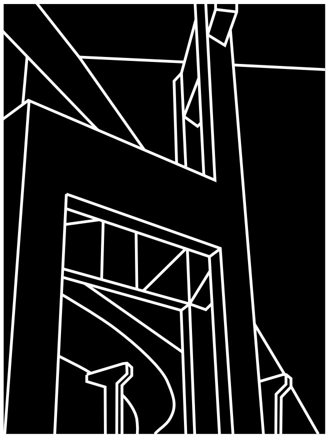
PROJECT SUMAMRY REPORT 1824-S

DEVELOP A METHODOLOGY TO EVALUATE THE EFFECTIVENESS OF QC/QA SPECIFICATIONS (PHASE II)

Mansour Solaimanian, Thomas W. Kennedy, and Huang-Hsiung Lin



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16. Abstract

The Texas Department of Transportation (TxDOT) has been implementing statistically based quality control/quality assurance (QC/QA) specifications for hot mix asphalt concrete pavements since the early 1990s. These specifications have been continuously revised and improved by TxDOT based on feedback and on the results observed during their use. This move towards development and use of QC/QA specifications may lead the way to performance-based specifications (PRS). The pavement performance predicted through prediction models, as well as the relationship between materials and construction (M&C) variables with pavement performance, form the basis for such specifications.

In this report, current performance-based specifications and performance prediction models are discussed. A sensitivity analysis of the prediction model used in this study was conducted and the important influencing factors were ranked. A methodology is presented and a framework is developed on the use of such specifications based on statistical concepts. An approach is developed and presented for determination of payments using PRS and pavement performance. A numerical example is provided on how such an approach could be used to determine payments using the level of reliability on performance of a specific pavement.

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DEVELOP A METHODOLOGY TO EVALUATE THE EFFECTIVENESS OF QC/QA SPECIFICATIONS
(PHASE II)

by

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Research Report 1824-S

Research Project 0-1824

Develop a Methodology To Evaluate the Effectiveness of QC/QA Specifications (Phase II)

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

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IMPLEMENTATION STATEMENT

This report presents a methodology useful in the development and deployment of performance-based specifications that derive from statistical reliability concepts. Specifically, the developed methodology can be used by TxDOT for improving current QC/QA specifications. It can also be used as the foundation for improving practical versions of performance-based specifications. The proposed method can be used to determine pay factors based on the predicted pavement performance.

Implementing an effective QC/QA performance-based specification is expected to improve pavement quality, increase service life, and reduce the overall cost of pavement in Texas. The specification is expected to provide contractors considerable latitude to use their expertise and ingenuity in constructing a high-quality pavement. According to standard method-based specifications, the agency accepts full responsibility for the outcome by specifying for the contractor precisely what needs to be done based on a provided recipe. Under QC/QA performance-based specifications, the responsibility for ensuring quality is entrusted to the contractor.

ACKNOWLEDGMENTS

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DISCLAIMERS

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SUMMARY

The Texas Department of Transportation (TxDOT) has been implementing statistically based quality control/quality assurance (QC/QA) specifications for hot mix asphalt concrete pavements since the early 1990s. These specifications have been continuously revised and improved by TxDOT based on feedback and on the results observed during their use. This move towards development and use of QC/QA specifications may lead the way to performance-based specifications (PRS). The pavement performance predicted through prediction models, as well as the relationship between materials and construction (M&C) variables with pavement performance, form the basis for such specifications.

In this report, current performance-based specifications and performance prediction models are discussed. A sensitivity analysis of the prediction model used in this study was conducted and the important influencing factors were ranked. A methodology is presented and a framework is developed on the use of such specifications based on statistical concepts. An approach is developed and presented for determination of payments using PRS and pavement performance. A numerical example is provided on how such an approach could be used to determine payments using the level of reliability on performance of a specific pavement.

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Pavement construction specifications continue to be modified in an effort to achieve finished products of the highest quality and at the lowest possible cost. Within the last few years, a number of state highway agencies have moved toward statistically based quality control/quality assurance (QC/QA) specifications. The use of such specifications is gradually gaining acceptance within most state highway agencies.

For its part, the Texas Department of Transportation (TxDOT), being among the pioneers in seeking better ways of achieving improved pavements, has been implementing a new set of specifications—developed beginning in 1990—in lieu of the method-type specifications used for the production and placement of hot mix asphalt concrete.

Under most current construction specifications, including method specifications, highway agencies cannot hold contractors liable for premature failure or unsatisfactory pavement performance. Once paid by the highway agencies, the contractors are relieved of their responsibilities regardless of the future performance of the pavements. However, sometimes it takes several years before pavement distresses (e.g., rutting, fatigue cracking, and roughness) develop to measurable levels. Consequently, most highway agencies expect that draft performance-based specifications will incorporate predicted pavement performance as part of the design phase and as a criterion in the determination of payments for the contractors. A performance-oriented specification is one that describes the desired levels of fundamental engineering properties that are predictors of performance and that appear in primary performance prediction relationships (Ref 1).

1.2 DIFFERENT SPECIFICATIONS AND RELATED TERMINOLOGY

A construction specification should be practical to implement and should be developed with the idea of achieving a high-quality product (constructed pavement) at a reasonable cost. As far as the quality of the final product is concerned, the level of responsibility of the state highway agency (i.e., the buyer of the product) and the contractor (i.e., the seller of the product) varies. This level of responsibility depends on the type of specification and on the limitations set forth in that specification. Briefly, the following terms are applied to different specifications:

1) Method Specification
2) Statistical QC/QA Specification
3) End-result Specification
4) Performance-related Specification
5) Performance-based Specification
6) Warranty Specification

While the differences between some of these terms are self-evident and are applied to different types of specifications (for example, method specification vs. performance-based specification), the differences between some others are not that distinctive (for example, the difference between a performance-related specification and a performance-based specification). In these cases, very frequently the terms are used interchangeably; consequently, one specification may not be easily distinguished from another.

In method specifications, the contractor is provided with specific details on the materials, design, and type and method of construction. It is for this reason that such specifications have been perceived as too restrictive in that they do not allow a contractor flexibility in making decisions about the design and/or process of the pavement construction. Moreover, there is no incentive for the contractor to explore innovative solutions in improving product quality.

The term *end-result specification* is often used to refer to a specification in which certain parameters believed to influence performance are used as criteria to judge the quality of the product and to make the payment. The contractor is responsible for the quality of the control parameter (end result), which is used to determine payment. As an example, deviation of such parameters as asphalt content, gradation, and air void from target values can be used as end-result parameters. In such a specification, and in contrast to method specifications, the contractor is entrusted with more responsibility and greater latitude: In other words, there are greater opportunities for using ingenuity to improve product quality. However, in an end-result specification, the end may be defined at any of the following different levels or stages:

Level 1: The end result will be not only the quality of the original material and the deviations of some material parameters from certain control limits, but also the quality of the compacted pavement. Parameters such as asphalt content and gradation deviations from target values, as well as air void levels of constructed pavements are some examples of this kind of end result. In this case, it is believed that effectively controlling the original materials and air void level will result in high-quality pavement. The parameter limits in this case can be established based on historical data and on the relationship of the parameters with the engineering properties of the compacted mixture.

Level 2: The end result at this level will be the quality of the compacted material right after construction. In this case, it is believed that effectively controlling the material properties and the method of construction in the beginning will result in good performance in the long run. Such control requires obtaining samples of the prepared material, preparing compacted specimens, and testing those specimens for engineering properties. Deviation of the measured properties from certain criteria will be the basis for judging performance and making the payment. Obviously, it is crucial that the compacted samples be representative of the constructed pavements. (It is necessary that tests be performed on the cores from the pavement.) It is also crucial that the properties used for measurement be defined, as well as their acceptable limits and ranges.

Level 3: At this level, the end result will be the performance quality and developed distresses at the end of the design life based on predictions from reliable models. The results from these predictions, along with life-cycle cost analysis, will form the basis for the level of payment.

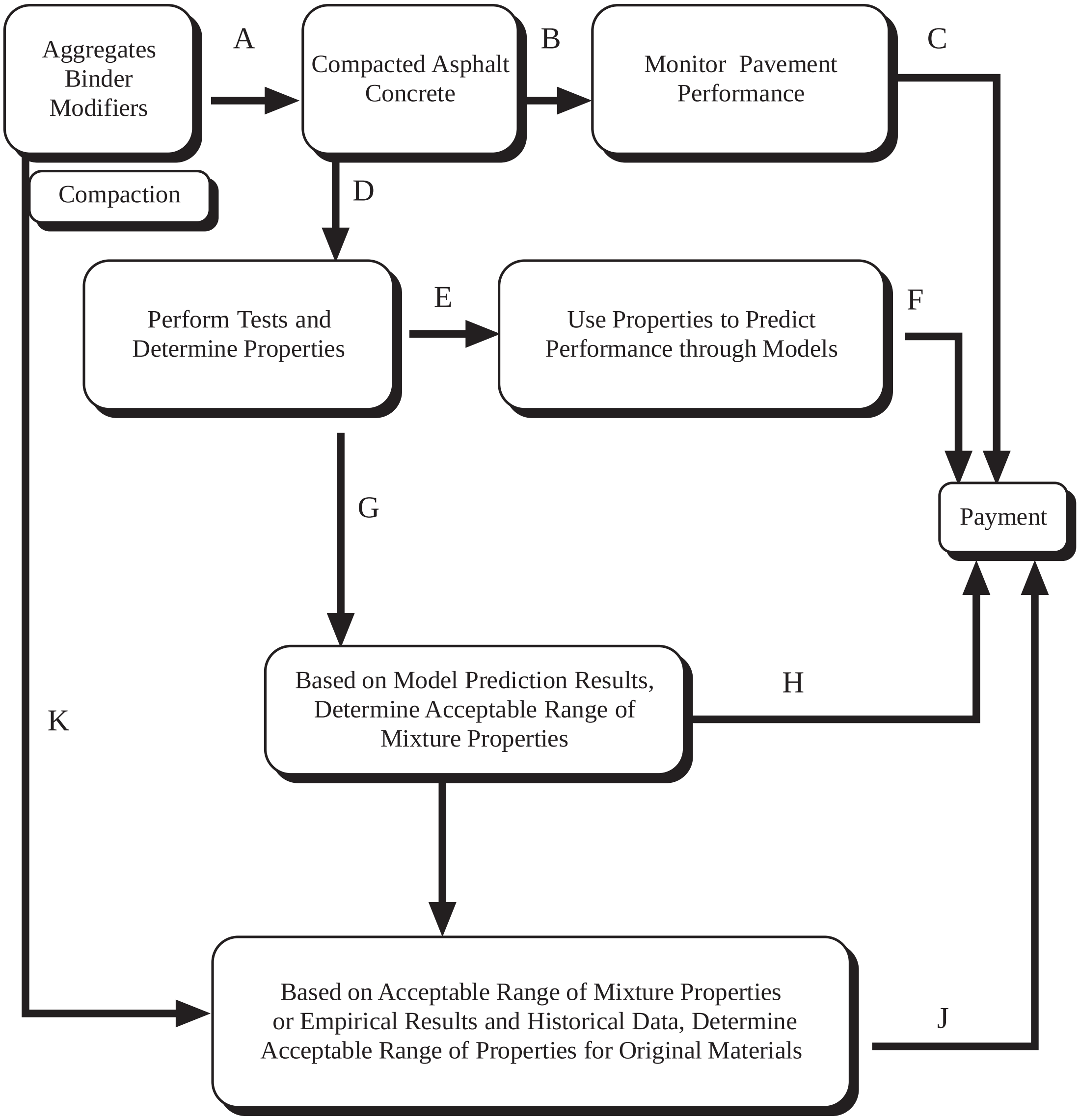
Level 4: At this level, the end result will ideally be at the end of the design life of the constructed pavement or overlay (i.e., how well the asset has delivered its service). In this case, the pavement or overlay quality at the end of its service life, based on a certain assessment, will be the end result.

As far as the quality of the end product is concerned, as an end result specification moves from level 1 to level 4, the responsibility of the agency is decreased and that of the contractor is increased. Existing specification Item 3022 falls in the first category (level 1), while warranty specifications, in which the contractor carries the highest level of responsibility, belongs to level 4 of an end-result specification. In the case of a warranty specification, the contractor is ultimately responsible for acceptable performance of the pavement, and in this regard the contractor is to choose the materials, design, construction equipment, and method. In this way the contractors are left with sufficient leverage and latitude for using their ingenuity and expertise to deliver a high-quality product.

Performance-related and performance-based specifications fall between the two extremes of method and warranty specifications, and correspond to the preceding levels 2 and 3. Some distinguish between the two by suggesting that a performance-related specification requires measurement of (and establishing limits on) properties that are not directly measures of performance, but are related to it. Measurements on quality and quantity of original materials or measurement of engineering properties of the compacted mixture are one example.

A statistically based QC/QA specification applies to any specification in which statistical concepts and methods are incorporated into the quality assurance process. Statistical quality assurance (SQA) is part of a well-planned program in which quality is based on the conformance of the results with established levels for certain parameters based on statistical concepts. Applying statistical concepts to quality control of paving materials has been widely covered in the literature (Refs 2, 3, 4).

Figure 1.1 shows the different paths taken by different specifications with respect to quality control and determination of payment.



Path ABC: Warranty Specification

Path ADEF: Performance-Based Specification

Path ADGH: Performance-Related Specification

Path KJ: Method Specification

Figure 1.1 Flowchart presenting different paths taken by specifications

1.3 USE OF PERFORMANCE-RELATED SPECIFICATIONS

The primary objective of using a performance-based or performance-related specification (PBS or PRS) is to achieve a quality pavement based on statistical quality control (SQC), process performance modeling, and continuous improvement (CI) principles. To meet this objective, the materials and construction variables that are related to performance, and over which the contractor has control, need to be separated from the materials, construction, design, and environmental variables over which the contractor has no control. Performance can be enhanced only by monitoring and controlling performance variables over which the contractor has control.

At the core of a PRS, there is a model or set of models that allows for the evaluation of the effects of materials and construction variables on future pavement performance. Ideally, the set of pavement performance models used for the PRS should be the same as that used for the design of the pavement structure. Using these models, the as-constructed pavement performance can be compared with the as-designed pavement performance and the results translated into a common indicator, such as annualized life-cycle costs or load-carrying capacity.

The concepts outlined in this report bring together statistical quality control, continuous improvement principles, and performance-related specifications as part of a framework for developing a methodology geared to evaluating the effectiveness of specifications.

1.4 OBJECTIVE

The overall objectives of this research study were to develop a rational, cost-effective methodology for use by TxDOT in preparing and evaluating new specifications, and to then apply the methodology to the QC/QA specification for hot-mix asphalt concrete (HMAC).

An important objective of this study was to develop a framework for a new set of performance-based specifications for asphalt concrete pavements. The framework was to be conceptual and independent of whatever performance prediction models were used. In addition, the framework was to be formulated into a step-by-step procedure that could serve as a guideline for highway agencies.

1.5 METHODOLOGY

The proposed research methodology takes advantage of integrating pavement performance prediction models and statistical methods. With the advent of such pavement performance prediction models as VESYS (Refs 5, 6), ILLIPAVE (Ref 7), MICHPAVE (Ref 8), and FLEXPASS (Refs 9, 10), engineers are capable of predicting pavement performance once proper environmental, structural, traffic, and material parameters (e.g., temperature, thickness, traffic loads, and mixture stiffness and visco-elasto-plastic properties) are input into the model. Even though the performance prediction models cannot guarantee 100 percent accuracy in a given pavement distress prediction, they provide a logical means for modeling the future pavement behavior, provided the models are based on sound mathematical and mechanical concepts and take advantage of appropriate engineering properties.

Statistical techniques are important in utilizing prediction models to assess the predicted performance and to decide the payment to the contractor. VESYS, for example, has sixty-seven input parameters. Even with two levels for each parameter, the resulting combinations of input parameter values will be staggeringly large, i.e., 2^{67}. Thus, it is necessary to use statistical methods to screen out insignificant parameters and to identify significant variables for further analysis. The usefulness of statistics in dealing with this subject becomes evident when one considers the complexity of the models and their myriad input variables.

Of greater importance is statistics' role in determining the level of reliability in predicted pavement performance (based on which payment is decided). In other words, it is obvious that there is a level of confidence associated with the prediction of distresses in the pavement. Statistics is needed to determine this level of confidence and, accordingly, to assist in making decisions on the acceptability of a certain design or construction.

1.6 SCOPE

This study has focused on the integration of asphalt pavement properties, statistical methodologies, and pavement performance models in order to develop a framework for performance-based specifications. Chapter 2 further discusses performance-based specifications, while current performance prediction models are discussed in Chapter 3. Performance-based specifications and determination of payment adjustment factors are covered in Chapters 4 and 5, respectively. Finally, conclusions and recommendations are presented in Chapter 5.

CHAPTER 2. CURRENT PERFORMANCE-BASED SPECIFICATIONS

This chapter describes the concepts, components, and framework of a performance-based specification (PBS) for portland cement concrete (PCC) and asphalt concrete (AC) pavements. Background concepts are provided first, followed by a summary of the key elements of a PBS. The chapter then concludes with a review of current PCC and AC PBSs.

2.1 CONTROL PARAMETERS

The Texas Standard Specification for Hot-Mixed Asphalt Concrete (Item 340) required monitoring the following factors during construction to ensure acceptable quality for the constructed pavement:

1) Deviations in gradation from the job-mix formula target values
2) Deviations in asphalt content from the job-mix formula target value
3) Deviations in the air void level of the compacted mixture from the acceptable limits
4) Stability values from the Hveem stability test
5) Ride quality evaluated vis-à-vis Item 585 of the standard specification (Ride Quality of Pavement Surfaces)

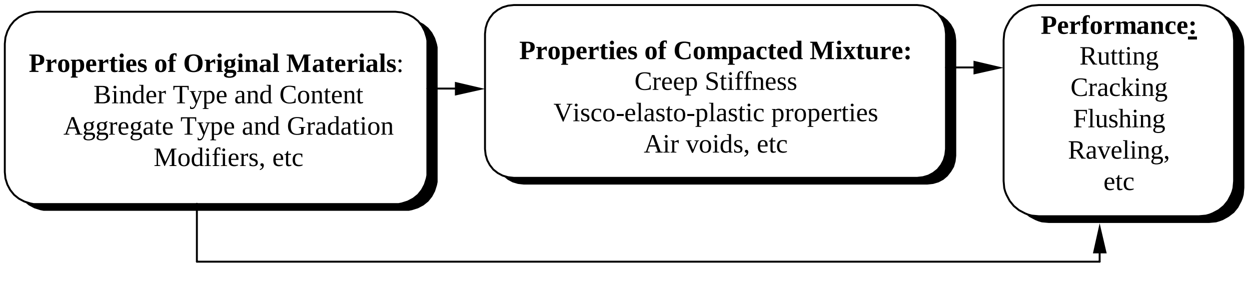
Large deviations from target values in gradation and asphalt content, while not direct measurements of performance, are believed to result in poor pavement performance. Too many or too few air voids in the constructed pavement, which is an indication of either a poor quality mixture or a poor quality compaction (or both), can cause premature failure of the pavement. In the move from method specifications to QC/QA specifications, the control of air voids, asphalt content, and gradation still remains part of the quality control process. Under the most recent QC/QA special specification—Item 3022 (Ref 11)—payments are determined based on air voids of laboratory compacted mixtures as well as on air voids in-place.

Once performance-based specifications (PBS) are put in place, it is expected that mechanical properties of the mixture, such as creep stiffness, will play a major role in determination of pay factors. Mechanical properties are used in performance prediction models to determine the pavement performance; therefore, it seems logical to use these properties as control parameters for determination of payment.

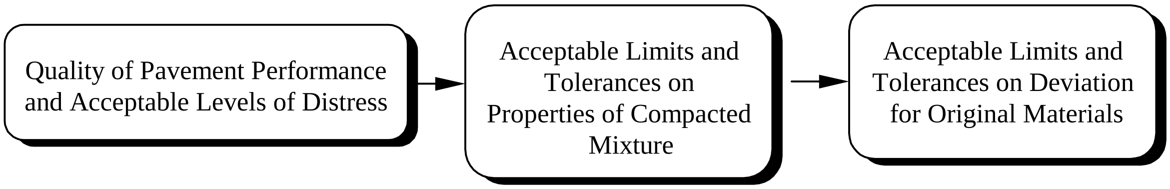
2.2 METHODOLOGY TO EVALUATE TOLERANCES

As mentioned before, in TxDOT current specifications (both standard and QC/QA) a series of parameters are considered important indicators regarding mixture quality and pavement performance. To ensure acceptable quality, deviation of these parameters from job-mix formula target values are limited within certain tolerances. Payments are affected by the magnitude of these deviations. It is important to assess how pavement performance is influenced by these deviations, and how tight a control is required in these deviations.

In its simplest possible form, *under certain environmental and traffic conditions,* the relationship among material and construction variables, mixture properties, and pavement performance is presented in the following flowchart.



An important effort in developing any kind of construction specification is establishing acceptable levels of tolerance for the parameters that are used for quality control or determination of payments. In developing an effective methodology to evaluate different specifications, it is important to keep in mind that the key item driving the magnitude of tolerances is the pavement performance, irrespective if this performance is measured in terms of individual distresses (e.g., rutting, various types of cracking, flushing, shoving, raveling, and roughness) or in terms of a general type of indicator (e.g., pavement condition index or pavement serviceability index). Thus, the first step is to determine the quality of performance through the service life of the pavement. The level of quality should be evaluated through either direct measurement of the pavement performance or through a reliable performance prediction model. Once the acceptable levels of distress are established, necessary limits on mixture parameters and properties (e.g., creep stiffness and air voids) are developed. The last step requires establishing the relationship between mixture properties and variabilities in original materials. The concept is presented in the following flowchart:



As a conceptual example of how this approach can be used, we assume that it is intended to establish limits on deviations in asphalt content and gradation so that rutting does not exceed a certain level, for example, 5 mm. The acceptable limit for rutting is used to determine the acceptable range in variability of creep properties of the mixture. Depending on the selected model for evaluating the effect of the properties of the compacted mixture on performance, limits may need to be established on several mixture properties—for example, creep stiffness and rate of creep. Once the required magnitudes and acceptable tolerances for mixture properties are established, the results are used to set the tolerances for the deviations in the original materials.

The framework explained in Chapter 4 presents how the predictions from the models along with statistical concepts can be used for this purpose. A sensitivity analysis of the prediction model discussed in Chapter 4 indicates how important influencing parameters can be identified and ranked.

Along with the determination of important parameters and their corresponding tolerances, a comprehensive measurement plan is required for analysis of the effects of specification changes on the quality of HMAC surface sources. A measurement plan must satisfy certain criteria to be considered acceptable. The plan must:

1) Be realistic and its implementation feasible
2) Produce meaningful and useful data that can be easily interpreted
3) Include an analysis system to summarize the data to draw conclusions
4) Be economical without sacrificing quality measurement

The flowchart in Figure 2.1 indicates an approach that could be followed for data measurement and collection.

2.3 CURRENT DESIGN APPROACHES

Currently, the mix design procedures for asphalt concrete in Texas take advantage of the Hveem stability for conventional mixes and static creep for coarse-matrix high binder mixes. The optimum asphalt content is determined based on the air voids of the compacted specimens and on the stability values from the stability test. Stability values are empirical in nature but have been used as major indicators of pavement performance.

The aggregate gradation used in the design should conform to the limits of the master grading for the specific type used. During the design phase, the voids in the mineral aggregate (VMA) and moisture susceptibility are also determined and are required to satisfy certain criteria. The current design procedures require that both the asphalt and aggregate used in the hot mix have specified properties.

While a number of models have been developed to predict the performance of asphalt concrete pavements, none of these models are used in practice by TxDOT for mix design purposes. There are probably numerous reasons for not using the models. One possible reason is that these models have not been thoroughly validated using actual field performance data; in some cases, their reliability is still questionable. In addition, some models require input data from tests that, at this point, may not be easily performed or implemented.

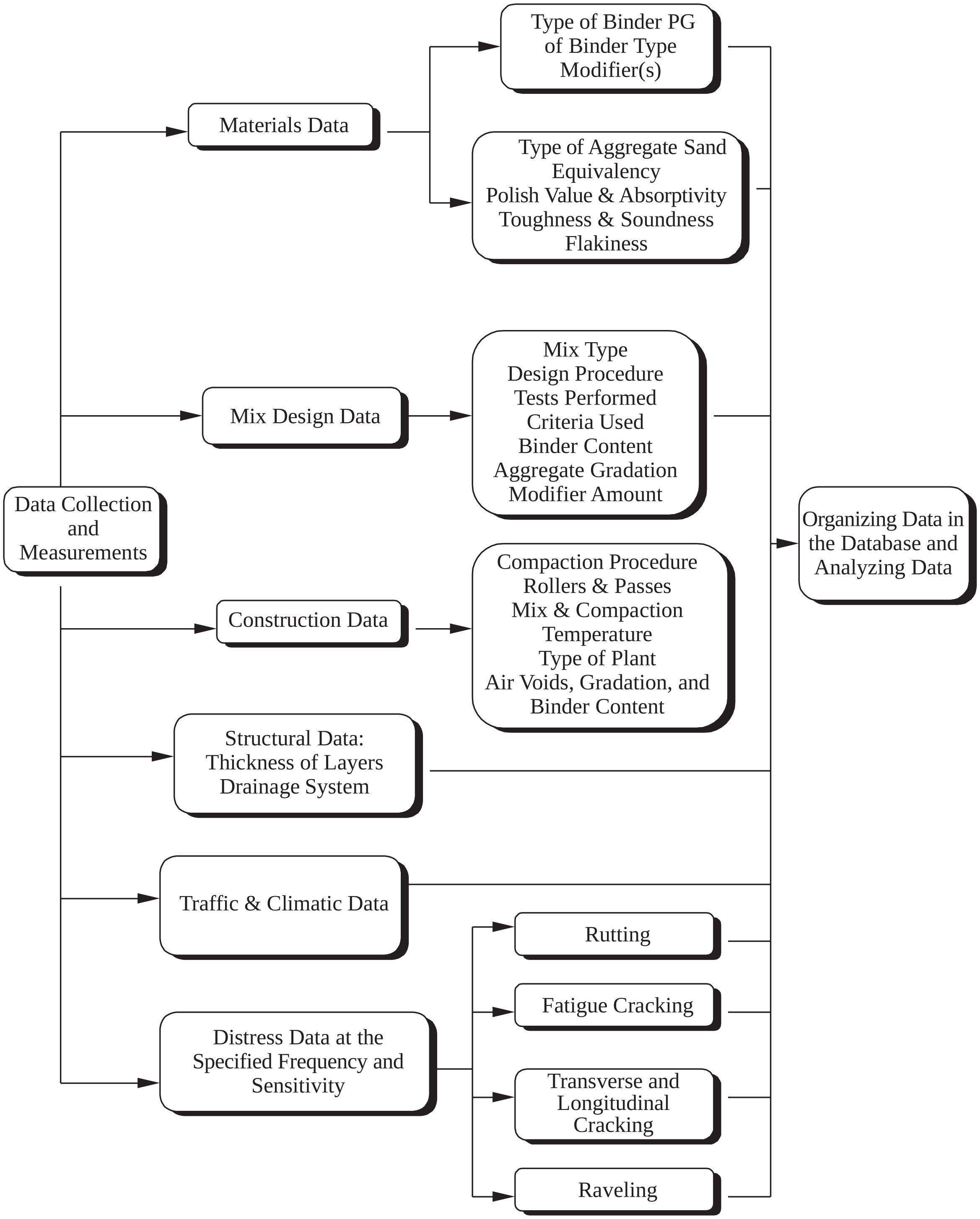


Figure 2.1 Flowchart indicating a measurement and analysis plan

2.4 CONCEPT OF PERFORMANCE-BASED SPECIFICATIONS

Performance-based specifications (PBSs) have been developed and explored to various degrees by different authorities. A key function of a PBS is to define the relationship among materials and construction (M&C) variables that characterize the performance of a pavement. The relationship is expected to be described in a specification such that the effect on the variations in the pavement performance can be described or quantified when the variations in M&C variables are controlled during design and construction phases. Meanwhile, the incentive or penalty for the pavement induced by the specification is another important feature of a PBS. The flowchart in Figure 2.2 shows the steps to be followed in order to obtain a performance-based specification for asphalt concrete pavements.

Irick summarized the principles that are generally applicable to the development of PBSs in any area of materials and construction—principles that serve as the foundation for the development of the conceptual framework of PBSs for PCC or AC pavements (Ref 12). The concepts behind the framework may be understood by describing two features: first, the design/construction/performance process variables; second, the steps to be taken in developing a PBS.

For the design/construction/performance process variables, Irick classified the major variables related to PBSs according to the five categories listed in Table 2.1. These include:

1) Primary dependent variables
2) Primary stress-distress prediction factors (primary independent variables)
3) Secondary stress-distress prediction factors (secondary independent variables)
4) Design criteria
5) Uncontrolled independent variables

Irick also presented four steps in developing a PBS (Ref 1).

1) Primary relationships: Derive prediction equations or models to describe the relationship between primary dependent and primary independent variables in Table 2.1.

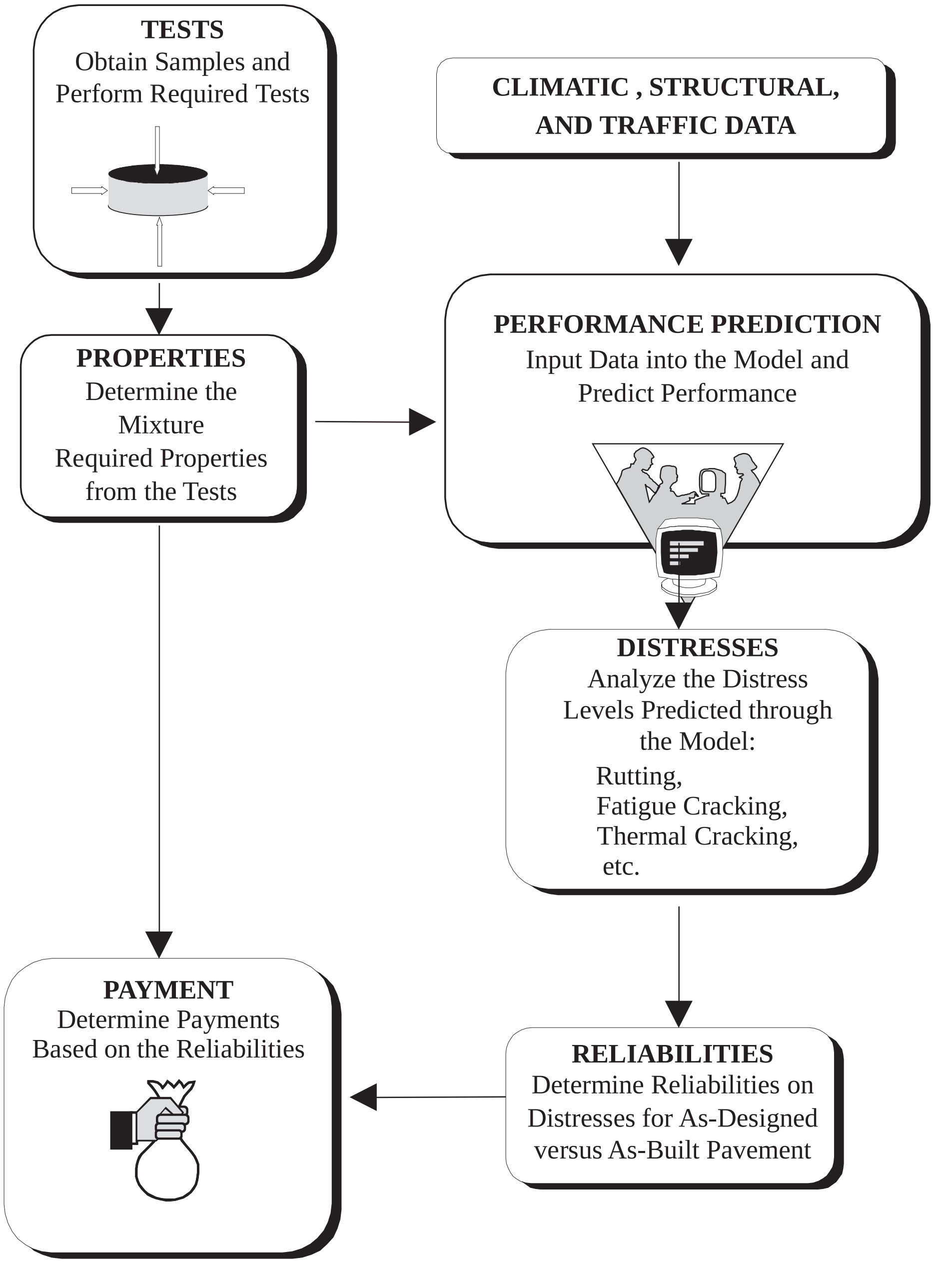


Figure 2.2 Steps to be followed in a performance-based specification

Table 2.1 Classification of pavement design, construction, and performance variables (Irick 1988)

Variable Classes and Subclasses
1. Primary dependent variables
1.1. Stress Indictors
1.2. Distress Indictors: a. Singular distress (cracking, rutting, etc.) b. Composite distress (roughness, PSI loss, etc.)
1.3. Performance Indicators: a. Fixed stress applications to terminal conditions b. Mixed stress applications to terminal conditions c. Performance period to terminal conditions
1.4. Cost Indicators: a. Cost component for M&C b. Life cycle costs for analysis period
2. Primary Stress – Distress Prediction Factors (Primary Independent Variables)
2.1. Traffic Factors: a. Load frequencies, distributions, growth rate, etc. b. Load equivalence factors and ESAL accumulations
2.2. Environmental Factors: a. Climate b. Roadbed and roadside
2.3. Structural Factors: a. Material and layer properties b. Construction and maintenance procedures
3. Secondary Stress – Distress Prediction Factors (Secondary Independent Variables)
3.1. M&C surrogate factors for primary prediction factors
3.2. M&C control factors
4. Design Criteria
4.1. Distress – performance criteria: a. Distress indicators and prediction functions b. Terminal distress levels and performance indicators
4.2. Reliability criteria: a. Reliability level b. Process standard deviation c. Reliability factor
4.3. Time and applications criteria: a. Design period b. Design applications c. Design period traffic
5. Uncontrolled Independent Variables
5.1. Uncontrolled deviations from specified levels a. Stress – distress prediction factor deviations b. Design criteria deviations 5.2. All remaining uncontrolled independent variables

2) M&C candidate variables: Identify primary and secondary independent variables that can be controlled prior to or during construction, including their variances, e.g., pavement thickness.
3) Secondary Relationships: Derive prediction equations for primary dependent variables and secondary independent variables in Table 2.1.
4) The M&C specification: Develop the algorithms and produce the M&C specifications (including design levels and tolerances, acceptance plans, and payment schedules) using as inputs the primary and secondary prediction equations, the significant M&C variables, and the project design criteria.

2.5 COMPONENTS OF A PERFORMANCE-BASED SPECIFICATION

Chamberlin (Ref 1) identified the following four key components constituting a PBS:

1) Statistical sampling: Design a scheme to extract the mean and variance of the primary and secondary stress-distress prediction factors in Table 2.1.
2) Performance modeling: Develop or adopt a model or equation to relate the information of the primary or secondary stress-distress prediction factors extracted in the sampling scheme to the primary dependent variables in Table 2.1. The modeling can be empirical, mechanistic, or empirical-mechanistic.
3) Adjustable payment plan: Devise a plan to adjust the contractor’s bid price according to the construction that deviates from the target quality level with net present worth conversion of the bid price.
4) Operating characteristic (OC) curves: Demonstrate the plots of pay factor (PF) vs. deviations from the target quality levels, or probability of acceptance vs. deviations from target quality levels, for the payment adjustment plan. The purpose of OC (or expected payment) curves is to show whether the payment plan will function as intended and whether it will be fair to both parties, i.e., highway agencies and contractors (Ref 14).

2.6 CURRENT PERFORMANCE-BASED SPECIFICATIONS

Current PBSs available for PCC or AC pavements are mostly conceptual and intended for demonstration of feasibility. The following two subsections will briefly describe two existing PBSs for PCC and AC pavements, respectively.

2.6.1 Performance-Based Specifications for PCC Pavement

Two well-recognized PBSs for PCC pavements were developed by the New Jersey Department of Transportation (NJDOT) (Ref 15) and by ERES Consultants, Inc. (Ref 16).

In the NJDOT, Weed et al. developed the first operational PBS for PCC pavements following several years of field trials. Five quality characteristics of a concrete lot are used for the NJDOT PBS: slump, air entrainment, thickness, 28-day compressive strength, and smoothness (riding quality) (Ref 17). The acceptance or rejection of a concrete lot is based on the slump and the air entrainment of the concrete measured when it is delivered to the job site. The other three quality characteristics—thickness, compressive strength, and smoothness—cannot be measured until the concrete is placed and cured for one month or more. In this case, the acceptance decision of the concrete lot takes the form of a payment adjustment in Equation (2.1).

$$PF = 105 - 0.12\, PD_{\text{Thickness}} - 0.10\, PD_{\text{Strength}} - 0.11\, (PD_{\text{Smoothness}})^2 \tag{2.1}$$

where

PF = pay factor for the contractor,
$PD_{\text{Thickness}}$ = thickness percent defective,
PD_{Strength} = strength percent defective, and
$PD_{\text{Smoothness}}$ = smoothness percent defective length.

The performance of the concrete lot is assumed to be directly linked to the uniformity of the construction process of Weed et al. Thus, the percent of defects of thickness, strength, and smoothness are considered as the surrogate performance indicators of the concrete, which are determined by standard tables developed by NJDOT.

The NJDOT PBS for PCC pavements is relatively simple, given that the worksheet for pay factor estimation provided for field use can be completed even by users having no intensive training in PBSs. However, the form and the coefficients of the pay factor estimation in Equation (2.1) are based on engineering judgment, experience, and historical data.

Darter et al. developed a prototype performance-related specification (PRS) for PCC pavements using the concept of life-cycle costs (LCCs) (Ref 15). One overall performance indicator LCC is used, which is the present worth of the total cost of construction and rehabilitation during the design life of the pavement. The distress indicators of each concrete sublot are calculated at the end of each year and the values are compared with those that triggered localized or overlay rehabilitation. If the percent of sublots that triggered rehabilitation is greater than a critical value (e.g., 15 percent), the lot is rejected. If the rejection measure is not activated, the rehabilitation costs for the as-designed and as-built lot LCCs are simulated by the PaveSpec program, depending on the rehabilitation policy adopted (Ref 16). The present worth of the lot LCCs is used for payment adjustment.

Four quality characteristics are used in the prototype PRS: 28-day concrete flexural strength, slab thickness, air content, and initial smoothness. The target values of the four characteristics are subjectively determined for the as-designed concrete lot by engineering judgment. The performance prediction models used in the prototype specification are listed in Table 2.2.

The performance models in Table 2.2 used in the prototype specification are a summary of forty new distress/performance models developed from condition evaluations of 418 sections (1,035 miles) of heavily trafficked PCC pavement in six states to quantify the relationships of design, traffic, climate, and other variables (Ref 1). NCHRP Report 227 (Ref 18) provides the details of the models shown in Table 2.2.

Table 2.2 Distress/performance models used in the FHWA/ERES prototype specification for PCC pavements (Ref 19)

DISTRESS/PERFORMANCE INDICATOR	MODEL SOURCE
1) Transverse joint faulting	FHWA-RD-89-138 (Ullidtz et al. 1983)
2) Transverse cracking	NCHRP/COPES (Darter et al. 1985)
3) Transverse joint spalling	FHWA-RD-89-138 (Ullidtz et al. 1983), as modified in the research
4) Pumping (feeds back into the cracking prediction model)	NCHRP/COPES (Darter et al. 1985)
5) Present serviceability rating (PSR) (as a function of initial smoothness, cracking, spalling, and faulting)	FHWA-RD-89-138 (Ullidtz et al. 1983)

The pay factor of the prototype PRS for a concrete lot is based on the quality achieved in the as-built pavement. The target LCCs for the as-designed pavement are simulated by *n* lots of concrete with agency-defined quality characteristic target means and standard deviations. The mean of the *n* simulated lot LCCs is used to represent the overall as-designed lot LCC ($\overline{LCC_{DES}}$) (Ref 16). The LCCs for the as-built pavement are simulated by *n* lots of concrete with field-sampled quality characteristic means and standard deviations. $\overline{LCC_{CON}}$ is calculated by the mean of the n LCCs using actual field data. The difference between $\overline{LCC_{DES}}$ and $\overline{LCC_{CON}}$ determines the incentive or penalty for the contractor, as expressed in Equation (2.2).

$$PF = [\text{ bid price} + (\overline{LCC_{DES}} - \overline{LCC_{CON}})\,] / \text{bid price} \tag{2.2}$$

where

PF = pay factor for the contractor,
Bid price = contractor's bid price for a concrete lot (\$/yd^2 times k yd^2),
$\overline{LCC_{DES}}$ = mean simulated LCC based on as-designed quality characteristic means and standard deviations, and
$\overline{LCC_{CON}}$ = mean simulated LCC based on field-sampled quality characteristic means and standard deviations for the as-built pavement.

If $\overline{LCC_{CON}}$ is less than $\overline{LCC_{DES}}$, the contractor will receive a bonus for the quality construction. If not, the contractor will get only a partial payment.

The advantage of the prototype PRS is that it uses a comprehensive performance indicator (the LCCs) to include the impact of multiple quality characteristics and the variability with each lot of concrete on the overall pavement performance. However, the LCC is highly dependent on the rehabilitation policy adopted.

Still, there are several PBSs for PCC pavements, including those proposed by ARE, Inc., (Ref 19) and by Gräter (Ref 20). Essentially, four key components of a PBS introduced in Section 2.3 can be identified in each of the proposed PBSs.

2.6.2 Performance-Based Specifications for AC Pavements

Several PBSs for AC pavements have been developed in tandem with those developed for PCC pavements. Two important works for AC PBSs will be discussed in this section: the PBS proposed by the Pennsylvania Transportation Institute (PTI) at the Pennsylvania State University (Ref 1), and the PBS developed by Shook et al. (Ref 22).

Anderson et al. proposed a conceptual framework for the development of PRSs for AC pavements. The framework outlines the generalized approach used to identify (1) primary and secondary stress-distress prediction factors in Table 2.1, (2) their relationships with predicted performance indicators, and (3) the life-cycle cost. The framework is depicted in Figure 2.3.

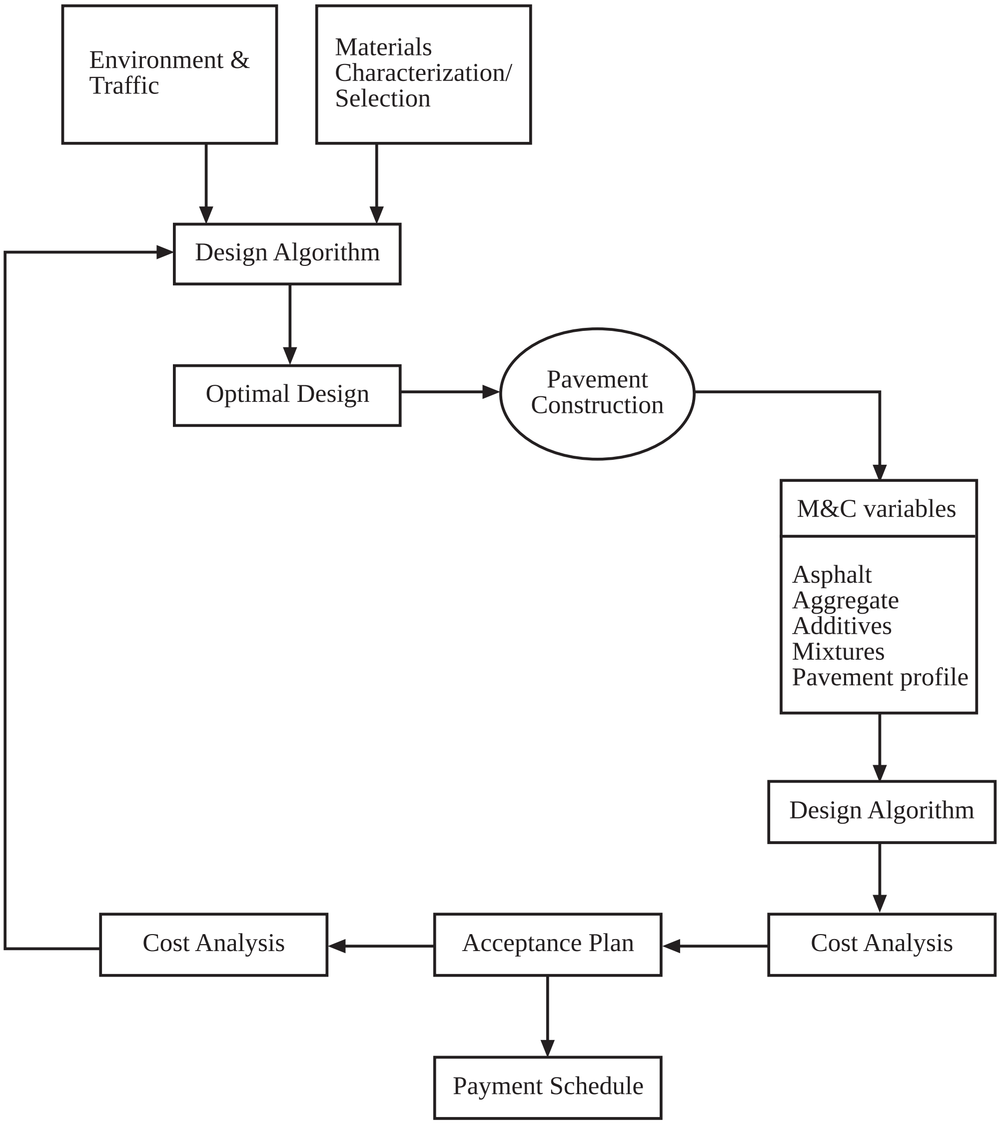


Figure 2.3 Generalized framework for a performance-related specification for hot mix asphalt concrete (Anderson et al. 1990)

The key elements of Anderson's framework for AC pavements are listed as follows:

1) Target design values, which include the pavement design (i.e., thickness, percent compaction, allowable roughness), as well as the target values for the mixture (i.e., percent asphalt cement, gradation, Marshall stability). These are target M&C variables.
2) A characterization of the M&C variables for the as-built pavement. These are the measured values of the as-built M&C variables.
3) The algorithms that are used to determine LCCs.
4) Predicted LCCs for the target and as-built pavement.
5) An acceptance plan and payment schedule.

The performance prediction models used in this framework are shown in Table 2.3.

Table 2.3 Primary relationships for calculating distress/performance differentials for AC pavement surfacing layers (Chamberlin 1995)

DISTRESS/PERFORMANCE INDICATOR	SOURCE FOR DISTRESS/ PERFORMANCE PREDICTION MODEL
Fatigue cracking	ARE (ARE Inc., 1975) Asphalt Institute (Shook et al. 1982) VESYS cracking model (Kenis 1977)
Low temperature cracking	Cold (Finn et al. 1986) Shahin-McCullough model for low-temperature cracking (Shahin 1977)
PSI/Roughness	PDMS (Luhr et al. 1982) AASHTO (AASHTO Guide, 1986) VESYS roughness model (Kenis 1977) Fernando (Fernando 1987)
Rutting	VESYS rut depth model (Kenis 1977) Shell (Claessen et al. 1977) AGIP (Battiato et al. 1982)
Skid resistance	Empirical models (Von Quintus et al. 1985)
Thermal fatigue cracking	Lytton-Shanmugham (Lytton et al. 1982) Shahin-McCullough Model for thermal cracking Fatigue cracking (Kenis 1977)

The payment adjustment of this framework is based on an LCC analysis including maintenance, rehabilitation, and user costs. The PF is calculated in Equation (2.3).

$$PF = 100\,(LBP - C) / LBP \tag{2.3}$$

where

LBP = lot bid price,
C = $(A_c - A_t)\{[(1+i)L_c-1] / [i(1+i)L_t]\}$,
A_c = annualized total cost at economic life of as-constructed pavement,
A_t = annualized total cost at economic life of target pavement,
L_c = economic life of as-constructed pavement, and
L_t = economic life of target pavement.

Shook et al. at ARE, Inc., developed a PRS for AC pavements that focused on identifying secondary relationships that could be used as the basis for prediction equations in a PRS (Ref 22). However, the project is limited to the surface layer of AC pavements only, and thus excludes roadbed soil properties, base/subbase properties, and shoulder construction (Ref 1).

The secondary relationships of M&C variables with the performance of AC, as summarized from the literature, are mostly regression-based equations relating dependent variables, such as resilient modulus (MR) of AC, to voids in mineral aggregate (VMA) and percent deviation from optimum asphalt content.

With service life being estimated as the number of equivalent single axle loads (ESALs) to failure by AASHTO Guide equations, the performance algorithm developed by Shook et al. includes such M&C variables as asphalt content, percent passing the #30 sieve, percent passing the #200 sieve, VMA, and percent air voids. The prediction of service life through the AASHTO equation is linked to these M&C variables through the layer coefficient of asphalt concrete, which, in turn, is a function of the M_R of the layer. This coefficient is estimated by the secondary equations for compaction index (CI) and the M_R (Ref 1). The independent variables in the secondary equations for CI and M_R are the aforementioned five secondary M&C variables.

Two methods of pay factor estimation were employed by Shook et al. (Ref 22).

$$PF = 105 - 0.5(PD) \tag{2.4}$$

where PD = percent defective in a test quality characteristic of a given lot

$$PF = 100 \left[1 + C_o \left(R^{L_d} - R^{L_e}\right) / C_p \left(1 - R^{L_o}\right) \right] \tag{2.5}$$

where

C_p = percent unit cost of pavement,
C_o = percent unit cost of overlay,
L_d = design life of pavement,
L_e = expected life of pavement,
L_o = expected life of overlay,
R = $(1 + R_{inf} / 100) / (1 + R_{int} / 100)$,
R_{inf} = annual inflation rate, and
R_{int} = annual interest rate.

Method 1 considers only one quality characteristic, whereas Equation (2.1) for NJDOT considers multiple characteristics.

2.7 SUMMARY

Two PCC and two AC PBSs were reviewed in this chapter. Four key components of a PBS were identified, namely, statistical sampling, performance modeling, adjustable payment plan, and its OC curves. Fernando et al. indicated that the major difference between a performance-oriented specification and an end-result specification is that the acceptance plan and payment adjustment schedule are tied to the predicted loss in pavement performance owing to contractor noncomformance. The payment adjustment plan is one of the key issues analyzed and addressed in this research study.

In general, three types of PF estimation are available for PCC and AC pavements:

1) PF, considering one quality characteristic only, e.g., Equation (2.4). The advantage of this approach is its simplicity, while the drawback is that it is not comprehensive.
2) PF, considering multiple quality characteristics, e.g., Equation (2.1). The advantage of this approach is that it is more comprehensive, and the drawback is that the form and the coefficients of the equation are subjectively assigned.
3) PF, based on LCCs, e.g., Equations (2.2) and (2.5). The advantage of this approach is that it uses a comprehensive performance indicator, LCC, to include the impact of multiple quality characteristics and the variability within each lot of concrete on the overall pavement performance. However, it has been noted (Refs 20, 21) that while the economic life approach is frequently used for replacement analyses in industrial applications, there may be a significant problem in applying it to pavements because of the short economic lives that appear to result at a time when serviceability is still quite high (Ref 1).

Under certain circumstances, highway agencies would like to identify what the PF would be if one or several quality characteristics or M&C variables were random in nature. In particular, instead of using an overall performance indicator like LCC, it would be desirable to simultaneously estimate the PF considering several performance indicators such as rutting, fatigue cracking, and roughness. These indicators differ in dimensions and are possibly correlated and variable.

CHAPTER 3. CURRENT PERFORMANCE PREDICTION MODELS

Flexible pavement modeling methodologies will be discussed in two sections in this chapter. Section 3.1 reviews traditional pavement modeling using empirical methods, while Section 3.2 presents current performance prediction models for asphalt concrete pavements.

3.1 TRADITIONAL METHODS FOR FLEXIBLE PAVEMENT MODELING

Conventional flexible pavement design can be classified according to five categories: empirical method with or without a soil strength test, limiting shear failure method, limiting deflection method, regression method based on pavement performance or road test data, and mechanistic-empirical method (Ref 23).

The major advantage of traditional methods is that they are able to reflect the materials characterization for the circumstances under which they are conducted. However, each of the five categories of traditional methods has its shortcomings. Empirical methods with or without a soil strength test are highly dependent on a certain set of climate and traffic conditions; if those conditions change, engineers need to repeat the experiment again in order to obtain the material properties of interest. The limiting shear failure method is used merely to determine the thickness of a pavement design without considering other aspects of a pavement (such as rutting or fatigue potentials). For limiting deflection methods, the vertical deflection of a pavement layer is limited to less than a critical limit, so that the permanent deformation of the surface layer can be controlled. Yet pavement failures are more stress-dependent than deflection-dependent. For regression-based methods, the nonlinear relationships between parameters and their variability are usually ignored, which may result in the loss of feasibility. Finally, the mechanistic-empirical method is based on such material properties as resilient modulus, densities, and voids in mineral aggregates, which are used to predict distresses based on laboratory tests and field performance data. However, the mechanistic-empirical method needs a set of instruments and a certain amount of time to obtain the response values for materials characterization. Nonetheless, the mechanistic-empirical method still has the advantages of the improvement in reliability of a design, the ability to predict the types of distress, and the feasibility to extrapolate from limited field and laboratory data (Ref 23).

With the advent of newer information technologies, various pavement design programs have been devised to better model pavement behavior. These models will be discussed in Section 3.2.

3.2 CURRENT PERFORMANCE PREDICTION MODELS FOR ASPHALT CONCRETE PAVEMENTS

To improve serviceability and the reliability of predicted distresses, a number of programs have been developed based on multilayer elastic theory, on the mechanics of materials, and on engineering judgment. Table 3.1 illustrates the input, assumptions, theories, output, and limitations of software models currently used by the industry.

BISAR, a flexible pavement program developed by researchers at Shell Petroleum Corporation (Ref 24), is based on multilayer elastic theory and can model both vertical and horizontal loads. DAMA, developed at the Asphalt Institute (Ref 25), assumes that subgrade and stabilized layers are linearly elastic and that untreated granular bases are nonlinearly elastic (i.e., they expand the modeling of granular bases from simplified homogeneous materials to nonhomogeneous constituents). Similar to BISAR, DAMA also adopts multilayer elastic theory as its modeling backbone. VESYS, a widely used flexible pavement software, was developed based on multilayer viscoelastic theory (VESYS II M) and elastic theory (VESYS III A, IV, and V) by Kenis et al. (Ref 5) at the Federal Highway Administration (FHWA). It was the first model to include prediction algorithms for various types of distress, including rutting, fatigue cracking, roughness, and present serviceability index (PSI). The distress indicators and PSI are calculated based on load responses, such as shear, vertical, and tensile stresses, and on strains obtained by the response model of VESYS under a specific set of traffic loads and environmental circumstances. One of the limitations of VESYS, however, is that it cannot model nonlinear materials properly. The basic assumption for multilayer viscoelastic or elastic theory, based on which VESYS was developed, is that a pavement section is made up of homogeneous and isotropic materials.

Therefore, load responses such as stresses and strains obtained by the theory are independent of the point of location of the material surface on which a load is applied. However, in reality, nonhomogeneous and nonisotropic materials will be encountered, especially in untreated subbases or unstabilized subgrades. Hence, load responses are expected to be location-dependent on the top or bottom surface of a layer. Fortunately, the finite element method provides a way to cope with such a problem.

The finite element method divides a material layer into a finite number of pieces (or elements). Depending on the computational capabilities and on how elaborate the division is expected to be, the number of elements can be determined by the user. The advantage of the finite element method is its capability of modeling the behavior of nonhomogeneous materials, so that approximated location-dependent load responses such as compressive, tensile stresses and strains will be more meaningful. Motivated by this idea, researchers developed ILLIPAVE (Ref 7) to incorporate the finite element method in flexible pavement modeling. This program assumes that a pavement section is an axisymmetric solid divided into a number of finite elements. Each element represents a section of concentric rings. The advantage of this approach over conventional multilayer elastic theory is that location-dependent pavement responses, such as modulus of elasticity, stresses, and strains, can be better modeled. However, the drawback of the finite element method is its high computational complexities in terms of time. Similarly, MICHPAVE (Ref 8) uses the finite element method to model nonlinear materials in a pavement section, its major change being the use of a flexible boundary beneath the surface of the subgrade instead of the rigid boundary adopted by ILLIPAVE. MICHPAVE is, however, computationally costly.

ELSYM5 (Ref 26) and PDMAP (Probabilistic Distress Models for Asphalt Pavements) (Ref 16) are two multilayer linear elastic models. ELSYM5 is a five-layer system that also offers the capability of multiple-wheel modeling. PDMAP uses Burmister’s layered theory to predict the surface layer deflection and the resilient modulus and compressive stresses on the surface of the granular base. Subsequently, the predicted pavement responses are input to an empirical regression equation (calibrated by road tests), so that the rate of rutting in microinches per axle load can be obtained along with the allowable number of repetitions for fatigue cracking. The advantage of regression-based empirical models is their simplicity. However, the drawback is that the regression coefficients are dependent on the materials used, the traffic loads, and on such environmental conditions as temperature and moisture levels at the test site. Undertaking a road test at a site different from where the empirical regression model was calibrated requires that the model be revised.

FLEXPASS (Flexible Pavement Analysis Structural System) (Ref 10), developed based on ILLIPAVE, is a model of the finite element method. Compared with ILLIPAVE, FLEXPASS added on several modifications, including multiple axle loads, slip elements between layers, seasonal materials characterization, and the capability to model different layer materials in different types of models (e.g., granular base and fine-grained subgrade). The basic assumption of FLEXPASS is that the profile of a pavement section is a mesh of finite elements. In addition, the program is able to predict rutting, identify fatigue cracking areas, and present the serviceability index (as VESYS does). Even though the computational time requirements for FLEXPASS are high, the program is by far the most versatile model among the finite element method programs.

Representing a recent advance in performance prediction modeling is the work conducted during the Strategic Highway Research Program (SHRP) from 1987 through 1993. It was this work that in fact led to the development of the Superpave^{TM} system. The models of the system were developed to predict fatigue cracking, thermal cracking, and rutting with time, using results obtained from the accelerated laboratory tests (used to identify visco-elasto-plastic properties of the materials). The models use traffic as well as detailed environmental data. While Superpave models underwent some validation during SHRP's five-year research program, modifications, improvements, and validations have been continued beyond 1993, with the goal of obtaining a thoroughly reliable model.

Table 3.1 Current performance prediction models for asphalt pavements

Model	Developer	Input	Assumptions & models	Type of Model	Output	Limitation
BISAR	Shell Petroleum De Jong et al. 1973	N/A	• Assumptions: - Horizontal and vertical loads in addition to vertical are cons • Models: multilayer elastic theory	Mechanistic	Stresses and strains at different layers	Up to 3 layers
DAMA	Asphalt Institute Hwang and Witczak 1979	• Mean monthly temperature • Variable monthly material modulus • Traffic loads	• Assumptions: - Subgrade and stabilized layers linearly elastic - Untreated granular base nonlinearly elastic • Models: - Multilayer elastic theory	Mechanistic	Min. thickness required to meet both fatigue cracking and rutting	Applicable to less or equal to 5 layers and 3 temp. regions (cold, normal, hot)
VESYS IIIA VESYS IV VESYS V	Fhwa Kenis et al. 1980 Rauhut et al. 1983 Brademeyer 1988	• Seasonal temperature • Thickness of N layers • Temperature-dependent material properties, e.g., Modulus of elasticity, rutting, and fatigue parameters, etc. for each layer • Time-dependent traffic • Tire pressure, contact area	• Assumptions: - All pavement responses can be stated in terms of the loading conditions, the geometry of the structure, the properties of materials and the effect of environment • Models: - Multilayer viscoelatic theory (VESYS II M) • Multilayer elastic theory (VESYS IIIA, IV and V)	Mechanistic	Rut depth fatigue cracking area, roughness, serviceability index	Cannot model nonlinear or non-homogeneous materials
ILLIPAVE	U. Of illinois Raad et al. 1980 Thompson et al. Developed regression based equations to predict the output 1985	• Materials characterization: thickness, modulus, etc. • Paving materials: asphalt concrete • Subgrade soils • Traffic and climate: • Traffic loads • Temperature	• Assumptions: • Considering the pavt. As an axisymmetric solid of revolutions divided into a number of finite elements, each as a section of concentric rings • Models: • Finite element model • Stress-dependent resilient modulus models for granular bases and fine-grained soils	Mechanistic	Tensile strain at the bottom of surface layer Compressive strain on the top of subgrade	Computationally expensive
ELSYM5	Kopperman et al. 1986	N/A	• Assumptions: • Multiple wheel loads • Models: • 5-layer linear elastic model under multiple wheel loads	Mechanistic	Stresses, strains & deflections at locations specified by the user	Up to 5 layers
PDMAP	UC-Berkeley Finn et al. 1986	Stress-dependent material properties	• Assumptions: • Probabilistic load responses • Models: • Burmister's layered theory and regression – based equations to predict stresses and strains	Mechanistic & Empirical	Rate of rutting per axle load Allowable no. Of load repetitions for fatigue cracking	Empirical model is traffic and environment dependent
MICHPAVE	Michigan State U. Harichandran et al. 1989	Similar to ILLIPAVE	Similar to ILLIPAVE with one major change in the use of a flexible boundary at a limited depth beneath the surface of the subgrade, instead of a rigid boundary at a larger depth	Mechanistic	Similar to ILLIPAVE	Similar to ILLIPAVE
FLEXPASS	Texas A&M U. Lytton et al. 1989	• Temperature-dependent materials characterization, e.g., Modulus of elasticity, rutting, and fatigue parameters, etc., for each layer • Thickness of N layers • Finite element mesh of a pavt. Profile • Time-dependent traffic • Vertical and horizontal tire contact stresses, tire pressure and contact area	• Similar to ILLIPAVE with several improvements: • Addition of slip elements between layers • Capable of modeling different layers in different models • Automatic generation of finite element mesh • Capable of modeling single, tandem and triple axles • Inclusion of prediction algorithms for rutting, fatigue cracking area and serviceability index	Mechanistic	Rut depth fatigue cracking area, Roughness, serviceability index	Computationally costly

CHAPTER 4. FRAMEWORK FOR PERFORMANCE-BASED SPECIFICATIONS

4.1 SELECTION OF PERFORMANCE PREDICTION MODELS

Performance prediction models provide a logical means for correlating the material and structural parameters of a pavement with its future behavior under certain climatic and traffic conditions. The underlying assumption is that pavement performance is a function of quantifiable distress indicators, owing to the progressive change that occurs in those parameters over time. Thus, to incorporate future performance into flexible pavement design and construction specifications, a reliable performance prediction model is needed. The selection of a performance prediction model hinges heavily on the need of the user and on the reliability of the model. If a highway agency is particularly interested in a specific type of distress condition, e.g., fatigue cracking, then a model that can reliably predict that particular distress condition of a pavement will be selected by the agency.

4.2 SENSITIVITY ANALYSIS OF THE SELECTED PERFORMANCE PREDICTION MODELS

The factors influencing pavement performance are used in prediction models in the form of input variables. The predicted performance is a function of the values used for these input parameters. Using a sensitivity analysis, it would be possible to identify the most important factors influencing performance. In other words, the purpose of a sensitivity analysis for a particular model would be to identify (1) the significant parameters that will contribute most to the variability of a system and (2) the ranges of those significant parameters that entail a mathematically meaningful model. Since the predicted performance of a pavement depends on the magnitude of model input variables, it is important to explore how sensitive each input parameter of the model will be and the range over which the parameter is allowed to vary.

In this report, sensitivity analysis is discussed in relation to the prediction models of the VESYS program. However, a similar approach can be taken with any other model. For VESYS, in which sixty-seven parameters are present, it is necessary to screen out the least significant parameters through sensitivity analysis, engineering judgment, and statistical techniques. If consideration is given to all input variables and not to the most important (influencing) ones, then even with only high and low levels for each parameter, the number of runs needed to observe the behavior of this model will be excessively high and impractical in terms of budget and time. Fortunately, one way to screen out insignificant parameters and identify the sensitivity of the remaining input parameters is by fractional factorial design, which requires one to rank the variance of the model explained by a specific parameter while holding others constant and assuming as negligible the interactions of three or more parameters.

4.3 SELECTION OF SIGNIFICANT PARAMETERS FOR PERFORMANCE PREDICTION MODELS

Two distinguished distresses—rutting and cracking—are used in sensitivity analysis because, in VESYS, rutting and cracking models are independent. Even though a number of parameters are shared by the two factorials, it will not be a concern with respect to a sensitivity analysis. The shared parameters are related to the pavement structure, traffic, and temperature. Fifteen input parameters are identified as significant for a rutting factorial, while eleven are identified for cracking. The sensitivity and ranges of the significant parameters for rutting and cracking are listed in Tables 4.1 and 4.2 and in Figures 4.1 and 4.2, respectively.

RUT_1 and RUT_2 are symbols indicating the rutting parameters for the model used in this research program. RUT_1 refers to *alpha,* which is related to the slope of the relationship between the logarithm of number of load repetitions and the logarithm of the accumulated permanent strain (S) through the formula: $alpha = 1 - S$. Slope S can be found from indirect tensile testing or from testing cylindrical specimens in axial mode. RUT_2 is used to indicate a parameter known as *gnu,* which is found from the relationship $gnu = IS/$. I is the magnitude of strain under the first load cycle, while ε_r represents the recoverable or resilient strain.

4.4 ASSUMPTIONS

A number of assumptions have been made for the purpose of developing the framework for a performance-based specification and for presenting the supporting concepts. The following assumptions are made for this study:

1) The pavement under consideration consists of four layers: surface, base, subbase, and subgrade. The subgrade is of infinite depth.
2) The first layer is asphalt concrete.
3) Pavement prediction models like VESYS or FLEXPASS can reliably forecast future flexible pavement behavior once reasonable input variables are used.
4) VESYS is temporarily selected as a tool for this research, given the fact that it is among the models most widely recognized and explored.
5) The input parameter values and the predicted pavement distresses are both normally distributed.
6) The eleven statistically significant input parameters of VESYS identified by Rauhut et al. will be used for further analysis. These parameters are ALPHA1, GNU1 (rutting model parameters for the first layer of a pavement), ALPHA3 (rutting model parameters for the third layer), LAMBDA (traffic level), LAYER1 (first layer stiffness), THICK1 (first layer thickness), LAYER2 (second layer stiffness), THICK2 (second layer thickness), LAYER3 (third layer stiffness), THICK3 (third layer thickness), and AMPLITUD (tire pressure).

Table 4.1 Sensitivity and ranges of fourteen significant parameters for rutting

Significant Parameters	Range			Ranking in Sensitivity
	Low	Mean	High	
RUT1_1	0.65	0.75	0.82	1
RUT1_2	0.20	0.40	0.60	2
STIFF1, kPa	2,758,000	3,102,750	3,447,500	3
THICK1, mm	76	152	228	4
TIRE Pres, kPa	400	518	655	5
TRAFFIC	2000	3250	4500	6
STIFF3, kPa	158,585	175,822	193,060	7
STIFF2, kPa	344,750	379,225	413,700	8
TEMPS (^oF)	10	24	38	9
ALPHA(3)	0.69	0.82	0.94	10
VARCOEF3	0.25	0.33	0.40	11
THICK2, mm	76	178	280	12
VARCOEF1	0.10	0.20	0.30	13
VARCOEF2	0.10	0.20	0.30	14

Ranking in Sensitivity: 1 is the most sensitive.

Table 4.2 Sensitivity and ranges of eleven significant parameters for cracking

Significant Parameters	Range			Ranking in Sensitivity
	Low	Mean	High	
(K1, K2)	(2.04 x 10^{-12}, 4.93)	(6.11 x 10^{-4}, 3.00)	(2.93 x 10^{-2}, 2.60)	1
TIRE, kPa	400	N/A	655	2
THICK1, mm	90	N/A	127	3
STIFF1, kPa	400,000	N/A	500,000	4
TEMPS	N/A	N/A	N/A	5
COEFK2	0.04	N/A	0.10	6
Traffic (ESAL)	2000	N/A	4500	7
STIFF3, kPa	50,000	N/A	90,000	8
STIFF2	16000	N/A	22,000	9
VCAMP	196	N/A	529	10
COEFK1	0.30	N/A	1.24	11

Ranking in Sensitivity: 1 is the most sensitive. K1 and K2 represent the fatigue constants found from a repetitive loading test.

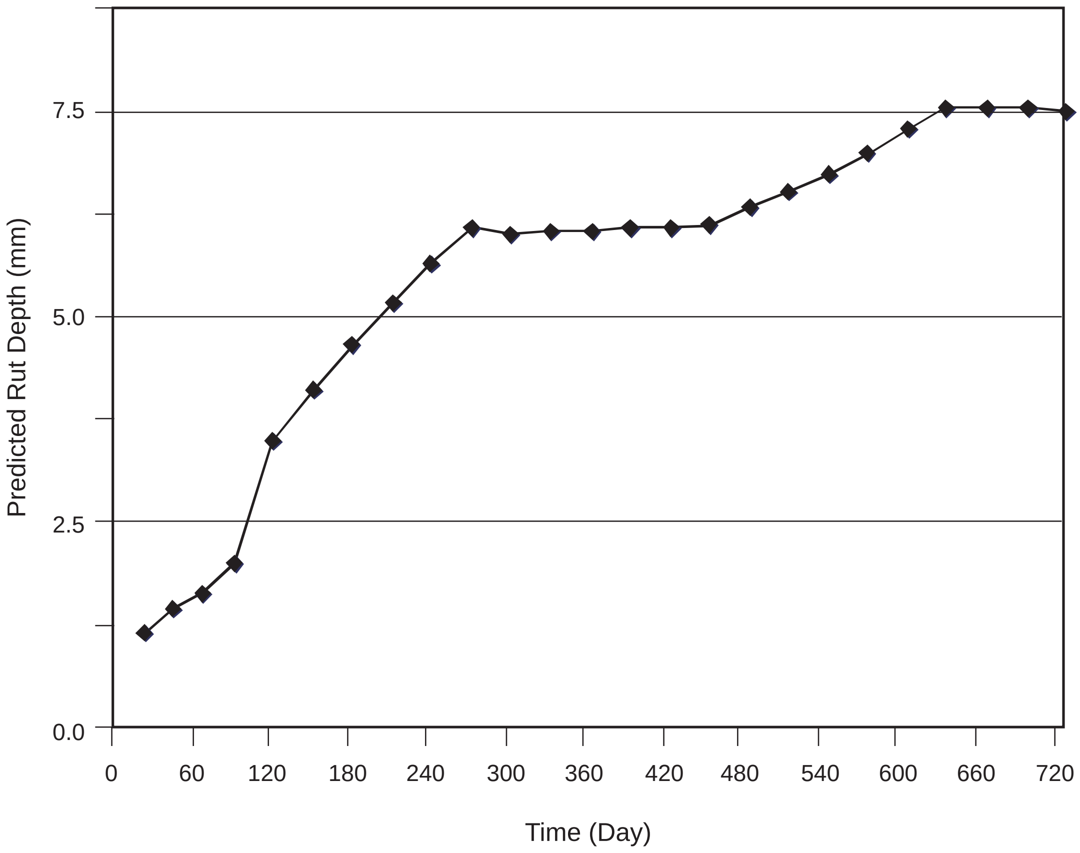


Figure 4.1 Plot of predicted rut depth as a function of time

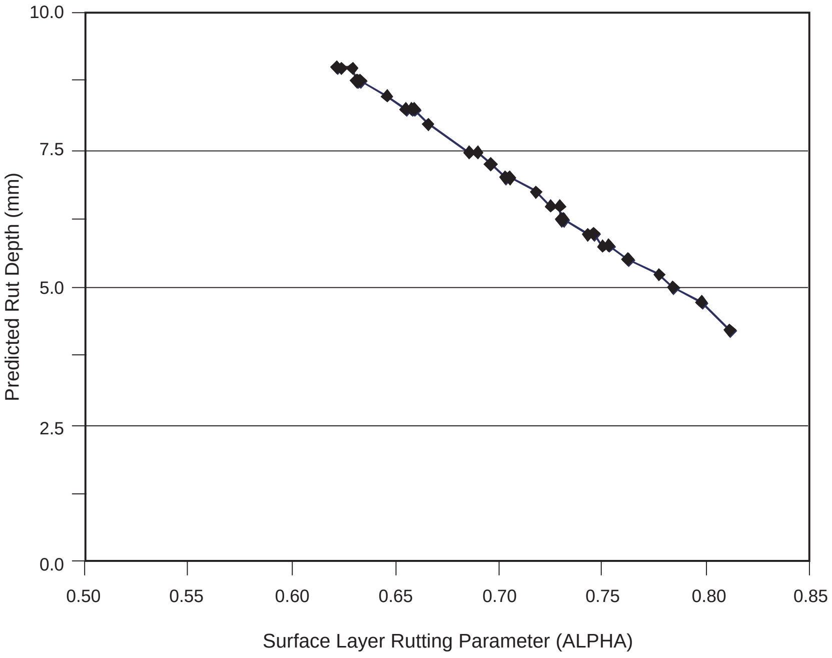


Figure 4.2 Plot of predicted rut depths over surface layer rutting parameter, ALPHA

4.5 PROCEDURE FOR DETERMINING PAYMENT ADJUSTMENT FACTORS

The following steps are taken to determine payment adjustment factors based on the predicted performance of the asphalt concrete pavement:

1) The most significant parameters are selected for the performance model (in this case, VESYS).
2) Realistic values are used for significant input parameters. Two highway categories are chosen: first, interstate highways with THICK1 (first layer stiffness) equal to 150–200 mm and tire pressure equal to 620 kPa; and, second, urban highways with THICK1 equal to 100–150 mm and tire pressure equal to 518 kPa.
3) For each of the preceding cases, the realistic values of significant influencing parameters are input into VESYS in order to predict the rut depths, which will serve as the expected and acceptable rut depth (i.e., the rut depth for which the pay factor is considered to be 1).
4) A variability analysis procedure (VAP) is proposed and used to determine the critical limit on rut depths in order to guarantee 95 percent reliability that the predicted rut depths will not be greater than the critical limit.

5) The critical limit on the predicted rut depth for the standard design is obtained from step (4). Once the means and standard deviations of the predicted rutting per as-designed and as-built AC lots are obtained, the pay factor for the contractor can be determined by the ratio of reliabilities for the lots.

The simplified approach to determine the pay factor is presented in Figure 4.3.

$$\text{Payment Adjustment Factor} = \frac{B}{A} \tag{4.1}$$

where

A = The reliability that the predicted rut depth of the standard design will be less than the critical limit, which is the area of parallel lines shown in Figure 4.4.

B = The reliability that predicted rut depth of a contractor’s construction will be less than the critical limit, which is the area of slanted lines shown in Figure 4.4.

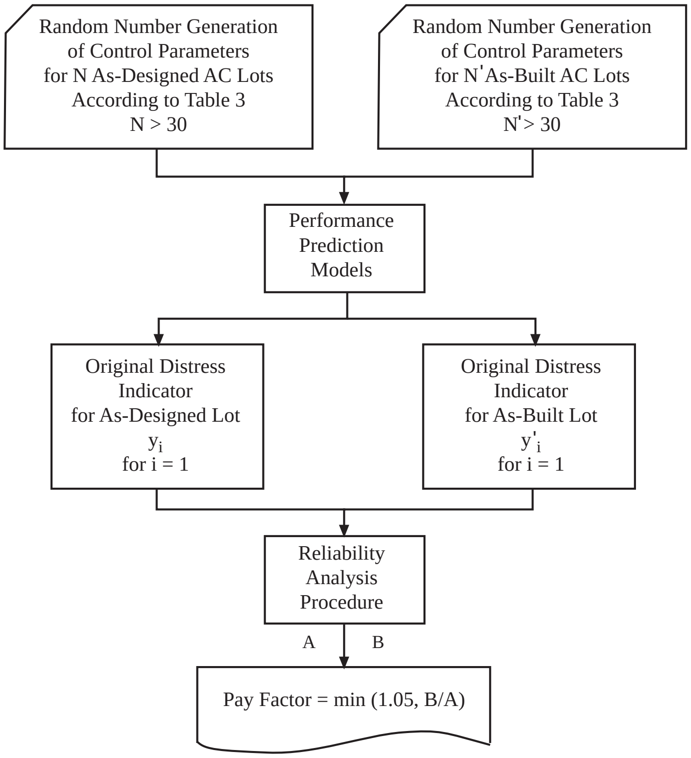
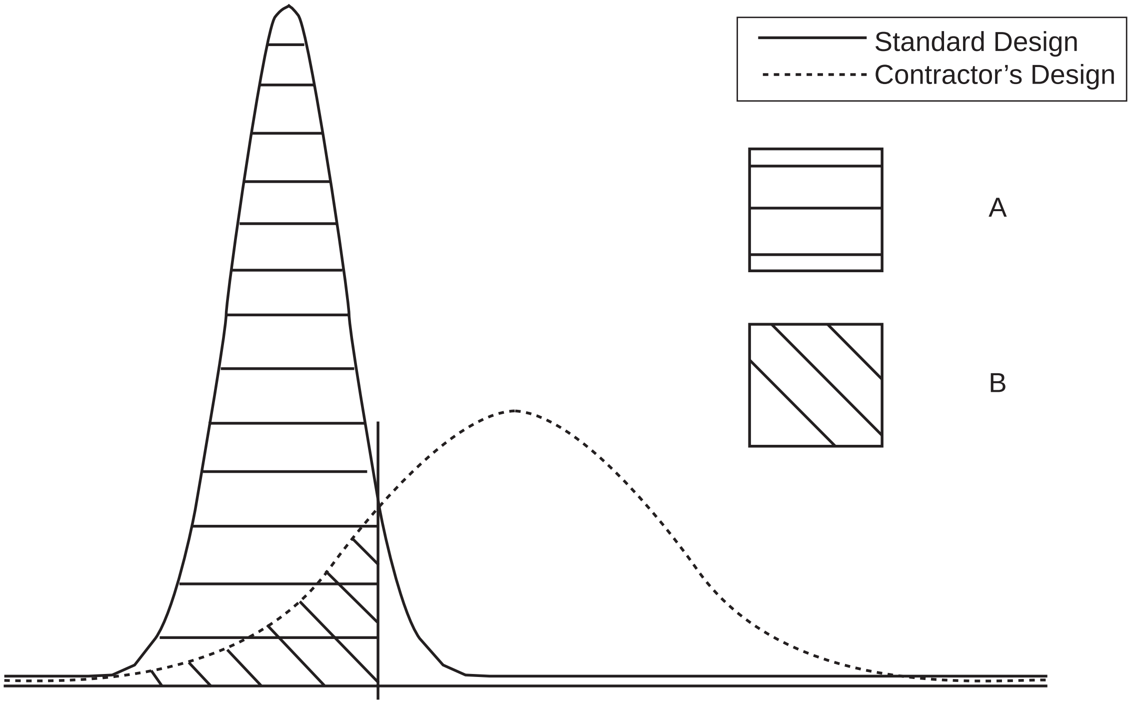


Figure 4.3 Simplified approach to determine pay factors considering one predicted distress indicator (A: as-designed reliability; B: as-built reliability)



$D_{95\%}$: 95th Percentile Critical Limit on Predicted Rut Depth

A = Reliability of Standard Design

B = Reliability of Contractor's Construction

Figure 4.4 Reliability of standard design and contractor's construction

4.6 RELIABILITY ANALYSIS PROCEDURE

The purpose of a reliability analysis procedure (RAP) is to identify the critical limit on the predicted rut in order to guarantee 95 percent reliability that the predicted rut depth will be less than the critical limit. The RAP is based on the assumption that the predicted distress (e.g., rut depth) is normally distributed. In this case, the standardized normal variable of rut depth can be used to identify the critical limit below which 95 percent of predicted rut depth will fall. The procedure is as follows:

(1) The input parameter (controlling factor), on which payment is to be based, is selected. An example will be the creep stiffness of the first-layer asphalt concrete.

(2) At least thirty values are randomly generated for the selected input parameter of step 1. The distribution of this parameter is assumed to be normal with the mean (μ_O) and standard deviation (σ_O).

(3) The values generated in step 2 are input into the pavement performance prediction model (e.g., VESYS) in order to produce corresponding predicted distresses (e.g., thirty rut depth values). These results would be used to calculate the mean (μ_D) and standard deviation (σ_D) of the predicted rut depths.

(3) The critical limit on rut depth ($D_{95\%}$) will be determined. This is the rut depth that exceeds 95 percent of all predicted values.

$$P\{Z \leq \frac{D - \mu_D}{\sigma_D}\} = 95\ \% \tag{4.2}$$

$$D_{95\ \%} = \mu_D + Z_{0.95}\ \sigma_D \tag{4.3}$$

where

$D_{95\%}$ = the 95th percentile critical limit on predicted rut depths,

μ_D = the mean of the predicted distresses, e.g., rut depths,

σ_D = the standard deviation of the predicted distresses, e.g., rut depths, and

$Z_{0.95}$ = the 95th percentile critical value of the standardized normal variable, which is equal to 1.645.

Figure 4.5 shows an example of the rut depth distribution for as-designed and as-built pavements using random number generation.

4.7 NUMERICAL EXAMPLE

A numerical example is provided to show the use of the proposed procedure for payment adjustment factors and RAP. A pavement design having the input parameter values listed in Table 4.3 is used as an example to show how the payment adjustment factors are calculated based on this methodology. The pay factor considered will be the surface asphalt concrete layer rutting parameter, ALPHA(1). The payment adjustment factors will be based on the reliability of the predicted rut depths.

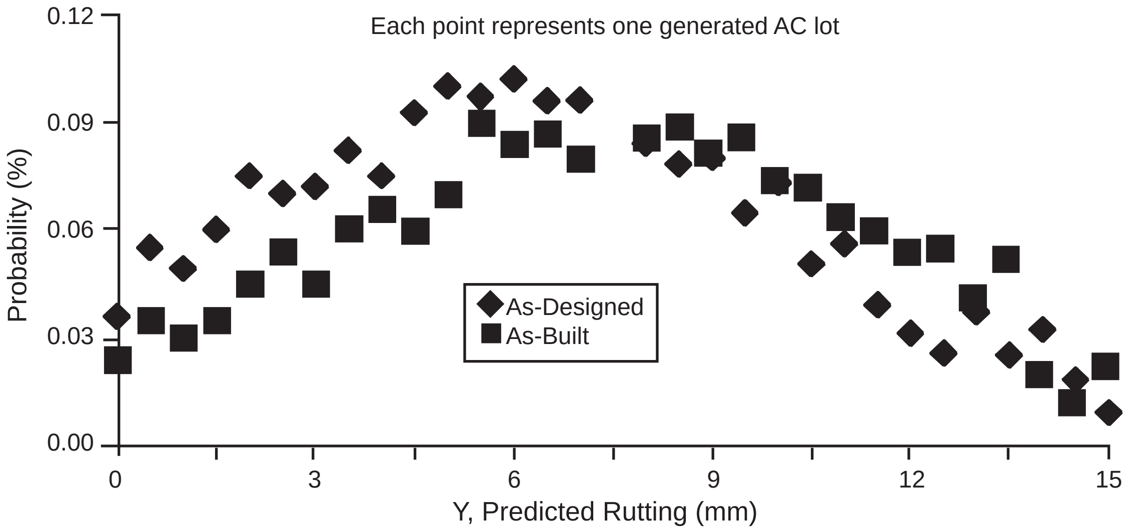


Figure 4.5 Distribution of the predicted rutting for the as-designed and as-built AC lot

Table 4.3 Pavement design scenario for VESYS

Selected Input Parameter	Rutting Parameter of the 1st Layer Asphalt Concrete in Summer, ALPHA(1)
w30 Expected Mean (μ_o) of ALPHA(1):	0.75
Expected Std (σ_o) of ALPHA(1):	0.07
1st Layer Thickness:	150 mm
Tire Pressure:	518 KPa

PSI: Pounds per square inch

The proposed procedure for payment adjustment factors and RAP for the case shown is described below.

Procedure for Payment Adjustment Factors

(1) The stiffness of the surface layer asphalt concrete rutting parameter in summer—ALPHA(1)—is selected as the input parameter of interest.

(2) The values for the influencing factors in design are provided and presented in a table (such as Table 4.3). These design values will be compared with the values obtained from construction.

(3) The mean (μ_O) and standard deviations (σ_O) of the first-layer asphalt concrete rutting parameter, ALPHA(1), are chosen as 0.75 and 0.07, respectively, for the standard design.

(4) The reliability analysis procedure is used to determine the 95th percentile critical limit on the predicted rut depths ($D_{95\%}$) in Table 4.3. This value can be considered the maximum rut depth acceptable to the highway agency. In this case, $D_{95\%}$ is determined by RAP to be 0.47 inches.

Subroutine Call to Reliability Analysis Procedure

[1] The input parameter selected in step 1 of the above procedure is used here, which is the first-layer rutting parameter in summer, ALPHA(1).

[2] At least thirty values are randomly generated for the selected parameter in step [1] by a normal distribution, with mean (μ_O) and standard deviation (σ_O) equal to 0.75 and 0.07 (Table 4.3).

[3] The thirty generated values from step [2] are input into the model so as to produce the corresponding predicted rut depths for the standard design. The mean and standard deviation of the predicted rut depths are obtained as μ_D (= 7 mm) and σ_D (= 2.8 mm).

[4] The critical limit on rut depth ($D_{95\%}$) guaranteeing 95 percent reliability will be obtained from Equation (4.5), using the mean and standard deviation of predicted rut depths of step [3]. For this case, there is a 95 percent reliability that the predicted rut depth will not exceed 0.5 inches.

$$D_{95\%} = 7 + 1.645\,(2.8) \approx 12 \text{ mm} \tag{4.5}$$

The reliability of standard design and contractor's construction can be obtained by Equations (4.6) and (4.7), respectively. Once this is determined, the payment adjustment factor for the asphalt concrete pavement is obtained through Equation (4.8).

$$\begin{aligned} A &= P\{Z \le \frac{D - \mu_D}{\sigma_D}\} \\ &= P\{Z \le \frac{0.47 - 0.29}{0.11}\} \\ &= 0.95 \end{aligned} \tag{4.6}$$

$$\begin{aligned} B &= P\{Z \le \frac{D - \mu_{D}^{C}}{\sigma_{D}^{C}}\} \\ &= P\{Z \le \frac{0.47 - 0.33}{0.13}\} \\ &= 0.86 \end{aligned} \tag{4.7}$$

Thus, by Equation (4.1):

$$\begin{aligned} \text{Payment Adjustment Factor} &= \frac{B}{A} \\ &= \frac{0.86}{0.95} \\ &= 0.91 \end{aligned} \tag{4.8}$$

Numerical Results

The numerical results of the exemplified scenario are shown in Table 4.4.

Table 4.4 Numerical results of standard design and contractor's construction

μ_E and σ_E of 1st Layer Rutting Parameter for Standard Design:	0.75 and 0.07
And σ_D of the Predicted Rut Depths for Standard Design:	7 and 2.8 mm
Critical Limit on Rut Depth ($D_{95\%}$):	12 mm
Reliability of Standard Design (A, by Equation 4.6):	0.95
μ_E^C and σ_E^C of Contractor's Measured 1st Layer Rutting Parameter:	0.70 and 0.08
μ_D^C and σ_D^C of Contractor's Predicted Rut Depths:	8.4 and 3.3 mm
Reliability of Contractor's Construction (B, by Equation 4.7):	0.86
Payment Adjustment Factor = $\frac{B}{A}$:	0.91

1st Layer Rutting Parameter: ALPHA(1) μ : mean , σ : standard deviation

From Table 4.4, the payment adjustment factor calculated is 0.91.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The Texas Department of Transportation has taken a positive step forward in the move from a method specification to QC/QA specifications. It will be another major step to move from current QC/QA specifications to performance-based specifications (PBS). Yet such specifications will gain wide acceptance and use only if they can take advantage of reliable performance prediction models, and only if proper material properties are used to judge the quality of the pavement as input into the prediction models.

This report discussed current PBS and performance prediction models, with the fundamental steps to be taken in such specifications identified. It was shown that obtaining the most important input parameters from reliable tests is essential. A sensitivity analysis was carried out to distinguish such parameters and to rank the significance of the influencing factors.

By introducing the reliability concept, we also demonstrated how statistical techniques can be utilized to enhance the validity and usefulness of a PBS. A methodology was developed and described for performance-based specifications; practical examples were then presented showing how such a methodology can be used for determination of payment to the contractor. The process indicated that a PBS, introduced through an appropriate model and reliability concept, can be a useful and practical tool. The following specific conclusions are drawn based on the material investigated in this research program.

1) The fact that one predicted distress indicator is considered at a time simplifies the development of the payment adjustment plan in an AC PRS.
2) Existing performance prediction models are utilized to model the relationship between predicted distress indicators and control parameters per AC lot.
3) The impact of the variations in materials and construction on pavement performance is included in the determination of the pay factor to the contractor using the reliability concept.

4) The pay factor to the contractor is determined as the ratio of the reliability of the pavement section corresponding to the as-built over that of the as-designed AC lot.

5.2 RECOMMENDATIONS

This study provides a theoretically logical way to tackle the issue of predicting pavement performance and determining pay factors. The procedure can be improved as better models become available. A fundamental issue in these specifications is the selection of tests that provide the required parameters for input into the model and, hence, the prediction of performance. Without the *right* factors and the *right values* for these factors, the predictions cannot be reliable even if the best models are used. If proper variables are not recognized, there will be no basis for either bonus or penalty, since no reliable prediction of performance exists.

The PBS and the payment adjustment plan were presented considering one distress indicator at a time. It is quite possible to utilize a general approach for determination of payments considering multiple distress indicators. For this purpose, principal component analysis, a multivariate statistical technique, can be used. A principal component (PC) is an integrated multicharacteristic condition indicator for AC pavements, one that includes information on rutting, fatigue cracking, and roughness. Hence, the pay factor determined based on a PC (an overall performance indicator of a pavement) will represent a global view of the overall pavement performance. A knowledge of principal component analysis is required only as a basis for the development of the method—it is not required for implementation. This study provides a theoretically logical way to tackle the issue of determining pay factors based on multiple correlated performance indicators. The findings of this study can ultimately yield a practical tool for determining these pay factors. Such a tool would allow not only a proper consideration of the interaction between different variables, but also the utilization of appropriate models.

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