included in each specification are tied to the roles and responsibilities and risk allocation deemed appropriate for a DBB, DB, warranty, or DBOM project.

To advance the state of practice under the DBB and DB cases, the guide specifications attempt to incorporate quality management and acceptance criteria that more closely correlate to durability. The overall objective of these specifications is generally consistent with the statistically-based acceptance procedures and pay factor adjustments found in today's QA and PRS specifications. The specifications have therefore been structured to both complement such existing practice where possible and to highlight (through provided commentary) where a different approach may be necessary or beneficial to advance the goals of rapid renewal.

To promote rapid renewal, the guide specifications:

- Emphasize properties known to affect durability, such as air quality, permeability, unit weight, steel placement, joint conditions, thickness uniformity, and mix uniformity.
- Recommend test methods that are more conducive to rapid renewal, such as maturity meters and thickness probes.
- Encourage contractors to use tools, such as HIPERPAV software, stringless paving, and real-time smoothness devices, to improve workmanship process control.
- Promote the use of non-destructive testing devices, such as ground penetrating radar and magnetic imaging tomography, which would reduce the need for destructive core samples.
- Incorporate financial incentives/disincentives to promote enhanced quality or durability.

Even with recent advancements with mechanistic-empirical design procedures and non-destructive evaluation methods, current gaps in knowledge and modeling and testing techniques suggest that, in the near term, performance specifications implemented under DBB or DB will likely retain some prescriptive elements or surrogate properties to ensure equitable risk allocation between the agency and the contractor.

More freedom can be extended to the contractor under warranty and maintenance provisions containing functional performance parameters that monitor and evaluate the actual performance of the pavement over time. However, organizational and industry-related issues may make it difficult for an

agency to immediately assign post-construction responsibilities to industry. Additional training, guidance, and mentoring will likely be needed before responsibility and control of performance can be shifted from agency to industry staff. This may involve re-training agency staff to “step back,” not prescribe how to perform the work, and adopt more of an oversight role to ensure that performance targets are met, and for industry to invest in the tools and training to take on greater responsibility for the entire project life-cycle, including design, construction, and long-term performance. Volume I of the Implementation Guidelines addresses organizational and industry considerations related to implementing performance specifications.

Recognizing such technological and business-related challenges to the advancement of performance specifications, the guide specifications incorporate a tiered implementation approach that balances a project’s needs and goals against available technology and resources, the capabilities of local industry (including materials suppliers and testing firms), associated costs, and industry’s appetite for assuming performance risk. The tiers generally represent a progression from minimal departure from current practice to a substantial shift in practice and organizational culture that would require technological advancement, improved understanding of long-term material behavior, and possibly a new business model.

- **Tier 1** requirements do not require a substantial departure from current practice, yet place more emphasis on properties known to affect performance, such as air content, and encourage the use of non-destructive testing techniques such as maturity meters and thickness probes as a rapid renewal consideration.
- **Tier 2** requirements incorporate more performance-oriented parameters, such as permeability and air quality, for which test methods may be currently available, but which would require further advancement or refinement to provide the repeatability and accuracy needed for acceptance purposes.

To implement other Tier 2 requirements, some investment may be necessary for contractors to acquire the necessary knowledge, skills, and equipment to fulfill its obligations under a performance specification without passing on excessive risk pricing to the agency. For example, if noise reduction is an agency goal, it would be possible to develop a functional parameter based on the noise generated from pavement-tire interaction, as measured using on-board sound intensity (OBSI) techniques. However, until industry gains sufficient understanding of how to modify its standard means and methods to meet a certain decibel level, it may be more cost-effective to simply use a prescriptive texturing specification to accomplish the same objective.

- **Tier 3** requirements assume improved understanding of long-term material behavior as well as advances in technology, particularly in the area of non-destructive testing (NDT) technology, which could allow for the inclusion of acceptance parameters that better reflect the future performance and design life of the pavement.

Figure 3.1 summarizes these different tiers and the motivations for implementing each. Although the figure suggests a timeframe for implementation, to some extent, this is agency-specific. For example, warranty provisions and long-term DBOM agreements may fall into the Tier 2 and Tier 3 categories, respectively, for agencies that would have to first foster the necessary internal and external support for assigning such post-construction requirements to industry. Some agencies, however, have already implemented such specifications, and can provide a roadmap for agencies interested in pursuing a similar program.

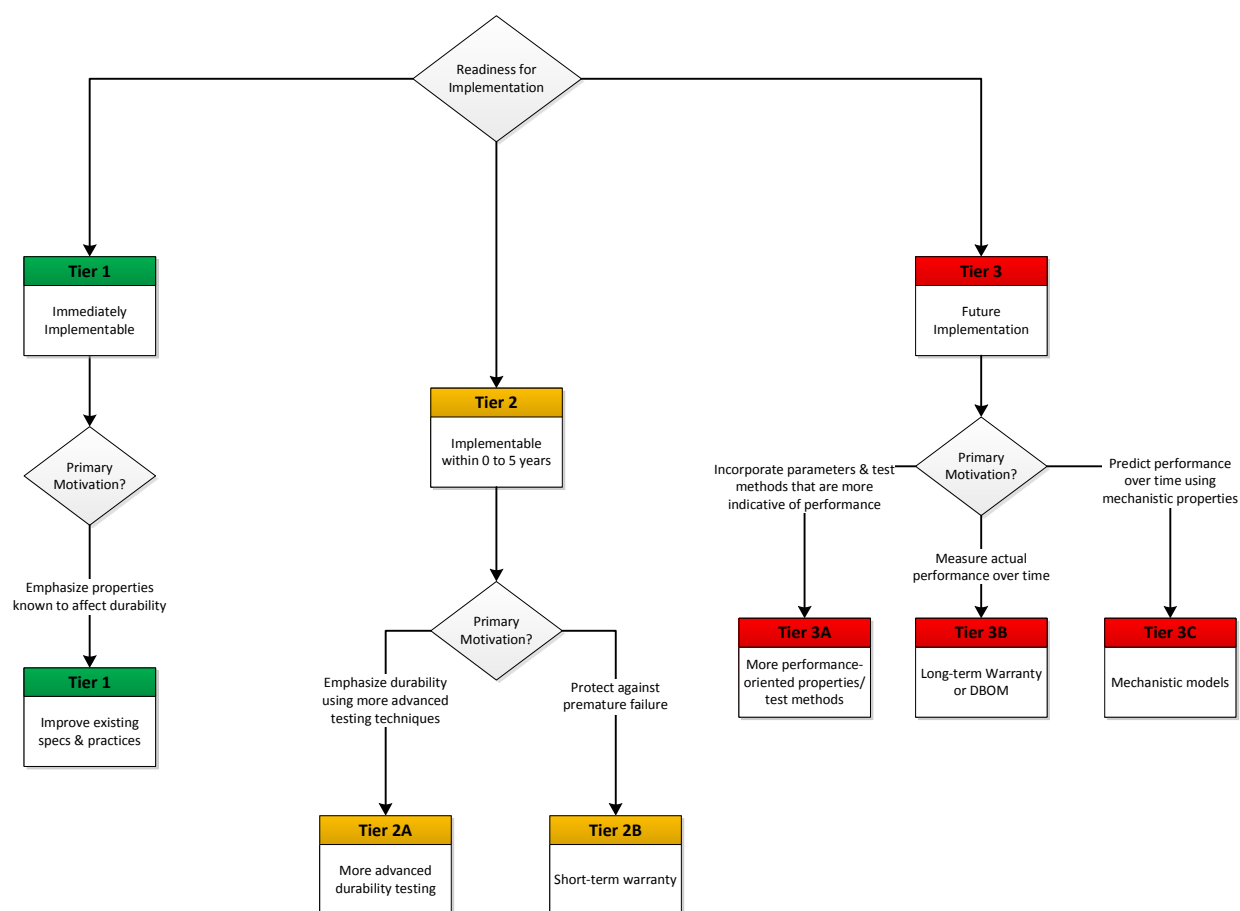


Figure 3.1: Implementation Tiers for PCC Pavement

Tables 3.1 through 3.3 below summarize the suggested performance specification strategy for each of these tiers. To help determine the appropriate tier, users should consider what would best fit the needs of their particular project or program, bearing in mind that possible barriers or gaps may preclude the immediate implementation of all of the proposed parameters and test methods. For example, some

agencies may have difficulty implementing even a so-called “immediately implementable” Tier 1 parameter if they lack the historic data needed to assign reasonable thresholds and targets.

Table 3.1: PCC Pavement, Tier 1 Summary

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 1	Improve Existing Specs and Practices <ul style="list-style-type: none"> Place more emphasis on properties known to affect durability Use test methods that are more conducive to rapid renewal 	Quality Control: <i>Fresh Concrete:</i> <ul style="list-style-type: none"> Unit Weight Slump Air content (pressure test) Placement temperature Evaporation rate Thickness (by probing) <i>Hardened Concrete:</i> <ul style="list-style-type: none"> Strength (by maturity) 	Construction Acceptance: <ul style="list-style-type: none"> Surface distress Thickness (by probing) Strength (by maturity method) Hardened air content Ride Quality Joint deficiencies (visual) <i>If using the existing PRS model as a basis for rational payment adjustments, PaveSpec 3.0 simulation software supports pay adjustments for the following quality characteristics:</i> <ul style="list-style-type: none"> Strength Thickness Initial Smoothness Entrained air content Percent consolidation around dowels 	<ul style="list-style-type: none"> Some additional testing \$ <i>If using existing PRS model as a basis for rational payment adjustments, additional issues may include:</i> <ul style="list-style-type: none"> DOT and industry acceptance of predictive model Need to develop database of local measurement values Not all factors that could affect performance are considered in the existing PRS simulation software (PaveSpec 3.0) 	<ul style="list-style-type: none"> Measure unit weight as part of process control (will help ensure that the mix that is poured meets the mix design) Reduce importance of strength as an acceptance parameter As a rapid renewal consideration, use maturity method to estimate in-place concrete strength

Table 3.2: PCC Pavement, Tier 2 Summary

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 2a	More Performance-Oriented Testing <ul style="list-style-type: none"> Place more emphasis on properties known to affect pavement performance 	Quality Control: <i>Fresh Concrete:</i> <ul style="list-style-type: none"> Unit Weight Slump Air quality (AVA) Placement temperature Evaporation rate Thickness (by probing) <i>Hardened Concrete:</i> <ul style="list-style-type: none"> Strength (by maturity) Permeability Workmanship Process Control: <ul style="list-style-type: none"> HIPERPAV software Stringless paving 	Construction Acceptance: <ul style="list-style-type: none"> Surface distress Thickness (by MIT Scan T2) Strength (by maturity method) Air quality (by air void analyzer) Ride quality Permeability testing (by Chloride Ion Penetration Resistivity) Joint deficiencies Load transfer efficiency (by FWD) Tire-pavement noise (OBSI) 	<ul style="list-style-type: none"> Additional testing \$ Training and more advanced skills required Chloride ion permeability test more representative of bridge decks than pavements 	<ul style="list-style-type: none"> Measure additional properties that are more performance-oriented (e.g., permeability, tire-pavement noise) Measure properties using techniques that are more indicative of performance (e.g., AVA) Incorporate use of non-destructive evaluation techniques
Tier 2b	Short-term Warranty <ul style="list-style-type: none"> Protect against early failure Open up requirements affecting short-term design life or materials close to the surface 	Quality Control: <i>Fresh Concrete:</i> <ul style="list-style-type: none"> Unit Weight Slump Air quality (AVA) Placement temperature Evaporation rate Thickness (by probing) <i>Hardened Concrete:</i> <ul style="list-style-type: none"> Strength (by maturity) Permeability Workmanship Process Control: <ul style="list-style-type: none"> HIPERPAV software Stringless paving 	Construction Acceptance: <ul style="list-style-type: none"> Surface distress Thickness (by probing) Strength (by maturity method) Air quality (AVA) Ride quality Joint deficiencies Load transfer efficiency (by FWD) Permeability (by Chloride Ion Penetration Resistance) Tire-pavement noise Skid resistance Post-Construction Acceptance: <ul style="list-style-type: none"> Ride quality (IRI) Skid resistance Cracking Surface defects 	<ul style="list-style-type: none"> Overcoming potential institutional, legal, and organizational barriers Additional agency monitoring/testing post-construction Setting reasonable thresholds based on duration of pavement warranty/maintenance agreement 	<ul style="list-style-type: none"> Less agency oversight and testing during construction No payment adjustments at the end of construction Post-construction monitoring

Table 3.3: PCC Pavement, Tier 3 Summary

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 3a	More Performance-Oriented Testing <ul style="list-style-type: none"> Incorporate parameters and test methods that are more indicative of pavement performance 	Quality Control: <i>Fresh Concrete:</i> <ul style="list-style-type: none"> Unit Weight Slump Air quality (AVA) Placement temperature Evaporation rate Thickness (by probing) <i>Hardened Concrete:</i> <ul style="list-style-type: none"> Strength (by maturity) Permeability Workmanship Process Control: <ul style="list-style-type: none"> HIPERPAV software, Stringless paving, Real-time smoothness 	Construction Acceptance: <ul style="list-style-type: none"> Surface distress Thickness (by MIT Scan T2) Strength (by maturity method) Air quality (by air void analyzer) Ride quality Permeability (Oxygen Permeability Index) Joint deficiencies Load transfer efficiency (by FWD) Tire-pavement noise Skid resistance Dowel bar alignment (MIT Scan or GPR) Steel location (GPR or MIT Scan) 	<ul style="list-style-type: none"> Additional agency testing \$ Training and more advanced skills required 	<ul style="list-style-type: none"> Measure additional properties that are more performance oriented (skid resistance) Measure properties using techniques that are more indicative of performance (e.g., Oxygen Permeability Index)
Tier 3b	Performance Warranty/DBOM <ul style="list-style-type: none"> Reduce oversight during construction Open up design and material requirements affecting design life 	Quality Control: <ul style="list-style-type: none"> Submit QMP 	Construction Acceptance: <ul style="list-style-type: none"> Conformance with design, QMP, and performance requirements Post-Construction Acceptance: <ul style="list-style-type: none"> Ride quality (IRI) Cracking Surface defects Skid resistance Structural integrity 	<ul style="list-style-type: none"> Limited to P3s or long-term concession agreements Overcoming potential institutional, legal, and organizational barriers Administration of pay adjustment systems and auditing of contractor performance self-reporting Setting reasonable thresholds Identifying appropriate handback criteria Adapting to changes in technology over time 	<ul style="list-style-type: none"> Shift complete performance risk to the contractor Monitor <u>actual</u> performance over time Emphasizes post-construction performance monitoring, with less oversight during construction
Tier 3c	Measurement of Mechanistic Properties <ul style="list-style-type: none"> Improved understanding of performance (measuring design input values) 	Quality Control: <i>Fresh Concrete:</i> <ul style="list-style-type: none"> Unit Weight Slump Air quality Placement temperature Evaporation rate Thickness (by probing) <i>Hardened Concrete:</i> <ul style="list-style-type: none"> Strength (by maturity) Permeability 	<ul style="list-style-type: none"> As-built conditions meet as-designed 	<ul style="list-style-type: none"> Necessary to build database of mechanistic properties for inclusion in/refinement of MEPDG DOT and industry acceptance of predictive models 	<ul style="list-style-type: none"> Incorporate as-built materials properties and construction conditions into mechanistic design models to predict performance and adjust pay

Precast Concrete Pavement. Modular pavement technology is a relatively new method for pavement construction. However, with the implementation of precast concrete pavements (PCP) in dozens of states and for hundreds of lane-miles of pavement, it is now recognized as a mature and no longer “experimental” technology. Although typically more costly than cast-in-place pavement, precast systems offer a viable solution for rapid renewal that can be deployed during short lane closures, minimizing the disruption to the traveling public.

To help increase the comfort level with modular pavement technology, the R07 Team prepared a guide performance specification, focusing on PCP, that highlights the requirements that have been determined to be most critical for the successful use of this technology. Much of the specification content was developed under the SHRP 2 R05 project, which specifically focused on development of modular pavement guidance and specifications for rapid renewal (Tayabji 2012). Although the guide specification focuses on precast systems, it can also serve as a template for specifying other modular systems addressed by the R05 project, such as rollable asphalt.

The R07 Team tailored the R05 recommendations to a performance specification framework to create a specification that promotes competition of different precast systems and that incorporates many of the functional performance parameters, such as ride quality, that are important to road users and are commonly applied to conventional concrete pavements.

A key component of the guide specification, described in greater detail in the R05 effort, is the System Approval and Trial Installation process (Tayabji 2012). A number of proprietary PCP systems are currently available and have been demonstrated as “proven” for PCP construction. These systems typically use patent-protected components and details for fabrication and installation of the precast panels. While such systems should not be precluded from use, agencies are typically unable to specify a sole-source proprietary product for use on a project, unless no other comparable alternatives are available. Similar to a “pre-approved products” list that an agency may create for a particular product to be used during construction, the System Approval and Trial Installation process will provide a method for vetting and approving the use of PCP systems, whether proprietary or not. This will allow a contractor to submit virtually any PCP system for use so long as it meets the requirements from the System Approval and Trial Installation process.

3.2 Asphalt Pavement

3.2.1 State of the Practice in Performance Specifications

Similar to PCC, asphalt performance has been the subject of numerous research studies over the years, which has supported the progression of asphalt pavement specifications from what was predominantly method statements to the end-result and statistically-based QA requirements prevalent in today's standard pavement specifications. Warranties have also been commonly applied to HMA pavement. A methodology for creating PRS for HMA has been developed, but remains in the validation stage.

Statistically-Based Specifications. Statistically-based acceptance plans (following a PWL approach) and pay adjustment systems have been widely applied to asphalt pavement construction.

AQCs for HMA are often separated into Materials and Construction categories. Acceptance of materials is normally based on plant-tested samples, while acceptance of construction is based on field samples. Commonly used materials AQCs include asphalt content, lab compacted air voids, and voids in mineral aggregate (VMA). Commonly used construction AQCs include density, thickness, and ride quality.

Agencies differ on the methods and weights used to combine pay factors, with most relying upon experience and engineering judgment to establish a composite pay factor equation. AASHTO R 42, Standard Practice for Developing a Quality Assurance Plan for Hot Mix Asphalt, suggests the following pay factor equation:

$$CPF = 0.35(PF_{\text{density}}) + 0.20(PF_{\text{asphalt content}}) + 0.35(PF_{\text{air void}}) + 0.10(PF_{\text{VMA}})$$

Performance Related Specifications. PRS would provide for a more rational way to apply payment adjustments. Although still in the validation phase, an HMA PRS was developed under NCHRP Project 9-22 using the spreadsheet solutions of the MEPDG originally developed in NCHRP Project 9-19 as specification criteria for the simple performance tests for permanent deformation and fatigue cracking. This version of the HMA PRS was named the Quality-Related Specification Software (QRSS).

The QRSS is a stand-alone program that calculates the predicted performance of an HMA pavement from the volumetric and materials properties of the as-designed HMA and compares it with that of the as-built pavement calculated from the contractor's lot or sub-lot quality control data. It computes a

Predicted Life Difference (PLD) based on fatigue, rutting, and thermal cracking that can be used to reward and/or penalize contractors for their product (Moulthrop and Witczak 2011).

Warranties. In contrast to PCC pavements, materials and workmanship issues capable of affecting long-term asphalt pavement performance can generally be observed within a few years of construction. For this reason, asphalt pavement warranties have been more readily adopted than those developed for PCC, and the most benefit can be gained from using HMA performance warranties to protect the agency from early failure of the pavement (Gallivan 2011).

The performance parameters typically monitored during the warranty period include:

- Ride quality – typically measured with laser-based inertial profilers and calculated as IRI.
- Rutting/Permanent Deformation – commonly measured with laser-based or ultrasonic-based inertial profilers and reported as average rut depth.
- Friction – typically measured with a skid trailer and reported as a friction number.
- Cracking – typically mapped using visual condition surveys and reported in terms of severity and extent (length or area).

Longer-term DBOM contracts in the U.S. (e.g., 20 to 99 years) have also been applied to asphalt pavement and other roadway features. Examples of projects involving public-private-partnership or long-term warranty or operation and maintenance agreements for HMA and other features include NMDOT US 550/NM SR 44 (20 years), FDOT I-595 P3 corridor Roadway Improvements (35 years), and the Capital Beltway 495 Express Lanes P3 Project (80 years). In addition to monitoring post-construction performance parameters similar to those found in a warranty provision, such operation and maintenance specifications also address the condition of the roadway at “handback” (i.e., when responsibility of the asset reverts back to the agency), using parameters such as structural capacity expressed in terms of a modulus value, deflection, or residual life (e.g., in years or remaining ESAL loads).

3.2.2 Guide Specifications

A set of guide performance specifications for asphalt pavement was prepared under the SHRP 2 R07 research project. Each specification was drafted with a specific delivery approach in mind. The recommended performance parameters and materials and construction requirements included in each specification are tied to the roles and responsibilities and risk allocation deemed appropriate for a DBB, DB, warranty, or DBOM project.

To promote rapid renewal, the guide specifications attempt to:

- Incorporate quality management and acceptance criteria that more closely correlate to performance (mechanistic structural and mix design properties).
- Promote use of NDT techniques, such as ground penetrating radar, that would provide continuous in-situ measurements and reduce the need for cores.
- Encourage contractors to use tools such as GPS-enabled compaction rollers to ensure adequate roller pass coverage and improve uniformity.
- Incorporate financial incentives/disincentives to promote enhanced quality.

One of the biggest challenges to implementing performance specifications, particularly under the DBB and DB scenarios, relates to the use of end-result properties that act more as surrogates than as direct indicators of future performance. Ideally, as more agencies move towards using mechanistic-empirical design procedures, measurement strategies may evolve to incorporate parameters that would better correlate field data to design assumptions. However, even as testing methods and predictive models mature, certain materials and workmanship issues that cannot be measured or modeled effectively may still affect pavement performance. For this reason, warranties and long-term DBOM contracts will likely remain viable options for certain projects.

The guide specifications provide a comprehensive example of the possible performance requirements that could be used to promote the construction of long-lasting pavements. From this menu of requirements, users should select those that best fit the needs of their particular project or program, bearing in mind that certain barriers or gaps may preclude the immediate implementation of all of the proposed parameters and test methods. For example, a performance measure may be technically valid, but difficult to implement due to a need for specialized equipment or expertise, a lack of standardized test methods, absence of historic data for calibration of design or predictive models, or similar obstacles.

Although each agency will have to identify and address possible gaps (particularly those related to historic data and specialized training) based on their own unique experience and needs, current technology and business practices generally point to three tiers of performance specifications for asphalt pavement, ranging from minimal departure from current practice to a substantial shift in practice and organizational culture that would require technological advancement, improved understanding of long-term material behavior, and possibly a new business model.

- **Tier 1** requirements do not require a substantial departure from current practice, yet place more emphasis on properties known to affect the performance of asphalt pavements, including volumetric properties such as air voids, asphalt content, and VMA, and as-constructed properties such as in-place density, joint compaction, and thickness.

- **Tier 2** requirements encourage the use of more rapid and continuous non-destructive evaluation methods for acceptance purposes, such as ground penetrating radar, which, although currently available, would require capital investment and/or further advancement to incorporate into a specification.

As an option under Tier 2 (“2B”), agencies may wish to prequalify or screen the contractor’s mix design using mechanistic, performance-based properties such as dynamic modulus, rutting resistance, and fatigue performance.

- **Tier 3** requirements assume improved understanding of long-term material behavior as well as advances in technology, particularly in the area of NDT technology, which could allow for the inclusion of acceptance parameters, such as stiffness, which better reflect the future performance and design life of the pavement.

Figure 3.2 summarizes these different tiers and the motivations for implementing each. Although the figure suggests a timeframe for implementation, to some extent, this will be agency-specific. For example, warranty provisions and long-term DBOM agreements may fall into the Tier 2 and Tier 3 categories, respectively, for agencies that would have to first foster the necessary internal and external support for assigning such post-construction requirements to industry. Several agencies, however, have already implemented such specifications, and can provide a roadmap for agencies interested in pursuing a similar program.

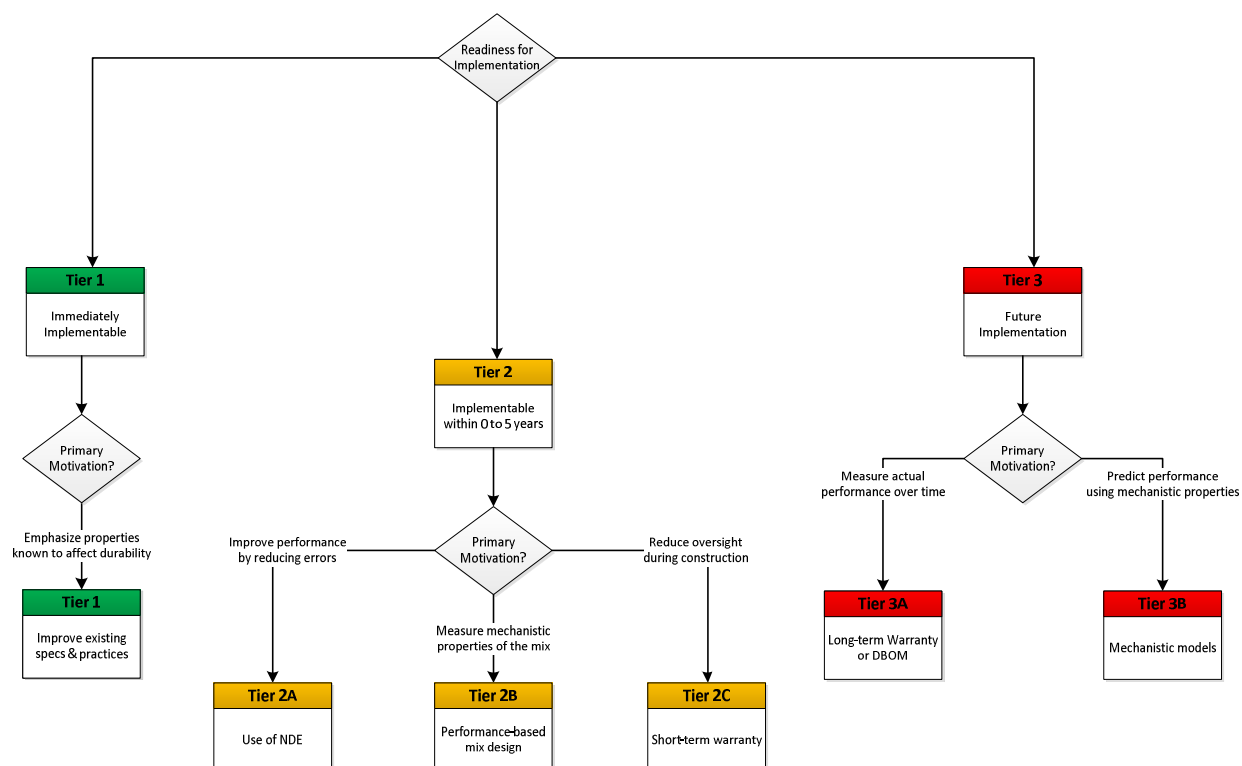


Figure 3.2: Implementation Tiers for HMA Pavement

In general, the three tiers represent a progression towards parameters and test methods that are more indicative of in-place pavement performance. Tables 3.4 through 3.6 below summarize the suggested performance specification strategy for each of these tiers. To help determine the appropriate tier, users should consider what would best fit the needs of their particular project or program. For example, if the goal is to simply reduce construction oversight, a short-term warranty may provide a better option than investing in new mechanistic or non-destructive testing equipment.

Table 3.4: HMA Pavement, Tier 1 Summary

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 1	Improving Existing Specs and Practices <ul style="list-style-type: none"> For rapid renewal – improve durability Reduce likelihood of poor performance 	Quality Control: <ul style="list-style-type: none"> Asphalt Content Air Voids VMA Compaction Smoothness Thickness Moisture Damage Mix Temperature Gradation Workmanship Process Control: <ul style="list-style-type: none"> Temperature Bar GPS-enabled roller pattern mapping (coverage) 	Construction Acceptance: <ul style="list-style-type: none"> Asphalt Content Air Voids VMA Compaction Joint compaction Surface defects Smoothness (IRI or straightedge) Thickness 	<ul style="list-style-type: none"> Payment by sq. yd. would change business model re. lump sum vs. unit priced contracts Additional testing \$ Same DOT manpower and skill level Additional contractor equipment needed 	<ul style="list-style-type: none"> Eliminate gradation as an acceptance parameter Measure VMA, thickness, and joint compaction for acceptance purposes If measuring thickness, consider paying by the sq. yd. Encourage contractors to improve process control by using a temperature bar and GPS-enabled rollers.

Table 3.5: HMA Pavement, Tier 2 Summary

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 2a	NDE of Tier 1 Properties <ul style="list-style-type: none"> Rapid, continuous sampling and testing Improved performance (reduced risk of errors) Reduced oversight (coring/testing) 	Quality Control: <ul style="list-style-type: none"> Asphalt Content Air Voids VMA Compaction Smoothness Thickness Moisture Damage Mix Temperature Gradation Workmanship Process Control: <ul style="list-style-type: none"> GPS-enabled roller pattern mapping (coverage) 	Construction Acceptance: <ul style="list-style-type: none"> Asphalt Content Air Voids VMA Compaction (GPR correlated to cores) Joint Compaction (GPR correlated to cores) Surface defects Smoothness (IRI) Thickness (GPR) 	<ul style="list-style-type: none"> Additional agency testing \$ Training and more advanced skills required (to interpret GPR results) Accuracy of testing 	<ul style="list-style-type: none"> Measuring the same properties but using different measurement techniques Continuous sampling Reducing destructive testing (i.e., cores)
Tier 2b	Mechanistic Mix Design <ul style="list-style-type: none"> Improved understanding of performance (measuring design input values) Build database of mechanistic properties for inclusion in, or refinement of, MEPDG 	Performance-based Mix Design <ul style="list-style-type: none"> E* (Dynamic Modulus) Rutting Resistance Fatigue (beam fatigue or S-VECD) Quality Control: <ul style="list-style-type: none"> Asphalt Content Air Voids VMA Compaction Smoothness Thickness Moisture Damage Mix Temperature Gradation GPS-enabled roller pattern mapping (coverage) 	Construction Acceptance: <ul style="list-style-type: none"> Asphalt Content Air Voids VMA Compaction (GPR correlated to cores) Joint Compaction (GPR correlated to cores) Surface defects Smoothness (IRI) Thickness (GPR) 	<ul style="list-style-type: none"> Use for collecting data on mechanistic properties and use traditional parameters for payment adjustment until predictive models become standard practice Perform post-construction monitoring to validate expected performance Additional agency testing \$ Training and more advanced skills required 	<ul style="list-style-type: none"> Pre-qualifying the mix based on mechanistic properties Measuring design-based properties Advanced testing methods/devices Reducing destructive testing
Tier 2c	Short-term Warranty <ul style="list-style-type: none"> Reduce oversight during construction Open up requirements affecting short-term design life or materials close to the surface 	Quality Control: <ul style="list-style-type: none"> Asphalt Content Air Voids VMA Compaction Smoothness Thickness Moisture Damage Mix Temperature Gradation 	Construction Acceptance: <ul style="list-style-type: none"> Compaction (cores or GPR) Joint compaction (cores or GPR) Thickness Post-Construction Acceptance: <ul style="list-style-type: none"> Ride quality (IRI) Rutting Cracking Surface defects Skid resistance 	<ul style="list-style-type: none"> Overcoming potential institutional, legal, and organizational barriers Additional agency monitoring/testing post-construction Training (changes in roles and responsibilities) Setting reasonable thresholds based on duration of pavement warranty/maintenance agreement 	<ul style="list-style-type: none"> Less agency oversight and testing during construction No payment adjustments at the end of construction Post-construction monitoring

Table 3.6: HMA Pavement, Tier 3 Summary

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 3a	Performance Warranty or DBOM <ul style="list-style-type: none"> Reduce oversight during construction Open up design and material requirements affecting design life 	Quality Control: <ul style="list-style-type: none"> Submit QMP 	Construction Acceptance: <ul style="list-style-type: none"> Conformance with design, QMP, and performance requirements Post-Construction Acceptance: <ul style="list-style-type: none"> Ride quality (IRI) Rutting Cracking Surface defects Skid resistance Structural integrity Other measures defined by contractor 	<ul style="list-style-type: none"> Limited to P3s or long-term concession agreements Overcoming potential institutional, legal, and organizational barriers Agency administration of payment adjustment system and auditing of contractor self-reporting of post-construction performance results Training (changes in roles and responsibilities) Setting reasonable thresholds based on duration of pavement warranty/maintenance agreement Adapting to changes in technology (testing, materials, etc.) over time 	<ul style="list-style-type: none"> Shift complete performance risk to the contractor Monitor <u>actual</u> performance over time Emphasizes post-construction performance monitoring, with less oversight during construction
Tier 3b	Predictive Models <ul style="list-style-type: none"> Predict the performance of the as-constructed pavement to establish a basis for rational acceptance/payment decisions Obtain a better understanding of the expected behavior and life of the as-constructed pavement to help plan for future maintenance needs 	Performance-based Mix Design <ul style="list-style-type: none"> E* (Dynamic Modulus) Rutting Resistance Fatigue (beam fatigue or S-VECD) Quality Control: <ul style="list-style-type: none"> Asphalt Content Air Voids VMA Compaction Smoothness Thickness Moisture Damage Mix Temperature Gradation GPS-enabled roller pattern mapping (coverage) 	Construction Acceptance: <ul style="list-style-type: none"> Compaction Joint Compaction Smoothness Thickness Stiffness Rutting Fatigue 	<ul style="list-style-type: none"> DOT and industry acceptance of predictive models Additional testing \$ Training and more advanced skills required 	<ul style="list-style-type: none"> Measuring design-based properties Basing payment on predictive models Advanced testing methods/devices

3.3 Bridge

3.3.1 State of the Practice in Performance Specifications

Bridges pose a unique challenge for developing performance specifications. Unlike other components of highway infrastructure, bridges may last several decades due to advances in materials and structural design. At the same time, long-term degradation processes such as corrosion, scour, and settlement make it difficult to predict performance over a bridge's design or service life. As a result,

mechanisms such as warranties and predictive models that may be effectively applied to pavements are not as amenable to bridge projects.

Published research related to developing performance specifications for bridges therefore primarily addresses specific material requirements, and to a lesser extent, design requirements, rather than overall bridge performance. The most common areas of research to genuinely target performance criteria are working towards hybrid specifications for structural concrete and bridge decks that couple more performance-oriented parameters (e.g., permeability and air content) with the prescriptive details needed to ensure the agency's goals will be met. Steel beams, reinforcement, and other bridge components are typically required to meet ASTM or AASHTO standards.

Attempts to incorporate higher level performance parameters are more commonly seen under longer-term contracts involving integrated services (design, construction, operation, maintenance), but the underlying design requirements often still reference agency or other FHWA-approved standards. Non-conventional materials or methods, such as fiber-reinforced polymer (FRP) composites for bridge decks and superstructures, precast systems, and accelerated bridge construction techniques, have generally only been applied on a pilot basis through the use of proprietary or prescriptive specifications, rather than through high-level performance specifications designed to motivate industry to offer such solutions in response to durability, completion time, or other renewal goals.

3.3.2 Guide Specification

Developing and implementing performance specifications for bridges presents several challenges. First and foremost, the general reluctance exhibited by safety-conscious bridge engineers to entrust contractors with decision-making responsibility provides few opportunities for innovation and risk transfer. Secondly, the comparatively long service lives expected of most bridge components suggests that *short-term* warranties or maintenance agreements would not provide agencies with an effective means of mitigating the risk of inferior materials and workmanship. Similarly, the length of time that would be required to make a long-term warranty meaningful in the bridge environment tends to make them impractical from a business standpoint (e.g., the likelihood that the contracting entity would dissolve or the initial costs would too high). The most viable options for performance specifications therefore include hybrid specifications implemented under DBB or DB for individual elements of the bridge and higher-level performance specifications for the entire bridge structure implemented under long-term DBOM contracts such as those proposed for the Goethals Bridge Replacement Project (35-40 year concession), the North Carolina Mid-Currituck Bridge (50-year concession), and the Indiana East End Bridge (35-year maintenance term).

As summarized in Figure 3.3, before the bridge community will embrace a performance specification for an entire bridge structure, it will be helpful to demonstrate the successful implementation of end-result specifications for major bridge elements, such as the deck.

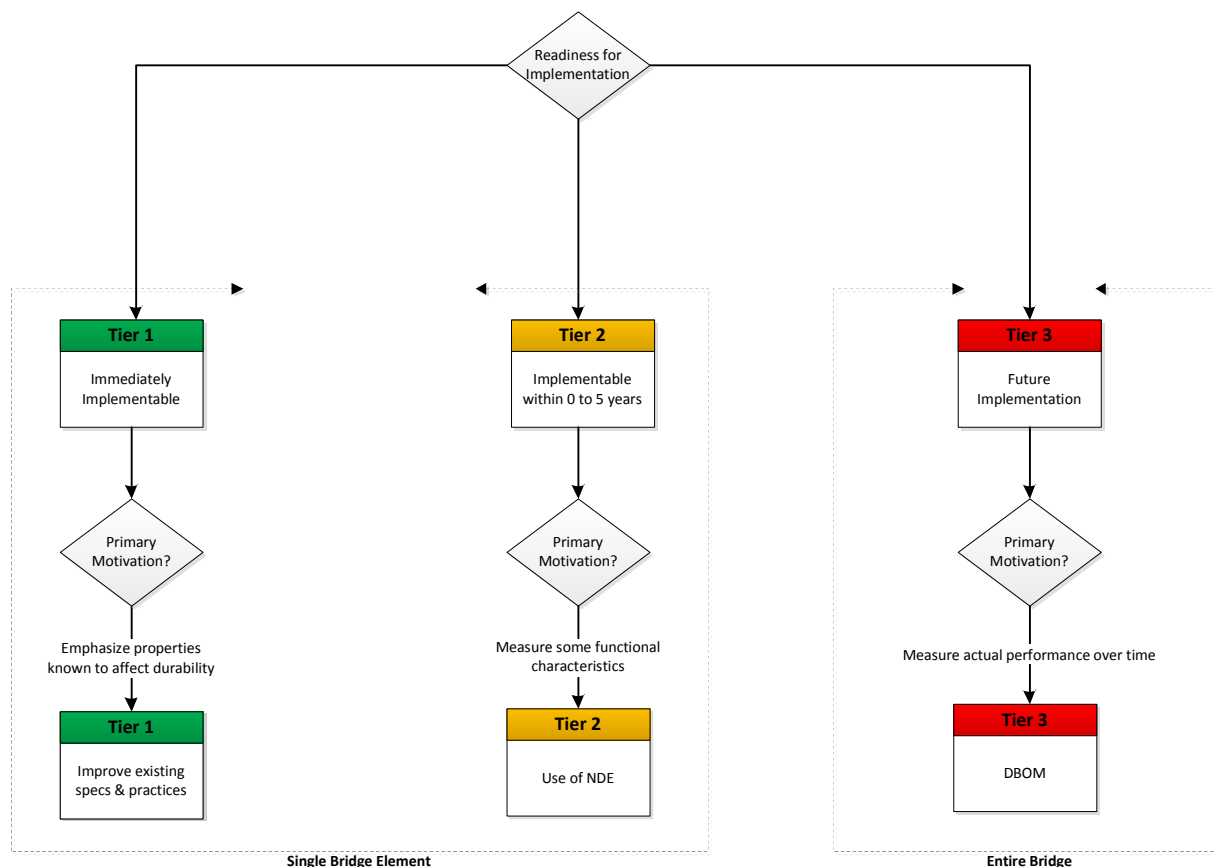


Figure 3.3: Implementation Tiers for Bridge

To begin building the support needed to transition towards higher level performance specifications for an entire bridge, a guide specification for hydraulic cement concrete deck was prepared under the SHRP 2 R07 project. The specification can be easily tailored to either the DBB or DB case as well as to other bridge components, such as abutments and piers.

As further summarized in Table 3.7, to advance the state of practice, the guide bridge deck specification recommends:

- Emphasizing end-result parameters that relate to the durability of the in-place concrete (such as permeability, rebar cover, and cracking), instead of the traditional measures of compressive strength and thickness.

- Incorporating pay factor adjustments to reward the contractor for providing superior product and penalize the contractor for providing product that is of lesser quality than specified. (Pay adjustments should be determined using a percent within limits [PWL] approach to encourage contractors to produce consistent quality work.)
- Addressing surface characteristics, such as ride quality and possibly skid resistance.

Table 3.7: Summary of Bridge Performance Tiers

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 1 (Concrete Bridge Deck)	Improve Existing Specs and Practices <ul style="list-style-type: none"> • Place more emphasis on properties known to affect durability 	Quality Control: <i>Fresh Concrete:</i> <ul style="list-style-type: none"> • Density • Slump • Air content • Water content • Placement temperature • Segregation • Setting time • Evaporation rate • Thickness <i>Hardened Concrete:</i> <ul style="list-style-type: none"> • Compressive strength • Permeability • Shrinkage • Freeze-thaw resistance • Scaling resistance • Alkali-aggregate reactivity resistance • Abrasion resistance 	Construction Acceptance: <ul style="list-style-type: none"> • Rebar location • Thickness (by probing) • Cover depth • Strength • Permeability by Chloride Ion Penetration Resistivity (ASTM C1202) • Air content • Cracking (visual) • Joint condition (visual) • Cross Slope • Cracking (visual) 	<ul style="list-style-type: none"> • Some additional testing \$ • Questions regarding the accuracy and repeatability of the chloride ion permeability test 	<ul style="list-style-type: none"> • Reduce importance of strength and thickness as acceptance parameters and instead emphasize durability of the in-place concrete by measuring parameters such as rebar cover, permeability, and cracking. • Incorporate pay factor adjustments for key acceptance parameters
Tier 2 (Concrete Bridge Deck)	More Performance-Oriented Testing <ul style="list-style-type: none"> • Place more emphasis on functional properties 	Quality Control: <i>Fresh Concrete:</i> <ul style="list-style-type: none"> • Density • Slump • Air content • Water content • Placement temperature • Segregation • Setting time • Evaporation rate • Thickness <i>Hardened Concrete:</i> <ul style="list-style-type: none"> • Compressive strength • Permeability • Shrinkage • Freeze-thaw resistance • Scaling resistance • Alkali-aggregate reactivity resistance • Abrasion resistance 	Construction Acceptance: <ul style="list-style-type: none"> • Rebar location • Thickness (by probing) • Cover depth • Strength • Permeability by Resistivity Meter • Air content • Cracking (visual) • Joint condition (visual) • Cross Slope • Cracking (visual) • Skid resistance • Ride quality 	<ul style="list-style-type: none"> • Some additional testing \$ • Need historical data to identify appropriate thresholds for ride quality and skid resistance 	<ul style="list-style-type: none"> • Measure functional surface characteristics such as smoothness and skid resistance • Incorporate use of non-destructive evaluation techniques

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 3 (Entire Bridge)	DBOM <ul style="list-style-type: none"> Open up design and material requirements affecting design life 	Quality Control: <ul style="list-style-type: none"> Submit QMP 	Construction Acceptance: <ul style="list-style-type: none"> Conformance with design, QMP, and performance requirements Post-Construction Acceptance: <ul style="list-style-type: none"> Loading Condition rating Geometry Deflection/Vibration Settlement Ride quality Noise Other measures defined by contractor 	<ul style="list-style-type: none"> Integration of instrumentation techniques, NDT technologies, monitoring, and 3D modeling to support bridge condition assessment Data management systems, particularly for health monitoring Adapting to changes in technology (testing, materials, etc.) over time 	<ul style="list-style-type: none"> Shift complete performance risk to the contractor Monitor <u>actual</u> performance over time Emphasizes post-construction performance monitoring

The parameters and test methods included in the guide specification were identified based on state-of-the-practice testing technology, which may or may not provide rapid and repeatable results, be representative of the anticipated field conditions, or relate directly to field performance (particularly if based on laboratory testing). For example, although permeability is a critical durability parameter, some questions remain regarding the accuracy and repeatability of the currently available test methods for evaluating this parameter (e.g. ASTM C 1202). Advancements in standardized test methods would eliminate some of the perceived risk in using such a specification.

Further development of non-destructing testing (NDT) techniques, such as those being studied under the SHRP 2 R06A project, would also help advance rapid renewal goals. However, as these technologies (e.g., impact echo, GPR) are primarily suited for evaluating problems with deteriorated structures, they will be more applicable to specifications and delivery methods that include post-construction responsibilities than to the DBB/DB case in which acceptance is based on end-of-construction measurement. A DBOM specification developed for the entire bridge structure could incorporate promising NDT devices, as well as other bridge health monitoring techniques, as possible means of conducting post-construction performance monitoring and condition assessments in a rapid and accurate manner that minimizes traffic disruption.

An ideal DBOM specification would also operate on a high enough level to encourage contractors to consider non-traditional materials and technologies, such as those addressed under the SHRP 2 R19A project, to achieve bridge service lives of 100 years and beyond. Given that several of the methods may have higher initial costs, it appears that a post-construction maintenance period, or a best-value selection

process that considers life-cycle costs, may be required to motivate contractors to consider using such techniques.

3.4 Earthworks

3.4.1 State of the Practice

Geotechnical projects face several unique challenges when it comes to defining and evaluating performance:

- Geotechnical materials are among the most variable construction materials. Higher testing frequencies are therefore needed to obtain statistically valid assessments of performance.
- As soil properties can change over time (e.g., due to post construction saturation), predicting long-term performance is problematic.
- The subsurface aspect of geotechnical projects makes post-construction maintenance and repairs difficult, if not impossible. This emphasizes needing to construct geotechnical infrastructure systems properly upfront with defined levels of risk.
- Warranty provisions are difficult to implement as little historic data is available to establish targets and thresholds. Furthermore, extensive exclusions may be required (e.g., to address changes in ground water conditions or vegetation over the life of the system).

Given these obstacles, geotechnical specifications have traditionally been prescriptive in nature. Although the literature contains several papers and reports describing performance measurements (e.g., settlement), monitoring techniques (e.g., in-ground instrumentation), and test methods (e.g. falling weight deflectometer) for evaluating geotechnical infrastructure systems, only a limited number of geotechnical performance specifications exist, and these are generally a hybrid of prescriptive and end-result requirements (e.g., requiring a minimum number of roller passes in addition to achievement of 95% compaction).

The challenge in developing a more performance-oriented specification is to move beyond the use of acceptance properties that only act as surrogates for performance (e.g., density) to using mechanistic measures (e.g., stiffness) that can be more directly correlated with performance and the assumptions used in the pavement design process. Including new and emerging technology, such as intelligent compaction (IC), in the QA process provides a means to advance the current end-result specifications for earthworks.

Roller compaction monitoring technologies with GPS documentation are particularly attractive for rapid renewal purposes because they offer 100 percent coverage information with real-time data

visualization of compaction data, which is a significant improvement over traditional QA plans involving tests at discrete point locations.

Several equipment manufacturers have been developing these technologies for both earthwork and asphalt materials over the past 30+ years. By making the compaction machine a measuring device, the compaction process can potentially be managed and controlled to improve quality, reduce rework, maximize productivity, and minimize costs. With data provided in real-time, a contractor could alter its process control parameters (e.g., moisture control, lift thickness, etc.) to ensure acceptance requirements are met the first time. Project schedules are thereby reduced, and delays due to post process inspections and rework can be avoided.

To date, results from research and demonstration projects have shown the application of the IC technologies for earthwork construction to be promising, although results are somewhat limited. The FHWA has been actively engaged in an IC demonstration program working with agencies to further develop and promote IC technology. To date FHWA has conducted more than 15 demonstrations to collect data and compare density with machine operation measurement values for earthwork and asphalt pavements. The FHWA has also developed a website (<http://www.intelligentcompaction.com/index>) dedicated to IC that includes information on the technology, benefits, implementation guidance, software for compiling and analyzing geospatial data, and draft IC specifications based on density control. FHWA's plan is to continue with demonstration projects, collect additional performance data, and further develop IC specifications.

In addition to the FHWA demonstration program, a few pilot specifications have and are being developed by state agencies in the U.S. (e.g., Mn/DOT) and a few specifications exist from European countries. Additional work is needed in the U.S. before IC machine values can be implemented for acceptance purposes. Clearly there are differences in IC equipment and machine measurement values, materials, GPS systems, data management, QC, and verification methods that need to be resolved or standardized before IC technology and specifications can be more widely implemented. The guide earthwork performance specification summarized later addresses this obstacle and was field tested on a demonstration project in cooperation with MoDOT.

Beyond compaction technologies, other recent developments in the geotechnical field warrant consideration of performance-oriented specifications, including shallow and deep ground improvement technologies. In the past only a handful of basic technologies were used, but now many options exist. In the field of vertical support elements there are now upwards of 8 or more possible systems that could

provide suitable solutions for soft ground improvement. Unfortunately, many of these new technologies are slow to be implemented due to their proprietary nature. Implementation of performance-oriented specifications that focus achieving overall settlement control or bearing capacity requirements would reduce barriers associated with proprietary technologies and increase competition that should be reflected in best value solutions.

Shallow ground improvements for pavement rehabilitation applications are another area where performance-oriented specifications should improve competition and allow for use of propriety technologies. Several states (e.g., Missouri, Pennsylvania, and Ohio) have been developing specifications for pavement foundation rehabilitation.

3.4.2 Guide Specifications

Challenges with long-term monitoring and the general absence of performance prediction models generally preclude the application of PRS and warranty provisions to geotechnical projects. The guide specifications are therefore primarily end-result specifications, suitable for use under any delivery method. The end-result criteria, however, are directly linked to performance characteristics where possible. In some cases, limitations in the ability to directly measure key engineering parameter values limits the applicability of performance specifications for geotechnical applications. Over time, new advancements in measurement technologies will ideally reduce this obstacle.

Earthwork/Pavement Foundation Systems. Recent developments and improvements to in-situ testing devices and integrated machine sensors (e.g., intelligent compaction rollers with accelerometer based measurements of ground stiffness) have provided opportunities to develop more performance-oriented specifications in the areas of embankment and pavement subgrade/subbase construction.

Two specifications related to pavement foundation systems were prepared under the SHRP 2 R07 project and are included in Appendix C of the Final Report. The first, and perhaps easiest to implement, entails substituting traditional forms of proof rolling with Roller-Integrated Compaction Monitoring (RICM) proof mapping to verify that pavement subgrade support conditions are satisfactory. Compared to traditional proof rolling, proof mapping can provide:

- geospatially referenced documentation of a RICM measurement value (MV)
- real-time information to the contractor during the construction process, and
- results that can be correlated to subgrade support values such as bearing capacity and stiffness.

The second specification represents a more comprehensive attempt to specify the construction of embankment and pavement foundation materials in terms of performance measures and quality statements. Key features of this specification include:

- Use of RICM technology to provide 100% sampling coverage to identify areas needing further work.
- Acceptance and verification testing using performance measures and parameters such as elastic modulus testing, shear strength, and permeability that relate to design assumptions.
- Protocols for establishing target values for acceptance.
- Quality statements and assessment methods that require achievement of at least some overall minimal value during construction, and achievement of a minimum level of spatial uniformity in a given lot area.
- Protocols for data analysis and reporting such that the construction process is field controlled in an efficient manner to ensure the final product meets design assumptions.

The specification contains two different implementation options.

- 1. RICM -MV maps to target locations for QA performance point measurements.** RICM-MV geo-referenced maps are used in this specification option to identify “weak” areas to focus on QA point measurements. Proper QC measures (e.g., controlling moisture content, lift thickness, etc.) should be followed during compaction. The contractor should provide the IC-MV map to the field inspector for selection of QA test locations. Judgment is involved with selecting the number of tests and test locations. Acceptance is based on achievement of target QA point measurement values in roller identified “weak” areas. If in-situ test QA criteria are not met, additional compaction passes should be performed and/or QC operations should be adjusted (e.g. moisture, lift thickness, etc.) and retested for QA.
- 2. Calibration of IC-MVs to QA performance point measurements.** This specification option requires calibration of RICM -MVs to QA point measurements from a representative calibration test strip prior to performing production QA testing. The MV-TV is established from project QA criteria through regression analysis and applying prediction intervals. For modulus/strength measurements simple linear regression analysis is generally suitable, while for correlation to dry unit weight/relative compaction measurements, multiple regression analysis including moisture content as a variable may be needed. If underlying layer support conditions are heterogeneous, relationships are likely improved by performing multiple regression analysis with RICM -MV or point measurement data from underlying layers.

Acceptance of the production area is based on achievement of MV-TV at the selected prediction interval (80% is suggested) and achievement of target QA point measurement values in the areas with MVs < MV-TV.

Ground Improvement Technologies. Several existing and emerging geotechnical technologies have the potential to promote the goals of rapid renewal, but are often overlooked because they entail the use of proprietary systems or lack a standardized analysis and design procedure. The SHRP 2 R02 project, “Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform,” addresses several of these technologies and has developed a selection tool to help users identify appropriate technologies for a given set of project conditions.

To help promote the use of some of these technologies, guide performance specifications have been developed for the following application areas:

- Vertical support elements (technological solutions could include aggregate columns, micropiles, jet grouting, etc.)
- Subsurface improvements for existing pavements (technological solutions could include injection of expanding foam, pressure grouting with cementitious materials, etc.)

By incorporating high-level performance requirements (e.g., settlement, bearing capacity, pavement smoothness etc.), the specifications allow agencies to compete several technologies at once, thereby avoiding the possibility of creating a proprietary specification and allowing contractors to select the technology that will best serve the project’s needs.

3.5 Work Zone Traffic Control

3.5.1 State of the Practice in Performance Specifications

Despite the growing concern among transportation agencies and contractors that traditional owner-developed, method-based specifications for work zone traffic control do not provide an efficient and cost effective means of managing the work zone, the majority of related specifications in use today are generally prescriptive, dictating to the contractor a set of clear, specific steps for work zone management. This system provides the contractor minimal latitude and no motivation to implement innovative and potentially more efficient traffic control measures.

While some agencies have begun to include performance specifications for work zone traffic control, particularly on DB projects, many of these are “performance” in title only. Although such

specifications identify some performance goals (e.g. “Provide a safe travel corridor”), they generally do not tie these objectives to a quantitative measurement strategy (e.g., “Limit work-zone crashes to two per month”).

Many state agencies have been more successful in implementing innovative contracting techniques than strict performance-based traffic control specifications as a means to accelerate construction duration and minimize traffic disruption. These techniques include A+B bidding, lane rental, active management payment mechanism (AMPM), and lump sum traffic control.

3.5.2 Guide Specifications

The guide specification developed under the SHRP 2 R07 project presents a menu of possible performance requirements (e.g., queue length, volume through a work zone, etc.) that an agency can customize to fit a particular project’s goals, jurisdiction, locale, and environment. To help promote rapid renewal, the specification allows contractors to develop a traffic management plan and construction sequence that will be most beneficial to their construction operations and resources, while at the same time holding the contractor accountable for meeting certain performance goals related to minimizing disruption to the traveling public.

Potential gaps may limit the ability to immediately implement all portions of the specification. For example, the use of a “trip time reliability” parameter appears promising, but may be difficult to implement in the near term without having the necessary network infrastructure in place. Technology, though continuing to improve, may not yet be developed to the level required to provide reliable data on a consistent basis. Such reliability is essential if an agency wants to tie payment to this data. New technologies are evolving that utilize detector and video cameras to count vehicles, which may address this issue.

3.6 Quality Management

Managing quality has traditionally been the responsibility of the agency. However, performance specifications, particularly when implemented as part of an alternative project delivery system, provide the opportunity to assign quality management responsibilities to the entity best suited to carry them out in a satisfactory manner. This assignment of quality management responsibilities should be consistent with the degree of risk assumed by the contractor for the performance of the work. Too much oversight by agency forces could shift significant risk back to the agency, while too little could compromise safety and performance. Given the importance of the quality management program to the outcome of the project, the

Contract Documents should clarify the role of all parties to the Contract (including third party inspection firms) in ensuring the project's goals are met.

A guide specification was developed under the SHRP 2 R07 project to highlight the essential elements of a General Provision for Quality Management. A key element of this provision is the contractor's preparation of a formal Quality Management Plan (QMP). A QMP requirement allows the agency to reduce prescriptive requirements in exchange for the contractor's development and adherence to a detailed plan of how it intends to complete the work and meet the performance requirements.

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