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16. Abstract

The primary objective was to develop and test a "Measurement Strategy" for evaluating the relative degree of success of new hot mix asphalt (HMA) pavement construction specifications using information from the Texas Department of Transportation (TxDOT) Pavement Management Information System (PMIS) database. The specific reason for developing a Measurement Strategy was for use in comparing relative performance as a function of time of HMA pavements constructed under Item 340 with pavements constructed using the newer quality control/quality assurance (QC/QA) specifications.

Researchers developed a paired analysis method and 30 pairs of pavements were identified to test the method. A paired set of pavements is defined herein as an Item 340 pavement and a QC/QA pavement that have similar locations, substrates, thicknesses, mixture type, and traffic but probably were constructed at different times by different contractors. Pavement performance information on these paired pavements from the TxDOT PMIS database was used in a statistical analysis in an attempt to determine which type of specification provided the best performing pavement. A second measurement strategy was developed and provided to TxDOT which uses a general analysis method; that is, it considers all the appropriate pavements in the PMIS database, even if the number of pavements prepared using the different specifications are unequal. The general approach is described in Research Report 1877-6.

Even if pavements constructed using the different specifications performed differently, the PMIS data were found to be unsuitable for detecting these differences. Therefore, one of the chief benefits of this work was to determine and recommend the type of data that is necessary for TxDOT to fully implement the measurement strategy in the future.

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Sponsored by the Texas Department of Transportation
In Cooperation with the
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DISCLAIMER

The contents of this report reflect the views of the author, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation. Not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Joe W. Button, P.E. #40874.

ACKNOWLEDGMENTS

Steven G. Smith, director of construction for the Odessa District, served as Project Director. His insight and guidance were extremely valuable to the researchers during this study. His complete understanding of the objectives of this project and the problems anticipated and encountered during the pursuit of these objectives were key in assuring the study provided meaningful information to TxDOT.

The late Jose E. Morales, the first Project Coordinator, was instrumental in initiating this project. His guidance and assistance are gratefully acknowledged.

Special thanks are extended to Lauren D. Garduno, who served as Project Coordinator through most of the project, and Ken Boehme for their direction and assistance during the conduct of this work.

All TxDOT districts responded to the requests made by the researchers. Several districts identified paired pavements for the analysis and provided valuable information.

TxDOT and FHWA provided the funding for this research project.

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IMPLEMENTATION RECOMMENDATIONS

Development of reliable specifications for HMA pavements is a continuous evolutionary process. This research provides TxDOT with a straightforward mechanism for generating accurate information needed to make intelligent decisions regarding future development of or improvements in construction specifications for HMA pavements.

Results of the research described herein will be of particular value to state highway departments because the results should provide an assessment of the relative cost-effectiveness of HMA pavements produced using Item 340 versus QC/QA specifications. Results may demonstrate that one specification gives improved long-term performance over the another. The ultimate benefits of this project should be viewed as a long-term process.

Since HMA pavement construction is one of the most commonly performed operations for TxDOT, it is clear that the findings of this study may have widespread application. It is believed that the findings of this study will have relatively little impact on initial pavement construction costs. However, the findings should lead to improved specifications which should eventually have a positive impact on long-term pavement performance and thus life-cycle costs.

In order to implement the measurement strategies developed during this research, TxDOT must begin to collect and record the data necessary to compare pavement quality as a function of time for pavements produced using different specifications. Ideally, these data would be consistently recorded in a database. Based on the findings from this study, the researchers recommend that the following data be recorded in PMIS (or another automated database that interacts with PMIS) to accommodate pavement performance analyses:

- date(s) of pavement construction - required for comparative evaluations of performance as a function of time for pavements not constructed at the same time,

- periodic traffic loadings - required for comparative evaluations of performance as a function of traffic loads,layer data - can be used to compare pavement layer thicknesses and/or quality vs. performance, it is also needed to assess influence of substrate on performance observed at the surface,
- type of specification or special provisions used during construction - specification type cannot be evaluated unless it is known,
- level of severity of any distress measured or observed - this is needed to maximize the sensitivity of any pavement performance analysis,
- pavement design life - this will permit relative evaluation of pavement quality as a function of percent of design life (if design life of pavements is different, meaningful comparisons of performance must be related to design life),
- degree of raveling and flushing - these are important performance parameters which, alone, may be the cause for maintenance or rehabilitation,
- maintenance activities - without this unexplained improvements in pavement condition will appear in the database and confound any analysis attempts,
- data on failed pavements that have been covered by subsequent maintenance or rehabilitation - considering only uncovered pavements would eliminate many poor performing pavements that were covered early in their service life and thus skew any analysis toward the poorer performing specification as being the most favorable,
- HMA mixture parameters from quality control tests (e.g., density, asphalt content, gradation, voids in mineral aggregate, voids filled with asphalt) and target (or mixture design) values - this will assist in forensic analyses when trying to determine the source of a particular distress or performance issue,
- name of contractor - construction quality is often associated with the expertise, equipment, and philosophy of the contractor.

INTRODUCTION

BACKGROUND

One of the duties of transportation agencies is to provide the general public with the best highway facilities possible with the available resources. Traditionally, agencies have engaged in extensive testing and inspection efforts to ensure construction quality, thereby, ensuring the satisfactory performance of the completed facility. Although they serve the public well, such efforts consume an appreciable amount of resources. Throughout the country, limitations on staffing levels, combined with expanding construction programs, have forced highway agencies to reexamine current levels of testing and inspection and the manner in which these quality assurance efforts are accomplished.

In the past 20 years or so, forward thinking state highway agencies that are experiencing downsizing of their work forces have been moving toward end-result or even performance-based pavement construction specifications. The implementation of quality control/quality assurance (QC/QA) specifications for hot mix asphalt (HMA) pavements by Texas Department of Transportation (TxDOT) was a move in that direction. QC/QA specifications typically impart to the contractor greater responsibility for control of pavement quality during design, production, and placement of paving materials. This effectively reduces the engineering and technical labor requirements for the highway owner-agency. Further, this type of specification ideally fosters cooperation and teamwork (partnering) between the contractor and the highway agency and should be equitable for both. More importantly, however, it is a generally held belief that QC/QA specifications should provide more uniform and thus better paving materials than Item 340 specifications.

For QC/QA specifications, the desired quality of work is defined by the highway agency, who is also responsible for assuring compliance with the standards established. The contractor or producer is given increased latitude in the methods by which the desired quality or standards are controlled or achieved. However, certain restrictions are set to ensure a minimum level of quality and to prevent the production or construction of a large quantity of material before defects are discovered. Under the TxDOT QC/QA specification, contractors are normally responsible for HMA mixture design as well as sample collection and testing for quality control during production and placement.

TxDOT began implementing new QC/QA specifications in numerous pilot projects across the state in about FY1993. Full implementation on all state projects began in about FY1994. This was a major change for TxDOT and the contractors. The change was from the Item 340 specification to the Item 3063 or Item 3022 (QC/QA) specification. Shortly after implementation, TxDOT revised the QC/QA specification to make improvements. The QC/QA specification was again revised in about 1996-97 to increase TxDOT's control of the assessment of bonuses and penalties for pay purposes. The wording was also modified to give TxDOT more authority regarding identification of segregation. Additional changes may be forthcoming as a result of the findings and recommendations emanating from Project 1721, "Effectiveness Comparison of Former HMA Specifications and the Most Current QC/QA Specifications for HMA." It is anticipated that this periodic revision process will continue for the foreseeable future.

The questions arise, "Have we improved our HMA pavements by changing from Item 340 to QC/QA specifications and, if so, by how much?," or "If QC/QA is better than Item 340 but costs more, is it worth the difference?," or "If QC/QA yields more uniform mixes than Item 340, how does that affect pavement performance?" Innovative techniques and methods to evaluate the relative success of HMA pavement specifications need to be developed and applied to answer these and other questions. The last few generations of HMA pavement specifications need to be investigated to assure continued quality in management of construction testing and inspection. The results of these investigations will have a direct bearing on evaluation and development of improved specifications for HMA pavements and other highway construction products.

OBJECTIVES

Development of rational specifications for HMA pavements has been and is expected to be a continuous evolutionary process for most highway agencies. TxDOT recognized the need to develop a formal evaluation process for use in continuous improvement of their HMA pavement specifications. This evaluation process must quantify the changes in the level of pavement quality, if any, that the changes in specifications have had as they relate to the service life of HMA pavement surface courses. The measurement strategy should be capable of appraising subsequent generations of HMA pavement specifications for perpetual use by TxDOT.

The goals of this study were to develop and test a “Measurement Strategy” to evaluate the degree of success of new HMA pavement construction specifications using information available in the PMIS database. The concept was to compare pavement quality (e.g., ride quality, rut depth, cracking severity, patching frequency) versus time for pavements constructed using two different specifications. Specifically, two measurement strategies were developed to compare the relative performance as a function of time of similar HMA pavement surface courses constructed using Item 340 (sometimes called methods & materials, recipe, or prescription specifications) with pavements constructed using the newer QC/QA specifications. It was necessary to compare performance as function of time because the pavements being studied were not (and will never) be constructed at the same time.

The measurement strategies consist of statistical processes for comparing the performance of Item 340 and QC/QA pavements in an automated format. For the attempted comparisons, researchers obtained pavement performance data from the Department’s PMIS database. The Measurement Strategy may subsequently be used by TxDOT to compare existing and future specifications.

SCOPE

Specific activities to achieve these goals include:

- Conduct a succinct, focused review of published information to determine if other agencies have developed pertinent measurement strategies.
- Conceptualize and evaluate alternative measurement strategies.
- Evaluate and verify the utility of the measurement strategy on a small scale data set.
- Revise and finalize the measurement strategy to maximize utility.

- Recommend modifications to the PMIS data collection process that will be necessary to accommodate the new measurement strategy.
- Estimate the number of projects required for a statistically valid analysis to determine differences between Item 340 and QC/QA pavements and the associated costs.
- Compile lessons learned that can be applied to specifications for other highway construction applications.

Reachers developed the paired analysis method and identified 30 pairs of pavements for testing the method. A paired set of pavements is defined herein as an Item 340 pavement and a QC/QA pavement that have similar locations, substrates, thicknesses, mixture type, and traffic but were probably constructed at different times. Pavement performance information on these paired pavements from the TxDOT Pavement Management Information System (PMIS) database was used in this statistical analysis strategy in an attempt to determine which type of specification provided the best performing pavement.

In the event that pavement construction specifications are developed in the future after the PMIS data collection process and database are upgraded, it may be desirable to compare performance of all suitable pavements in the database. Therefore, a second measurement strategy was developed and automated using a general analysis method which is designed to compare performance of all appropriate pavements in a database without paring even if the number of pavements constructed using each specification is different. Appropriate pavements are those constructed using one of the specifications of interest. Since the PMIS data was proven to be unsatisfactory, no attempt was made to test this method. The general approach is described in Report 1877-6.

BRIEF DISCUSSION OF DIFFERENT TYPES OF SPECIFICATIONS

RATIONALE FOR QC/QA TYPE SPECIFICATIONS

Insuring the highest possible level of performance for highway facilities is a major goal of transportation agencies. In order to attain this goal, agencies traditionally rely upon testing and inspection practices to control construction quality and influence performance. Performance is only indirectly affected by the systems used to assure quality of the constructed facility. This indirect relationship is based upon the belief that conformance to the specifications will result in good performance of highway facilities.

Quality control, quality assurance, and acceptance sampling procedures are the primary methods by which transportation agencies attempt to insure that contracting agencies obtain a satisfactory level of quality and compliance to specifications (NCHRP, 1979). The limited availability of inspectors, both in quantity and level of training, to perform adequate testing is a serious constraint within which transportation agencies must continue to function. As the number of trained inspectors decreases and the amount of construction work increases, highway agencies are looking for ways to decrease their inspection and testing effort.

There are three immediately identifiable strategies researchers should investigate to help develop an implementable guideline which optimizes inspection and testing. They are:

- specification revisions which shift more testing and inspection responsibility and risk to contracting agencies,
- statistical process and control analyses to limit the type and quantity of inspecting and testing to that necessary to achieve the desired quality, and
- automation of testing and inspection procedures to increase testing and inspection frequencies for less manpower requirements.

Inspection and testing are integral parts of quality control, quality assurance, and quality acceptance sampling required to provide the best highway facilities possible within the given constraints. Inspection and testing are completed to (Pyzdek, 1988):

- determine acceptability of the product being tested;
- determine product reliability;
- qualify a process, material, etc.; and
- verify that some requirement has been met.

TYPES OF SPECIFICATIONS

Generally, two major categories of HMA pavement materials and construction specifications are currently employed by state DOTs:

1. Methods and materials (M&M) specifications, also known as prescription or recipe type specifications and
2. End-result specifications subdivided into three categories:
   a. End result (or QC/QA),
   b. End result performance based without warranty, and
   c. End result performance based with warranty.

Traditionally, state DOTs have relied almost exclusively on M&M-type specifications (e.g., Item 340). Although this concept recognizes material and construction variability, there is no quantitative method for evaluating what constitutes reasonable conformity or substantial compliance based on expected performance. What is reasonable is left to the interpretation and judgment of the inspector, a situation that lends itself to non-uniformity in product acceptance. Statistical concepts are seldom employed in methods-type specifications.

In the past couple of decades, a number of state DOTs have adopted QC/QA or end-result specifications in which the contractor is given more freedom to choose construction methods and equipment and is responsible for construction quality control (Anderson et al., 1990). As the name implies, the concept places emphasis on the end-product rather than the methods or procedures used to produce the final product. Conceptually, under these specifications, the DOT defines what it wants and will inspect and test only the final product for purposes of acceptance. However, this broad concept allows for varying types of specifications which has led to some confusion in the use of the terminology. At the far end of the spectrum, an "end-result" specification could define the required performance the final pavement must provide over some defined time period (warranty). This latter type is referred to by many as a performance-based specification and is considered by some as being different from an end-result specification. For simplicity, however, performance-based specifications are also classified as end-result specifications. End-result specifications are characterized by the following elements:

1. Use of statistical concepts for the purpose of:
   a. Ensuring unbiased accurate information.
   b. Effective and timely process control.
   c. Objective evaluation of quality characteristics in terms of both central tendency and dispersion.
   d. Making acceptance decisions on a rational basis.
2. Clear delineation of responsibilities with respect to:
   a. Process control by the contractor.
   b. Acceptance sampling, testing, and inspection by the highway agency.
3. A realistic, equitable, and legally defensible price adjustment schedule for materials and construction that are not in full compliance.

Whereas end-result specifications are generally judged to be superior to traditional M&M specifications, they are not performance based. For example, a contractor could receive only 90 percent of a contract price base on conformance to specification; however, this in no way relates to a 10 percent decrease in the expected level of performance of the final pavement. Therefore, there is no guarantee that QC/QA specifications will increase quality or performance over M&M specifications.

As yet, no end-result performance-based specifications have been implemented on any significant scale in the United States, although they have been used even with warranties in Europe (AASHTO, 1991).

Table 1 summarizes some of the potential effects of specification type on selected factors related to inspection, testing, man-power requirements, and risk.

Table 1. Potential Effects of Type of Specification on Selected Factors.

Type of Specification	Inspection Staff Requirements	Risk if Performance Unsuitable	Quality Control Testing	Acceptance Testing	Techniques for Assuring Quality	Suitability for Automated Testing by Owner	Types of Testing by the Owner Agency
Methods and Materials (M&M)	Highest for owner	Highest for owner	Mostly by owner	Mostly by owner	Tests on pavement materials (finished product)	Less suitable	Empirical & fundamental tests on individual materials & finished products
End Result (QC/QA)	More even split between owner & contractor	Shared between owner & contractor	Shared between owner & contractor	Mostly by owner	Tests of materials, ride quality, & safety (finished product)	More suitable	Empirical & fundamental tests on finished products
End Result-Performance Based (w/o Warranty)	More shift toward contractor	More shift toward contractor	More shift toward contractor	Mostly by owner	Tests of materials, ride quality, & safety (finished product)	More suitable	Performance-based surrogate tests on the final constructed product
End Result-Performance Based (with Warranty)	Highest for contractor	Highest for contractor during warranty period	Mostly by contractor	Mostly by owner	Assessment of ride quality and safety (long term)	Very suitable	Measurement of actual performance of the finished product

RELATED FINDINGS IN PREVIOUS STUDIES

In a study of quality control programs in Minnesota and Texas, Brown (1995) claims that contractors across the United States are emerging as the driving force behind a quality control movement in asphalt pavement construction. The shift from agency quality assurance testing to contractor testing has evolved from the realization that both groups want a superior product. Further, contractors can provide on-site testing at more frequent intervals -- 4 to 5 times a day as compared to once a day by state agencies.

The Alabama Highway Department (AHD) implemented their QC/QA program for HMA pavements in 1990 to 1992 (Parker and Hossain, 1994). For several projects, AHD and various contractors measured asphalt contents and air voids for base mixtures, surface mixtures, and surface mixtures containing latex. Accuracy and precision of measurements increased as the period proceeded, indicating improved control of construction quality, or possibly improved technician sampling and testing skills, or both. No statistically significant differences occurred between AHD and contractor measurements, but numerically AHD measurements tended to have higher variability and mean deviation from target values, particularly in 1992, when contractor measurements were used for computing pay adjustments. No statistically significant differences in asphalt contents or air void contents occurred among the three mixture types, but there were some indications that the use of latex modifier decreased asphalt content variability.

The Australian Road Research Board (Auff, 1992; Auff, 1993; Auff, 1994; Auff, 1994) has been quite active in studying QC/QA specifications. They have developed sampling procedures and statistical compliance schemes for conditional and unconditional acceptance of materials and pavement properties. Their quality assurance program is based on results of analyses of actual data (measured pavement properties and performance) obtained from previously accepted local construction projects. Reduced payment schemes, proposed for acceptance of sub-standard pavement quality, are touted to be performance based.

RESEARCH APPROACH

TxDOT PAVEMENT MANAGEMENT INFORMATION SYSTEM

TxDOT has been collecting PMIS data or Pavement Evaluation System (PES) data since about 1984. The pavement condition data in PMIS is used to report the status and trends in pavement conditions to the legislature, to determine pavement needs and priorities in most districts, and to determine appropriate maintenance, rehabilitation, or reconstruction treatments in some districts. The data collected includes distress, skid, and profile on a 0.8 km (0.5 mile) basis and, with less frequency, deflection. For distress data collection, trained raters are given a list of sections which are rated using the definitions and rating procedures in the current PMIS Raters's Manual.

Historically, the frequency of data collection depended on the type of highway and on the guidelines provided by the individual district administration. In general, interstate highways were surveyed every year, while U.S. and state highways were surveyed every other year. FM and RM roads were surveyed at least every five years, but many districts surveyed these more often. Since TxDOT began contracting distress data collection, they have increased the frequency to 100 percent for all categories of roads.

Once input, the data on these measures is accessible through the TxDOT Teleprocessing Applications menu for PMIS. In addition to current year data, reports can be generated to review data from previous years.

Many other systems interact with PMIS, including DCIS (Design/Construction Information System), and RLSE (Road Life System Data Entry). These systems are not updated with the frequency and attention to detail exercised in the entry of PMIS data. Even with these databases available, the specific data needed to compare performance of pavements is often unavailable (e.g., date of construction, name of contractor, and pavement layer data).

VARIABILITY IN PAVEMENT PERFORMANCE

Pavement construction, even with tightly controlled specifications, can produce pavements that can vary considerably for several reasons. Construction contractors have different philosophies, equipment, materials and methods, as well as crews with different skill levels. It follows then that they will produce pavements with different quality levels even when using the same specification. Subtle differences in density or air voids levels in HMA pavements can induce significant differences in susceptibility to cracking, rutting, shoving, and, thus, roughness. Construction during different seasons of the year and even during different times of the day can affect density and moisture content of new HMA pavements. Obviously, the substrate on which any pavement or overlay is placed will affect its performance. These and other factors introduce variability in performance that has nothing to do with the construction specification employed.

A methods and materials specification will doubtless permit a range of material properties that will meet the specification. Varying the material properties within the specified range will directly affect performance of the resulting pavement. QC/QA specifications offer pay incentives when certain density levels are achieved; this, in turn, encourages some contractors in certain situations to raise asphalt content to the maximum level to achieve the specified density. These are just a few examples of how mixture variability and pavement performance can be influenced by the type of specification.

Therefore, variability in quality and performance is routinely introduced into pavements during the construction process. Proof of this fact is readily apparent as one observes that almost all pavements begin to exhibit distress and even begin to fail in isolated areas and not uniformly along the pavement. It is often difficult to determine why the pavement quality changed. The goal of this project is to develop a methodology to determine the differences in pavement performance that is due to the type of specification used during construction.

DEVELOPMENT OF PAIRED ANALYSIS METHOD

The researchers and the TxDOT research project panel recognized that the data required to perform a comparative analysis of performance of pavements constructed using the different specifications would be highly variable and often unavailable. Therefore, a paired analysis method was proposed to focus the measurement strategy on specific “paired” pavements in order to minimize the number of pavements analyzed and to minimize variability between the specific pavements compared. This paired technique was also designed to drastically reduce the number of pavement sections to be analyzed and maximize the sensitivity of the comparative analysis.

A paired set of pavements is defined as a pavement prepared using Item 340 specifications and a pavement prepared using QC/QA specifications that have similar locations, substrates, thicknesses, mixture type, and traffic but were probably constructed at different times by different contractors.

Pavement performance information on these paired pavements from the TxDOT PMIS database was used in a statistical analysis in an attempt to determine which type of specification, Item 340 or QC/QA, provided pavements with the better performance. The analysis method was tested using a sample consisting of 26 pavement pairs. It was assumed that, if differences between these paired pavements could not be ascertained, differences between all Item 340 and QC/QA pavements placed within a selected time period certainly could not be ascertained. That is, the paired approach should minimize data scatter and provide the most robust statistical analysis.

QUESTIONNAIRE

The research team and the PD developed a questionnaire and sent it to all TxDOT districts to assist the researchers in identifying paired pavements suitable for inclusion in the analysis. A copy of the questionnaire is provided in the Appendix. Twenty-six suitable pairs of pavements were identified by TxDOT and the research team and used to test the viability of the paired analysis method as well as the suitability and availability of the information recorded in the PMIS database.

In an attempt to minimize variability in the pavements considered, TxDOT limited the study to dense-graded Type D or Type C paving mixtures. This constraint eliminated all coarse matrix-high binder (CMHB) mixtures and, as a result, many of the newer QC/QA pavements in several districts.

GENERAL ANALYSIS METHOD

Near the end of the study, TxDOT requested that the researchers prepare a second Measurement Strategy using a general analysis method in addition to the paired approach. In the event that pavement construction specifications are developed in the future after the PMIS data collection process and database are upgraded, it may be desirable to compare performance of specific types of pavements in the database. Therefore, a second measurement strategy was developed using a general analysis method which is designed to compare performance of all appropriate pavements in a database without identifying qualified pavement pairs. The general analysis method is valid even if the number of pavements constructed using each specification is different. However, researchers did not test this general analysis method measurement strategy as a part of this project. The general analysis method is described in detail in Report 1877-6.

DEVELOPMENT AND TESTING OF THE PAIRED ANALYSIS METHOD

MEASUREMENT STRATEGY - PAIRED APPROACH

An alternative approach to a procedure where essentially all pavements constructed using the two specifications of interest is to identify and select “paired” pavements for statistical comparison. A paired set of pavements is defined herein as an Item 340 pavement and a QC/QA pavement that have similar locations, substrates, thicknesses, mixture type, traffic, etc. but probably were constructed at different times. This type of paired analysis will significantly reduce the size of the data set required as well as minimize the effects of environmental factors such as substrate, traffic, and climate and thus provide the best opportunity to detect significant differences in performance. The statistical process is one in which researchers match or pair each pertinent measurement in one sample with a particular measurement in the other sample. This paired procedure is designed to examine more detailed data on a much smaller sample than the approach where essentially a complete population would be studied. Pavements chosen for this comparison procedure will need to be carefully selected, requiring significant input from TxDOT district personnel. Histories of each of these sections must be reasonably well documented. Variables between the sections should be specifically identified. Using paired similar pavement sections will minimize the random variability and maximize the sensitivity of the comparison between specification types.

The paired procedure is designed to statistically compare the quality measures (scores or ratings) of pavements produced using two different specifications. The analysis procedure is designed to identify differences in average ratings for the PMIS categories such as distress, ride, deflection, skid, condition score, and time to first treatment.

The variability, or statistical spread in the values, of the quality scores could be compared to determine if one specification type can be characterized as having greater process control versus the other. Trends could also be examined with respect to performance over time. Statistical prediction techniques can be applied to determine the likelihood of differing quality values or pavement performance in future years. This paired approach may negate much of the uncertainty and variability likely to be encountered in the general approach where essentially a complete population may be evaluated.

An attempt was made to test the paired analysis method by using pavement condition data (e.g., ride quality, rut depth, cracking severity, patching, etc.) versus time obtained from the Department's PMIS database. Certain indispensable data was unavailable from PMIS database, (e.g., type of specification used, date of construction, project limits, design life, etc.). TxDOT district personnel provided the additional data to facilitate the analysis.

PROCEDURES

Comparison of the pavement pairs required a detailed statistical analysis of each set of pavement condition data. PMIS requires that the pavement raters evaluate each pavement based on eight basic distress types. The data is then used to calculate a pavement distress score, which is combined with a ride score to yield the overall pavement score. Through a detailed statistical analysis of each of the eight distress types, pavement distress score, ride score, and overall pavement score, an adequate evaluation of a particular pavement section was obtained and compared with other pavement sections.

Researchers can evaluate each distress type and pavement score for a pavement of any age by fitting a statistical distribution to the data that is collected in the field. The data can be characterized statistically using the following three equations (Benjamin and Cornell, 1970) for sample mean ($\bar{X}$), sample variance (s^2), and sample coefficient of variation (v), respectively:

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i \tag{1}$$

$$s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (X_i - \bar{X})^2 \tag{2}$$

$$v = \frac{s}{\bar{X}} \tag{3}$$

where n is the sample size and x_i is one data point in the set of data, $\{x_1, x_2, \ldots, x_n\}$. The larger the data set the closer these approximated values will be to the actual statistics (mean, m_x, variance, σ_x^2, and coefficient of variation, v_x) for the type of distress. The data sets obtained for this study were small and erratic. The sample statistical values determined above were used to select a statistical distribution to represent a pavement distress.

The lognormal distribution was selected to represent the pavement distress type and the ride score because zero is its lower bound, and mean and variance alone define the probability distribution function (PDF). Its PDF is defined below:

$$f_Y\ (y)\ =\ \frac{1}{y\sqrt{2\pi\sigma_{lnY}}}\ \exp\left\{-\frac{1}{2}\left[\frac{1}{\sigma_{lnY}}\ \ln\ \left(\frac{y}{\breve{m}_y}\right)^2\right]\right\} \tag{4}$$

where $\breve{m}_Y$ is the median of the sample data and σs_{lnY} is standard deviation of the natural logarithm of the sample data. The two parameters that define the lognormal distribution are determined as follows:

$$\sigma_{lnY}\ =\ \ln\ (v^2+1) \tag{5}$$

$$\breve{m}_y\ =\ \overline{X}\ \exp\ \left(-\frac{1}{2}\ \sigma^2_{lnY}\right) \tag{6}$$

The cumulative distribution function (CDF), $F_Y(y)$, is determined by integrating the PDF between zero and y as follows:

$$F_Y\ (y)\ =\ \int_0^y f_x\ (x)dx \tag{7}$$

A “goodness-of-fit test,” such as the chi-square test or the Kolmogorov-Smirnov test, should be used to verify the accuracy of the CDF selected to approximate the data set.

Similarly, the beta distribution was selected to approximate the pavement distress score and the overall pavement score because it is defined by the mean, variance, and upper and lower bounds. Its PDF is described as follows:

$$f_x(x) = \frac{1}{B}\, x^{r-1}\, (1-x)^{t-r-1} \qquad 0 \le x \ge 1 \tag{8}$$

$$B = \frac{\Gamma(r)\Gamma(t-r)}{\Gamma(t)} \tag{9}$$

t and r are functions of the mean and variance of the data set as described by the following equations:

$$t = \frac{m_x(1-m_x)}{\sigma_x^2} - 1 \tag{10}$$

$$r = m_x t \tag{11}$$

where, m_x and σ_x^2 are replaced by $\overline{X}$ and s^2 respectively when fitting the distribution to the sample data. Note that the above distribution exists only between zero and one. Extension of the beta distribution to pavement distress score and overall pavement score simply requires dividing the data in the set by 100 before determining the sample characteristics and fitting the distribution. Calculation of the CDF and the goodness-of-fit test should be performed as described in the previous paragraph. For consistency with the data provided, the beta distribution CDFs were plotted between 0 and 100 in the Results section.

The next step in the analysis is to determine the probability of failure for the pavement as a function of time. Pavement failure can be defined by excessive deterioration of the pavement characterized by excessive rutting, cracking, or other distress type, or it may be defined by pavement distress score (combination of multiple distresses described by one number), ride score, or overall pavement score. The analyses for both cases are similar. Failure, resulting from pavement deterioration by a single distress type is characterized by the quantity of that distress exceeding some limiting value (e.g., the development of 20 percent shallow rutting requires patching, repaving, etc.). In this case, the probability of failure for any given year may be determined using the following equation:

$$P(y > y_c) = 1 - F(y_c) \tag{12}$$

where y_c is the limiting value for the pavement distress type. Conversely, failure in terms of pavement distress score, ride score, and overall pavement score is defined as the probability that the score has dropped below some limiting value (e.g., a pavement distress score of 60 means that the road must be repaved). The corresponding probability of failure follows:

$$P(Y \leq y_c) = F(Y_c) \tag{13}$$

For any given pavement section, the probability of failure of any of its defining distress types can be determined for any year that a PMIS evaluation of that pavement was performed. Plotting probability of failure versus pavement age will serve as the means for comparing two paired pavements, as discussed earlier.

The pavement pairs identified and the basic pavement condition data obtained from the PMIS and district records is presented in Table 2. All of the analytical procedures outlined above can be performed in a MS Excel spreadsheet. As an example, the results of analyzing one pavement pair are presented in the following subsection.

Table 2. List of Pavement Pairs Identified for Study.

District	Const. Spec.	Highway ID	Beginning Reference Marker	Ending Reference Marker	Initial Construction Date	Date of Rehab/ Reconstruct
Amarillo	340	LP 171	82-0.069	76-0.034	1973	10-95
	QC/QA	RM 1061	102-0.577	94+1.631	1957	6-95
Atlanta	340	US 59	304+0.364	310+0.255	4-8-96	006303041 AC-10+latex
	QC/QA	US 59	300+0.006	304+0.363	10-1-98	006310008 AC-30P
Austin	340	SH 21	571.392	571.889	7-7-98	11-3-98 to 1-8-99
	QC/QA	SH 95	454.946	458.489	8-3-97	2-19-99 to 3-2-99
Beaumont	340	US 69	500+0.731	.502+1.246	10-14-92	N/A
	QC/QA	US 69	496-1.00	492-.066	11-21-96	N/A
Beaumont	340	SH 62	446+0.552	448+0.647	May 1992	N/A
	QC/QA	SH 62	444+0.062	446+0.560	Oct. 1998	N/A
Beaumont	340	US 69 NB	532	536	1936	1985
	QC/QA	SH 87 NB	496-0.3 ka	488+1.566 km	1990	1997
Beaumont	340	FM 1942	708+.309	708+1.857	1953	5-7-93
	QC/QA	SH 124	492+1.01	490-1.596	1941	5-19-97
Bryan	340	SH 47	0.0	9999	1993	1997
	QC/QA	FM 2154	620+0.6	624+.878	1995	1997
Corpus Christi	340	FM 3036	582+0.000	584+0.000	1994	N/A
	QC/QA	FM 1069	596-0.136	594+0.57	1995	N/A
Corpus Christi	340	FM 43	M.P. 7.850	M.P. 9.028	1988	N/A
	QC/QA	Green-wood Dr.	0+0.800	2+0.560	1998	N/A

Table 2. List of Pavement Pairs Identified for Study (Continued).

District	Const. Spec.	Highway ID	Beginning Reference Marker	Ending Reference Marker	Initial Construction Date	Date of Rehab/ Reconstruct
Corpus Christi	340	SH 357	562+1.533	566+1.191	1991	N/A
	QC/QA	Green-wood Dr.	0+0.800	2+0.560	1998	N/A
Corpus Christi	340	IH 37	9-1.283	9+0.383	1991	N/A
	QC/QA	IH 37	9+0.383	13+0.407	1994	N/A
Ft. Worth	340	IM 820-4(221) 454	23	24	--	--
	QC/QA	NH 97(600)	460	466	--	--
Houston	340	FM 1097	Lake Conroe	IH 45	1992	2000
	QC/QA	FM 3083	IH 45 N	FM 1484	1996	2002
Houston	340	FM 1488	FM 1774	FM 149	1990	1999
	QC/QA	LP 336 N	IH 45 N	SH 105 W	1997	2003
Houston	340	SH 36	STA. 0+00	184+80	1990	N/A
	QC/QA	SH 36	STA. 678+1.020	688+1.806	1995	N/A
Houston	340	SH 35	STA. 65+00	418+60	1990	N/A
	QC/QA	SH 35	496+1.461	508+1.767	1997	N/A
Lubbock	340	US 84	246+1.412	238+0.021	9/1933	Summer, 1995
	QC/QA	US 84	264+0.965	272+0.721	9/1933	July 2-3, 1997
Pharr	340	US 281	US 281 0782	US 83 0866	7-1990	N/A
	QC/QA	US 83	0868	0870	N/A	4-98

Table 2. List of Pavement Pairs Identified for Study (Continued).

District	Const. Spec.	Highway ID	Beginning Reference Marker	Ending Reference Marker	Initial Construction Date	Date of Rehab/ Reconstruct
Pharr	340	LP 499	0722	0722.5	4-90	N/A
	QC/QA	FM 507	0720	0722	N/A	3-1-93
Pharr	340	SH 186	0518	0538	N/A	10-89
	QC/QA	SH 1017	0709	0716	12-27-95	N/A
Pharr	340	FM 1847	0727	0735	N/A	1994
	QC/QA	US 281	0770	0773	N/A	1995
Tyler	340	US 69 S.	346+0.918	352+0.446	195?	6-93
	QC/QA	US 69 S.	338+0.513	342+0.508	195?	11-95
Tyler	340	US 69 S.	352+0.446	356+1.011	195?	8-93
	QC/QA	US 69 S.	342+0.508	346+0.918	195?	11-96
Waco	340	IH-35E	371+0.307	378+0.845	2-66	8-92
	QC/QA	IH-35W	0+0.236	14+0.341	4-67	10-95
Waco	340	IH-35	380+00	10478+00	3-55	5-95
	QC/QA	IH-35	291+1.68	1+392 509	3-55	10-97
Wichita Falls	340	US 183	0262-0.821	0264-0.215	N/A	1998
	QC/QA	US 380	0466+ 0.992	0470+ 0.815	1931	1994
YKM	340	Victoria US 77	572+0.05	572+1.28	N/A	6-96
	QC/QA	Victoria US 5996	600+1.50	644+0.11	N/A	9-97
YKM	340	Gonzales I-10	634+0.514	653+0.060	N/A	4-94
	QC/QA	Colorado I-10	689+0.798	694+0.976	N/A	7-96

EVALUATION OF PAIRED APPROACH AND RESULTS

Pavement pair 16-4 had the most complete and consistent PMIS data of any of the pairs; therefore, researchers selected that pair as the most suitable for performance of the analysis outlined in the above procedures. Pavement 16-4a was constructed in 1991 on IH-37 between mile marker 7.0 and mile marker 9.6 using Item 340 procedures. Data from lanes A1, A2, X1, and X2 were excluded from this analysis because the traffic demands were significantly different from the demands on lanes L1, L2, and R1. Pavement 16-4b was constructed in 1994 on IH-37 between mile marker 9.6 and mile marker 13.0 using QC/QA procedures. Since the two stretches of road adjoin, the average annual daily traffic (AADT), 18K traffic, and substrate are similar, making 16-4 an ideal pair for comparison.

Researchers performed the statistical analysis of the data for pavement sections 16-4a and 16-4b as described in the previous section. Tables 3 through 14 contain the sample means, sample variances, and sample coefficients of variation for each year of PMIS data. In many cases, the mean and variance both were zero and the coefficients of variation (COV) is not applicable. In 1996, the ride score was not determined, and the overall pavement score could not be calculated.

In order to demonstrate the fitting of statistical distributions to real data, Figures 1 through 8 compare the CDFs of the lognormal and beta distributions to the actual data for pavement 16-4a in 1995. The results from performing the Kolmogorov-Smirnov test are displayed in the inset. Note that, for some of the data, any realistic distribution would be rejected according to this test because most of the actual data points are zero. In these cases, the lognormal distribution is assumed to be adequate for the purposes of this study.

Figures 9 through 13 demonstrate the evaluation of the probability of failure of pavement 16-4a according to the pavement distress score for each year that PMIS data was collected. The probability of failure for 1996, 1997, and 1998 is zero because the pavement distress score was measured as 100 for every point inspected on the pavement. Keep in mind that the probability of failure equation for the pavement distress types differs from that presented in Figures 9 through 13.

Table 3. Mean of Sample Data, $\overline{X}$, for the Deterioration Characteristics of Pavement 16-4a.

Year	Shallow Rutting	Deep Rutting	Patching	Failures	Block Cracking	Alligator Cracking	Long. Cracking	Transverse Cracking
1992	4.5	0	0	0	0	0	50	1.6
1993	1.6	2.5	0	0	0	0	61	3.4
1994	3.6	0.8	1.1	0	0	0	80.7	2.6
1995	0.4	0	0.6	0	24.5	0.9	44.1	0.9
1996	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0
1998	0	0	0	0	0	0	3.1	0
1999	0	0	0	0	5.2	0	11.1	0

Table 4. Variance of Sample Data, s^2, for the Deterioration Characteristics of Pavement 16-4a.

Year	Shallow Rutting	Deep Rutting	Patching	Failures	Block Cracking	Alligator Cracking	Long. Cracking	Transverse Cracking
1992	52.5	0	0	0	0	0	0	0.71
1993	9.38	62.5	0	0	0	0	1705.11	20.93
1994	42.49	1.51	5.43	0	0	0	2649.12	6.49
1995	0.49	0	1.6	0	1142	3.66	744.1	1.21
1996	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0
1998	0	0	0	0	0	0	23.21	0
1999	0	0	0	0	99.07	0	181.66	0

Table 5. Coefficient of Variation of Sample Data, v, for the Deterioration Characteristics of Pavement 16-4a.

Year	Shallow Rutting	Deep Rutting	Patching	Failures	Block Cracking	Alligator Cracking	Long. Cracking	Transverse Cracking
1992	1.61	N/A	N/A	N/A	N/A	N/A	0	0.53
1993	1.91	3.16	N/A	N/A	N/A	N/A	0.68	1.34
1994	1.81	1.54	2.12	N/A	N/A	N/A	0.64	0.98
1995	1.75	N/A	2.11	N/A	1.38	2.12	0.62	1.22
1996	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1997	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1998	N/A	N/A	N/A	N/A	N/A	N/A	1.55	N/A
1999	N/A	N/A	N/A	N/A	1.91	N/A	1.21	N/A

Table 6. Mean of Sample Data, $\overline{X}$, for the Pavement Scores of Pavement 16-4a.

Year	Distress Score	Ride Score	Overall Score
1992	94.8	4.08	94.8
1993	85.8	3.98	85.8
1994	84.7	4.31	84.7
1995	78	4.06	78
1996	100	N/A	N/A
1997	100	4.22	100
1998	100	4.10	100
1999	93.2	4.02	93.2

Table 7. Variance of Sample Data, s^2, for the Pavement Scores of Pavement 16-4a.

Year	Distress Score	Ride Score	Overall Score
1992	16.18	0.064	16.18
1993	415.96	0.16	415.96
1994	144.68	0.12	144.68
1995	247.33	0.13	247.33
1996	0	N/A	N/A
1997	0	0.033	0
1998	0	0.029	0
1999	191.07	0.026	191.07

Table 8. Coefficient of Variation of Sample Data, v, for the Pavement Scores of Pavement 16-4a.

Year	Distress Score	Ride Score	Overall Score
1992	0.042	0.062	0.042
1993	0.24	0.1	0.24
1994	0.14	0.08	0.14
1995	0.20	0.089	0.20
1996	0	N/A	N/A
1997	0	0.043	0
1998	0	0.041	0
1999	0.15	0.04	0.15

Table 9. Mean of Sample Data, $\overline{X}$, for the Deterioration Characteristics of Pavement 16-4b.

Year	Shallow Rutting	Deep Rutting	Patching	Failures	Block Cracking	Alligator Cracking	Long. Cracking	Transverse Cracking
1995	0.23	0	0	0	18.68	0	44.14	1.04
1996	0	0	0	0	0	0	0	0
1997	0.091	0	0	0	0	0	0	0
1998	0	0	0	0	0	0	1.82	0
1999	0	0	0	0	0	0	81	0

Table 10. Variance of Sample Data, s^2, for the Deterioration Characteristics of Pavement 16-4b.

Year	Shallow Rutting	Deep Rutting	Patching	Failures	Block Cracking	Alligator Cracking	Long. Cracking	Transverse Cracking
1995	0.47	0	0	0	560.2	0	884.69	8.80
1996	0	0	0	0	0	0	0	0
1997	0.18	0	0	0	0	0	0	0
1998	0	0	0	0	0	0	62.16	0
1999	0	0	0	0	0	0	2227.43	0

Table 11. Coefficient of Variation of Sample Data, v, for the Deterioration Characteristics of Pavement 16-4b.

Year	Shallow Rutting	Deep Rutting	Patching	Failures	Block Cracking	Alligator Cracking	Long. Cracking	Transverse Cracking
1995	3.02	N/A	N/A	N/A	1.27	N/A	0.67	2.84
1996	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1997	4.69	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1998	N/A	N/A	N/A	N/A	N/A	N/A	4.34	N/A
1999	N/A	N/A	N/A	N/A	N/A	N/A	0.58	N/A

Table 12. Mean of Sample Data, $\overline{X}$, for the Pavement Scores of Pavement 16-4b.

Year	Distress Score	Ride Score	Overall Score
1995	78.59	4.00	77.14
1996	100	N/A	N/A
1997	100	4.52	99.27
1998	99.95	4.51	99.95
1999	89.59	4.53	89.59

Table 13. Variance of Sample Data, s^2, for the Pavement Scores of Pavement 16-4b.

Year	Distress Score	Ride Score	Overall Score
1995	366.63	0.25	346.22
1996	0	N/A	N/A
1997	0	0.14	11.64
1998	0.045	0.016	0.045
1999	83.68	0.011	83.68

Table 14. Coefficient of Variation of Sample Data, v, for the Pavement Scores of Pavement 16-4b.

Year	Distress Score	Ride Score	Overall Score
1995	0.24	0.12	0.24
1996	0	N/A	N/A
1997	0	0.081	0.034
1998	0.0021	0.028	0.0021
1999	0.10	0.023	0.10

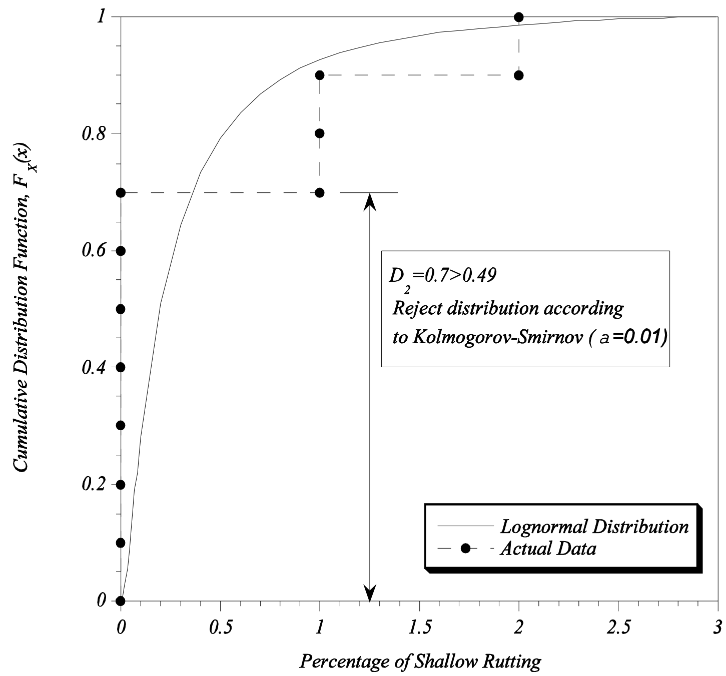

Figure 1. Lognormal Distribution for Shallow Rutting of Pavement 16-4a in 1995.

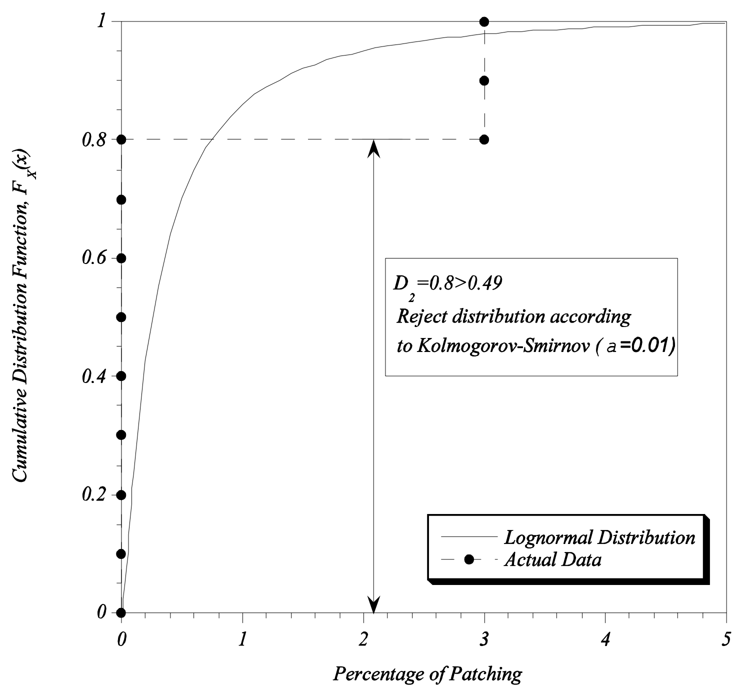

Figure 2. Lognormal Distribution for Patching of Pavement 16-4a in 1995.

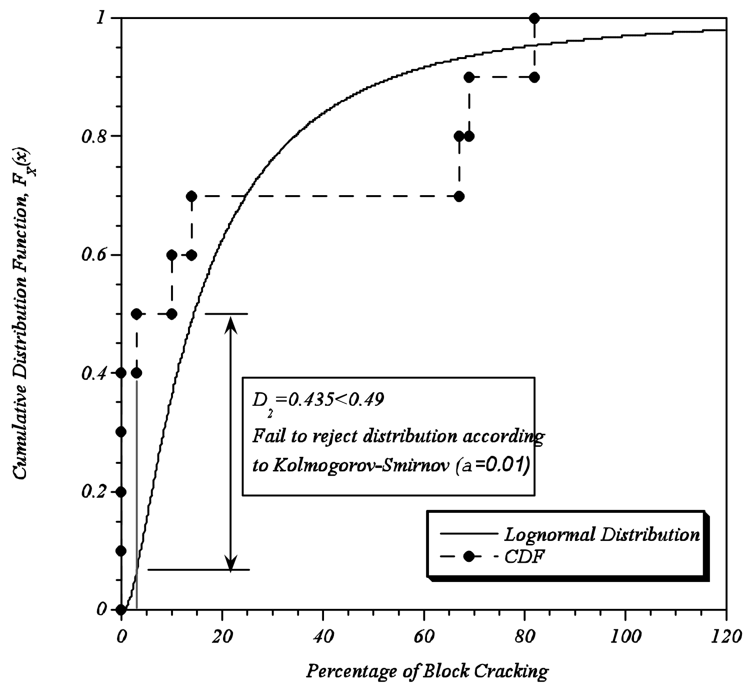

Figure 3. Lognormal Distribution for Block Cracking of Pavement 16-4a in 1995.

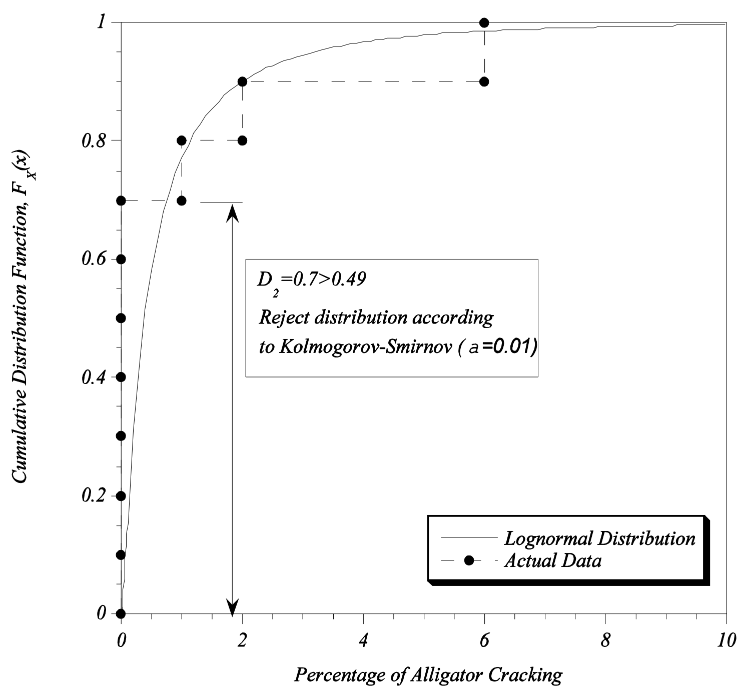

Figure 4. Lognormal Distribution for Alligator Cracking of Pavement 16-4a in 1995.

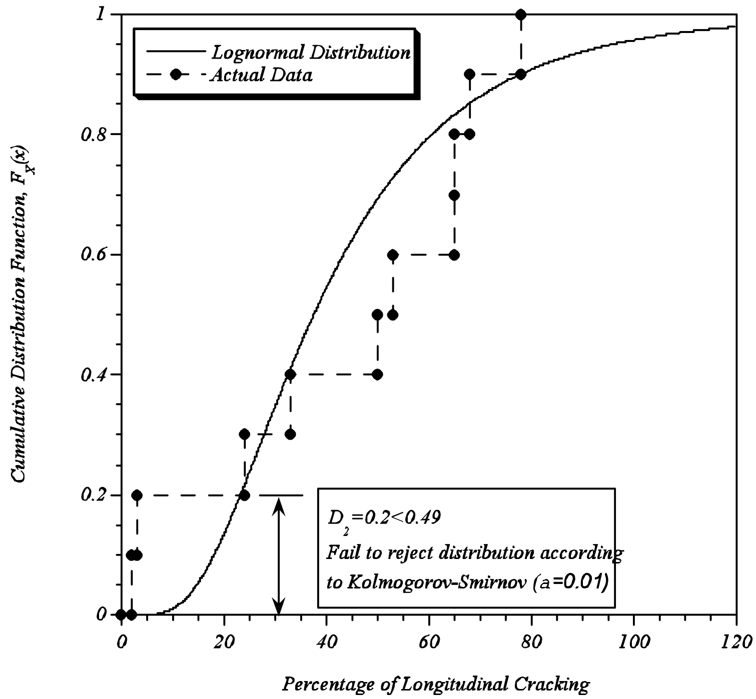

Figure 5. Lognormal Distribution for Longitudinal Cracking of Pavement 16-4a in 1995.

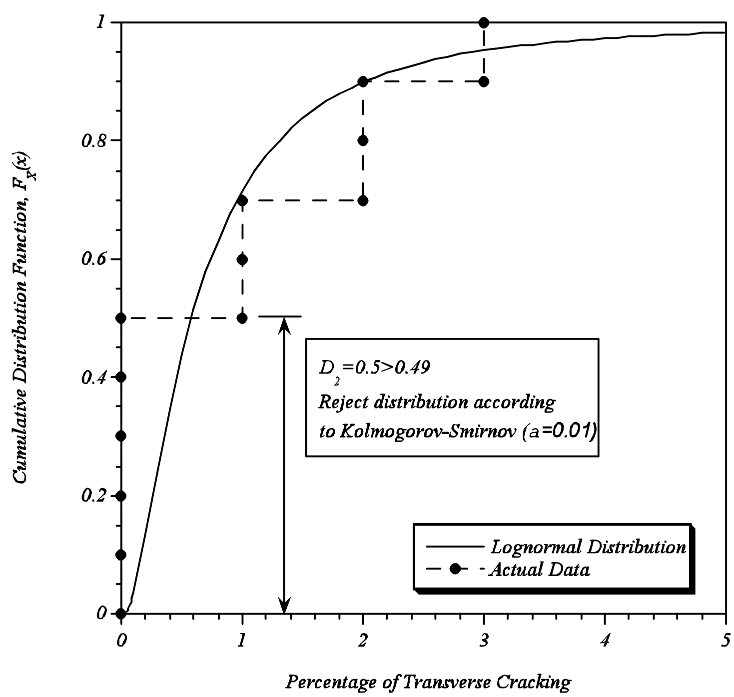

Figure 6. Lognormal Distribution for Transverse Cracking of Pavement 16-4a in 1995.

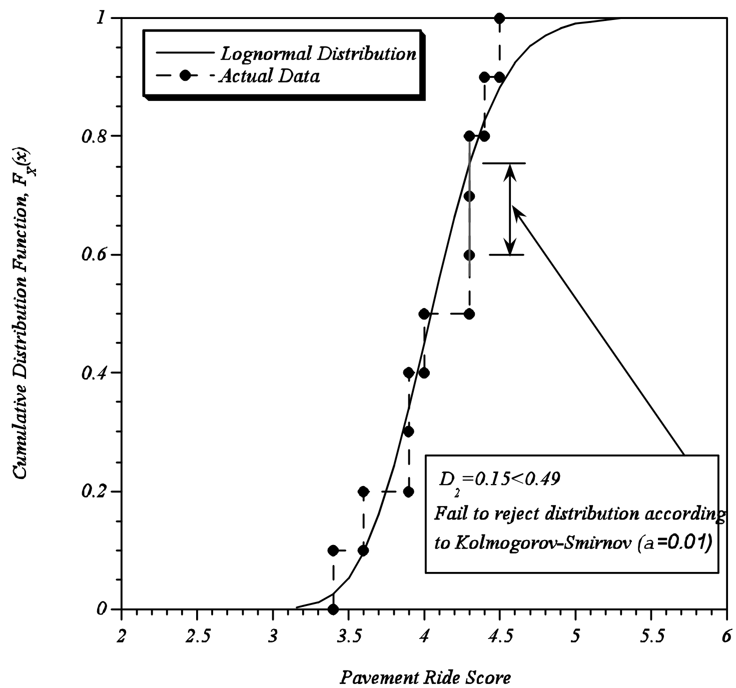

Figure 7. Lognormal Distribution for Ride Score of Pavement 16-4a in 1995.

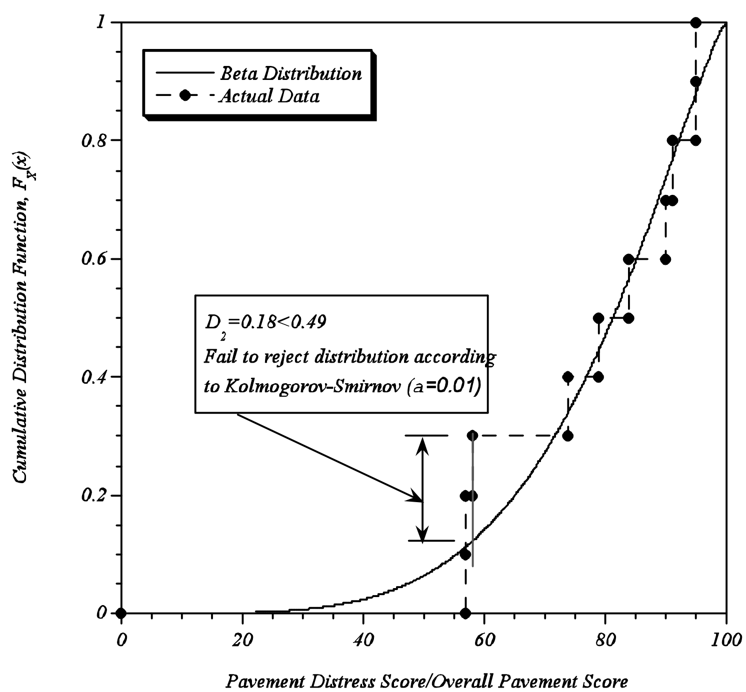

Figure 8. Beta Distribution for Distress Score and Overall Score of Pavement 16-4a in 1995.

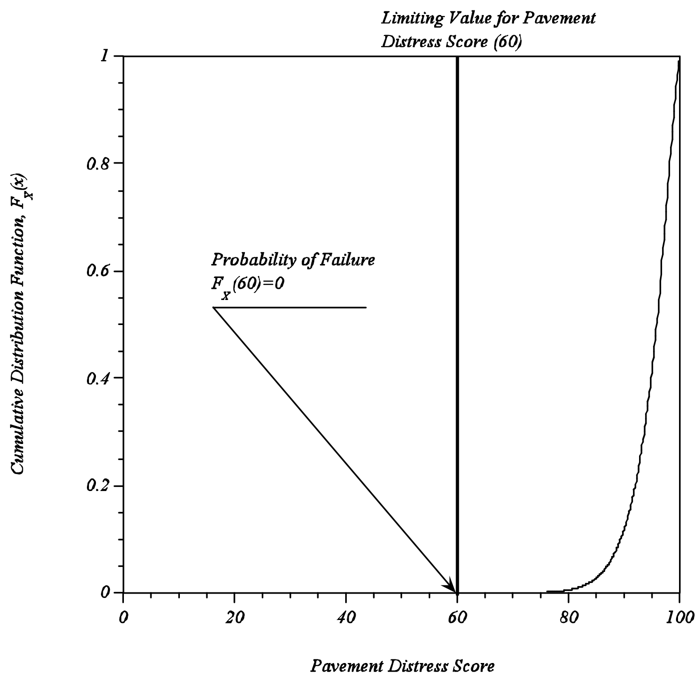

Figure 9. Determination of Probability of Failure of Pavement 16-4a According to its Distress Score in 1992.

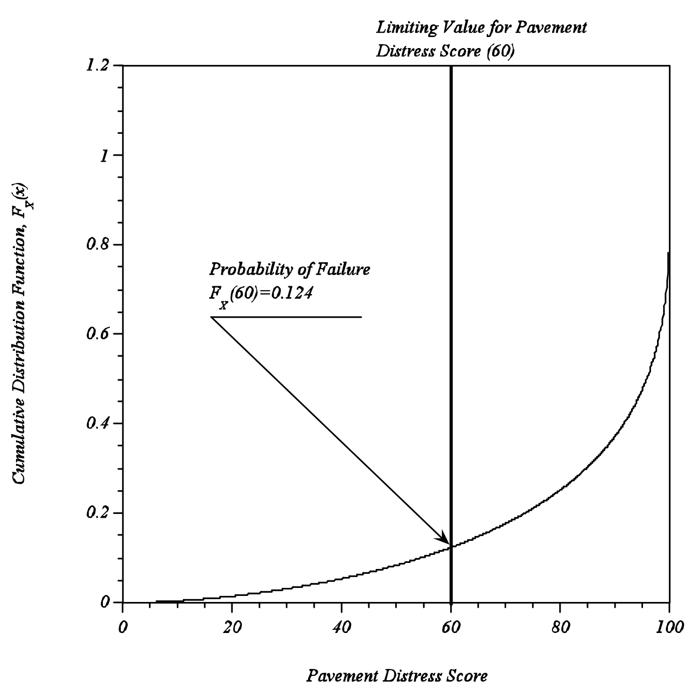

Figure 10. Determination of Probability of Failure of Pavement 16-4a According to its Distress Score in 1993.

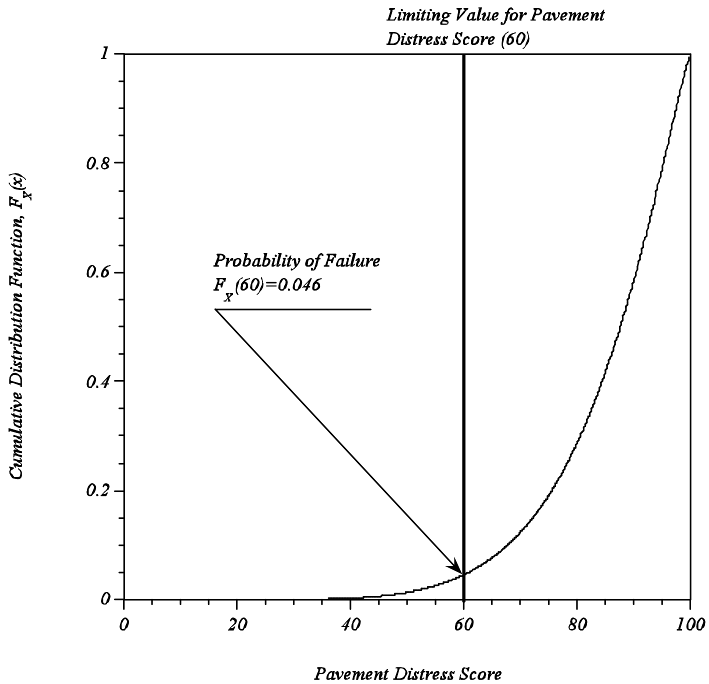

Figure 11. Determination of Probability of Failure of Pavement 16-4a According to its Distress Score in 1994.

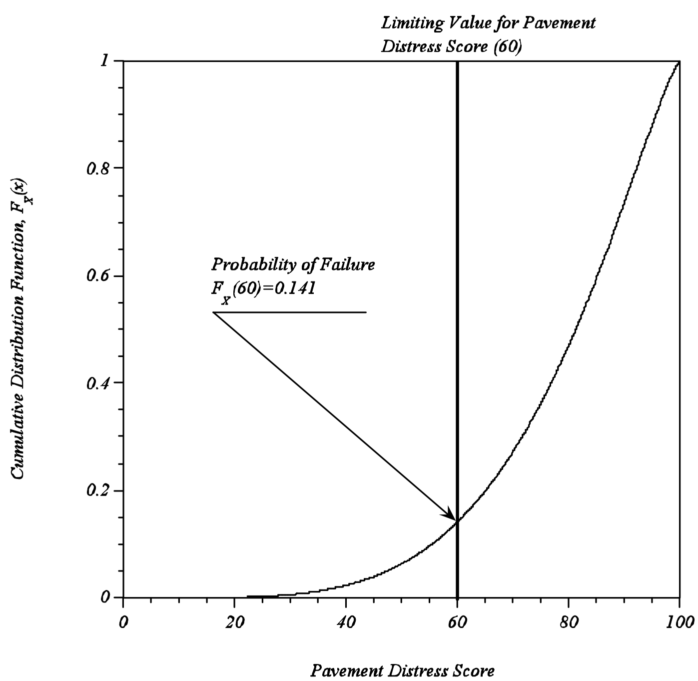

Figure 12. Determination of Probability of Failure of Pavement 16-4a According to its Distress Score in 1995.

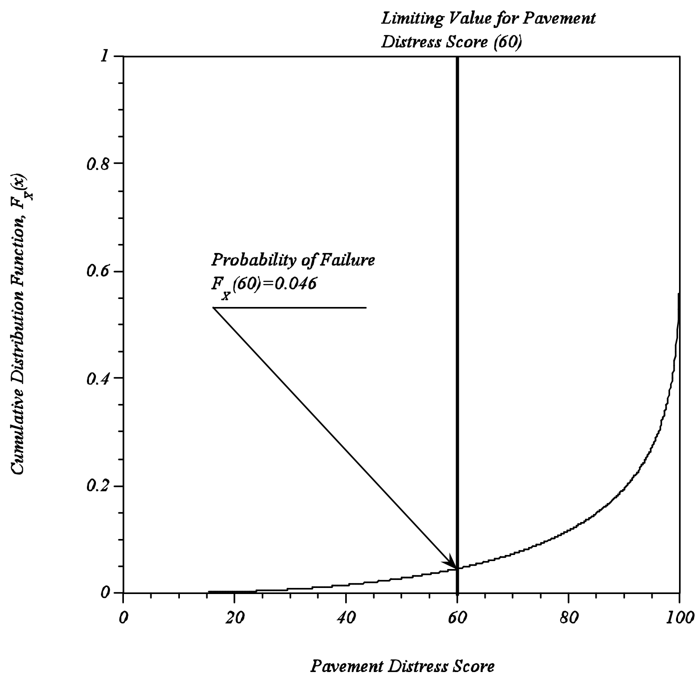

Figure 13. Determination of Probability of Failure of Pavement 16-4a According to its Distress Score in 1999.

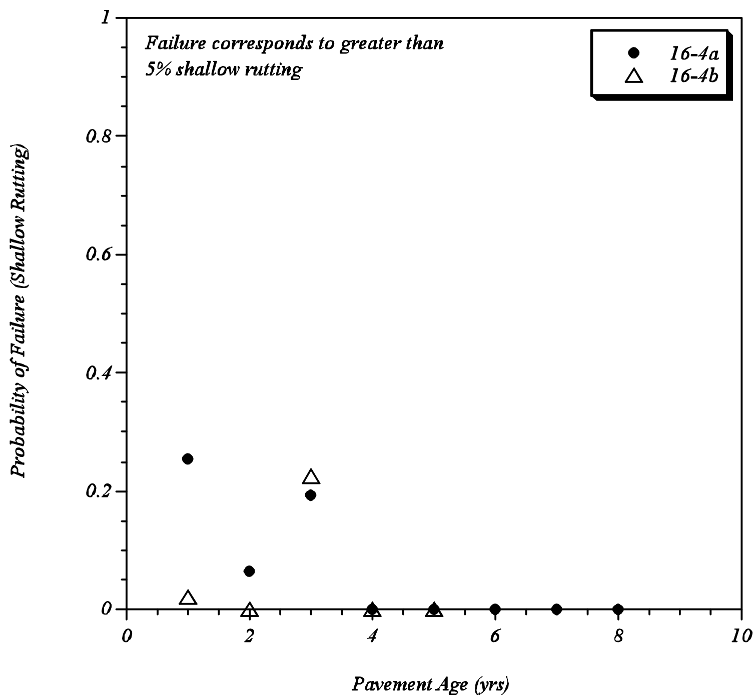

Figure 14. Probability of Failure by Shallow Rutting of the Pavement Pair with Respect to Time.

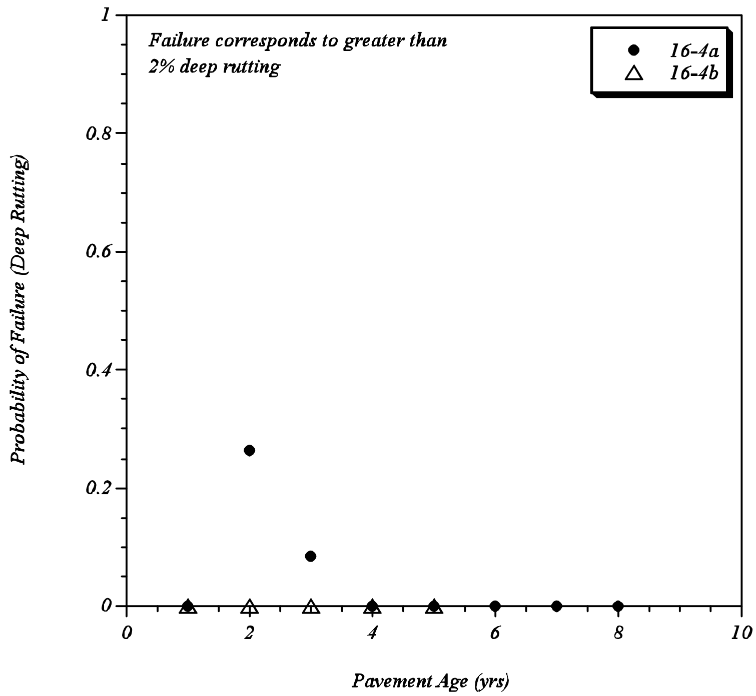

Figure 15. Probability of Failure by Deep Rutting of the Pavement Pair with Respect to Time.

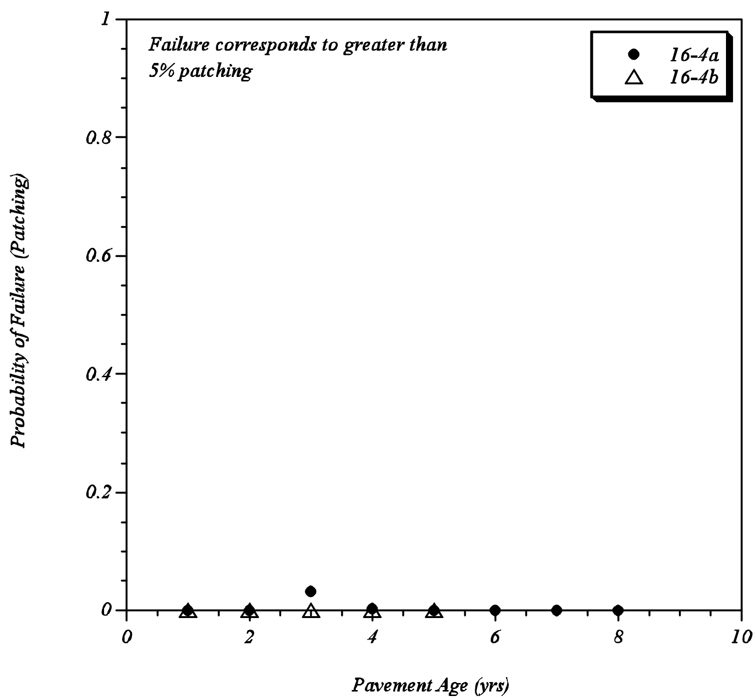

Figure 16. Probability of Failure Indicated by Patching of the Pavement Pair with Respect to Time.

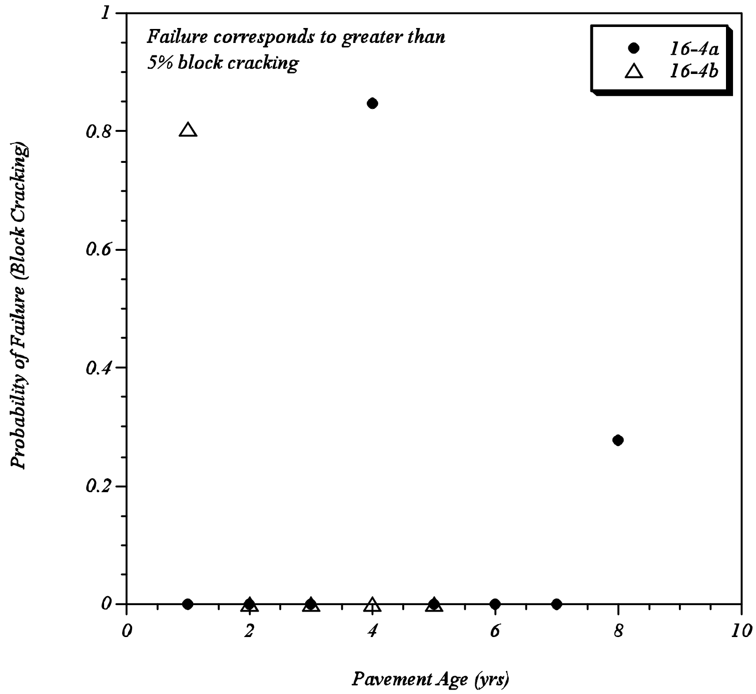

Figure 17. Probability of Failure by Block Cracking of the Pavement Pair with Respect to Time.

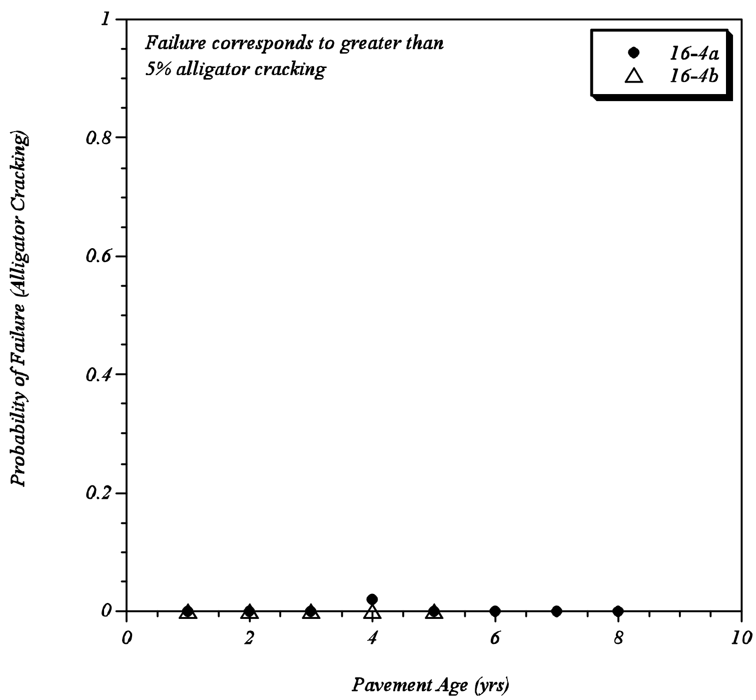

Figure 18. Probability of Failure by Alligator Cracking of the Pavement Pair with Respect to Time.

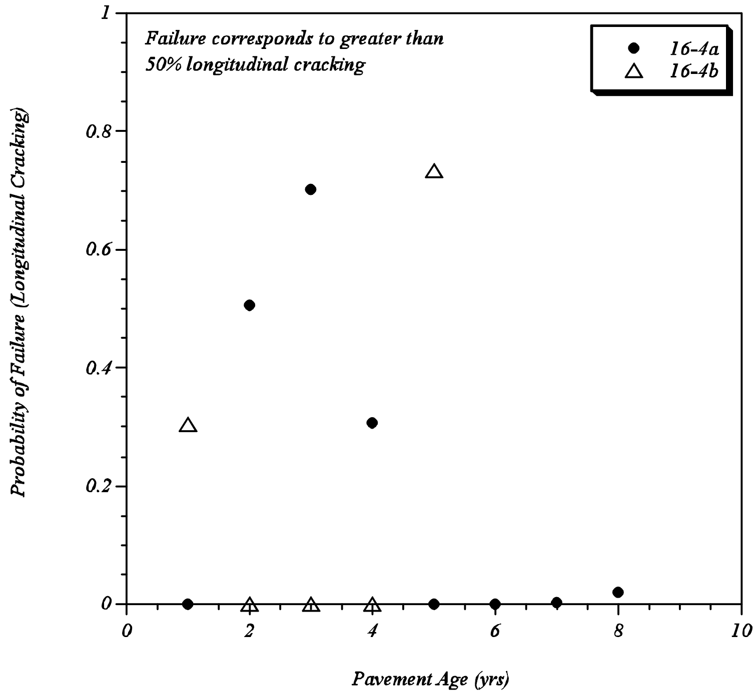

Figure 19. Probability of Failure by Longitudinal Cracking of the Pavement Pair with Respect to Time.

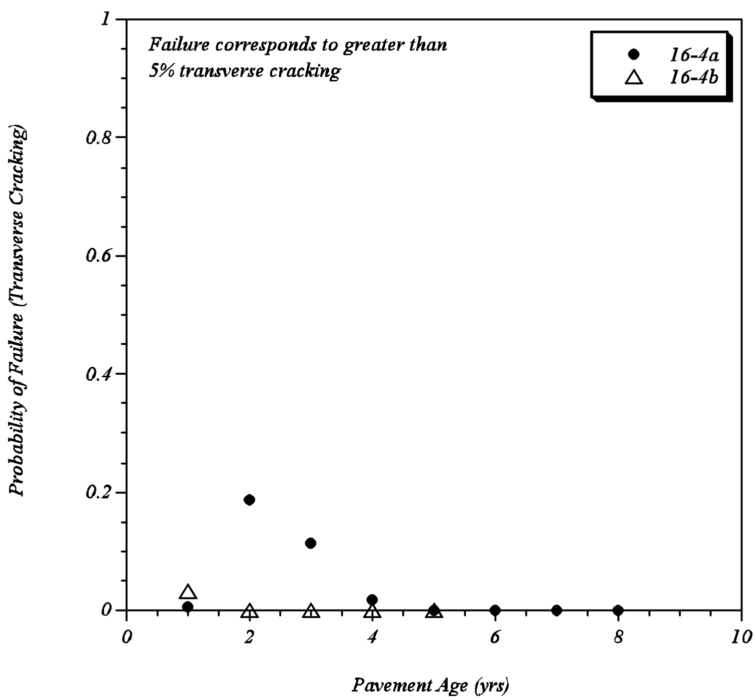

Figure 20. Probability of Failure by Transverse Cracking of the Pavement Pair with Respect to Time.

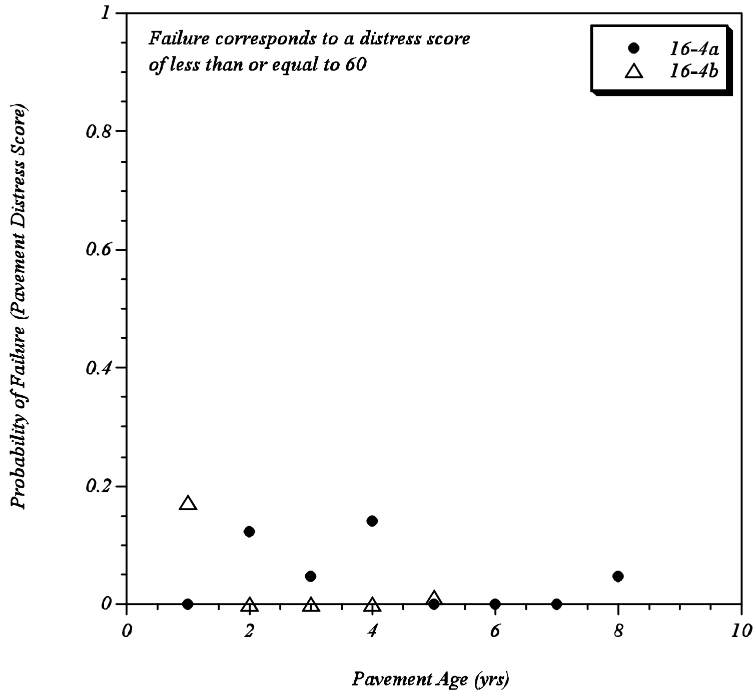

Figure 21. Probability of Failure Indicated by Distress Score for the Pavement Pair with Respect to Time.

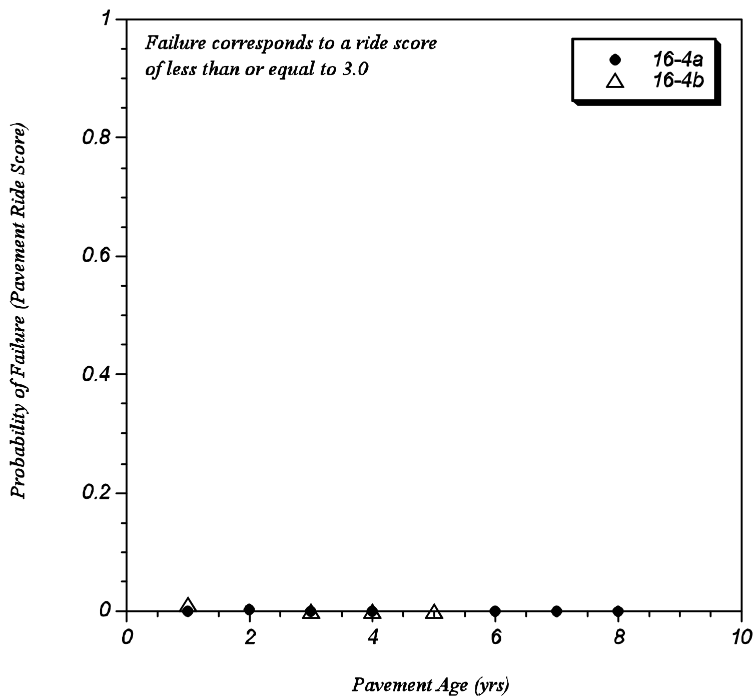

Figure 22. Probability of Failure Indicated by Ride Score for the Pavement Pair with Respect to Time.

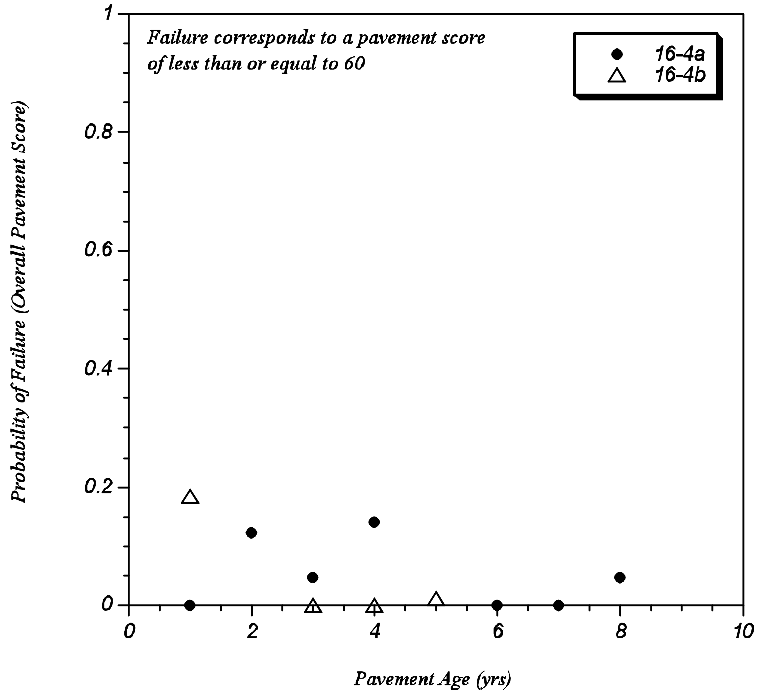

Figure 23. Probability of Failure Indicated by Overall Score for the Pavement Pair with Respect to Time.

Probability of failure versus time for both pavements is plotted for each of the distress types and pavement scores in Figures 14 through 23. The limiting values for the pavement distress types were selected arbitrarily. The corresponding values follow: 5 percent for shallow rutting, patching, block cracking, alligator cracking, and transverse cracking; 2 percent for deep rutting; 50 percent for longitudinal cracking; 60 for pavement distress score and overall pavement score; 3.0 for ride score.

FINDINGS AND DISCUSSION

The statistical method described in this report appears to give a reasonable approximation of pavement behavior. Based on our experience, the statistical distributions seem reasonable, even for those segments that fail the Kolmogorov-Smirnov test. The failed distributions were typically rejected due to a disproportionate number of zeros in the set (i.e., Figures 1, 2, 4, and 6). Analysis of a larger data set would likely give better agreement between the sample data and the statistical distribution.

The results of estimating the probability of failure with time for pavement pair 16-4 are discouraging because they predict improvement of road conditions with time. Obviously, visible distress in a pavement on a heavily trafficked road will not normally decrease with time. The apparent improvement in road condition is either due to inconsistency of inspection results, undocumented repairs to the road, or one form of distress evolving into a different distress type (e.g., longitudinal cracking ⇛ alligator cracking ⇛ patching or transverse cracking ⇛ block cracking). Comparison of the Item 340 and QC/QA processes requires accurate and consistent data. Unfortunately, this was not an isolated case, as all of the pairs showed this disturbing trend of distresses disappearing with time.

Further development of this model should include development of probability of failure versus pavement age curves. A CDF (perhaps a log-normal distribution) should fill this role. Unfortunately, we were unable to verify the adequacy of a lognormal CDF, or any other curve, due to the lack and unrealistic distribution of data points. One remedy for this problem is collecting data more frequently; however, this may not be practical for TxDOT. Other options include the populating of a rigorous pavement layer database that would accurately track work performed on a pavement to ensure that, when maintenance functions (e.g., seals or patches) are performed, they are recorded. Another option that would improve the accuracy and predictive power of the model would be more accurate distress surveys. Currently, the repeatability of the PMIS inspections is low, and two different inspection teams often differ by more than 15 points in the distress score for a single 0.5-mile section.

The statistical model developed in this study will provide engineers with a method for analyzing the relative deterioration of pavements. The model requires a reasonably large, consistent, and accurate data set.

PROBLEMS ENCOUNTERED

This section describes some of the challenges the researchers faced during the completion of this work, which TxDOT will need to address in a formal fashion in order to make full use of the PMIS database in future pavement performance comparisons. One charge of this study was to specify the additional data that TxDOT needs to record during future pavement construction and condition survey operations in order to accommodate performance comparisons. The following was used to develop the researcher's recommendations.

The PMIS data does not contain the date of construction for a pavement. This obviously presented major problems when attempting to relate pavement performance with time.

No significant pavement layer data exists which can be used to compare pavement thickness versus performance and traffic. This topic has been addressed during other research.

The type of specification or special provisions used during construction was not listed in PMIS. Data such as these had to be obtained from other databases or files by TxDOT district personnel. Currently, significant effort is required at the district level to obtain data such as these to accommodate implementation of the measurement strategy.

It is presumed that, in most cases, specific HMA pavement performance comparisons will involve overlays. Ride quality, cracking, and rutting of HMA overlays may be more dependent on movements within the substrate, workmanship and quality control during construction, and/or paving materials than on the type of specification used during construction. These and other factors will effectively increase the variability in the measurements of pavement "quality" and, therefore, decrease the level of confidence in the comparisons of performance of pavements produced using Item 340 and QC/QA specifications.

For comparing overlay performance, it may be more meaningful to compare times to first major maintenance or rehabilitation activity. Pavement surface layers are often *designed* with different time periods to the first overlay. For example, an Item 340 pavement with a longer time period to the first overlay may be "designed" to perform better than a similar QC/QA pavement with a comparatively shorter design period to the first overlay (and vice versa). Therefore, pavement design procedures could confound or add variability to the comparative analysis process. If these situations exist and are known, i.e., recorded in a database, they can be easily overcome by examining pavement quality as a function of percent of design life rather than as a function of time.

The degree of raveling and flushing had not usually been rated during routine pavement condition surveys even though these are important performance factors for asphalt pavements. In fact, major maintenance and rehabilitation may be required specifically to address either one of these types of distress. To perform a valid comparison of performance between Item 340 and QC/QA pavements, ratings of these surface phenomena as a function of time may be necessary. Rating of flushing and raveling during future pavement condition surveys should be performed.

Another problem encountered was the consistency or repeatability and lack of severity levels in the PMIS distress surveys. In many of the pavement pairs, distresses were identified in a given year, and then they would disappear completely for several years. Table 15 and Figure 24 illustrate some of the problems the researchers encountered with the data. TxDOT Project 1722 and others have studied the variability in PMIS distress score data. TxDOT audit guidelines allow for a 30-point ($\pm$ 15 points) acceptance range in the distress score, where the maximum score is 100, meaning no distress, and the minimum score is 0 points, meaning substantial distress. That is, if the contractor survey is within 15 points of the audit survey, it is considered correct. In the most recent PMIS survey, the contractor's surveys were outside of this limit more than 14 percent of the time. The inclusion of distress severity levels in the PMIS survey would significantly benefit any comparison of pavement performance (for example, the impact of a crack would be further differentiated by its width or presence of spalling or tenting).

A comparison of pavement performance for new and old specifications (i.e., implementation of this measurement strategy) cannot be successfully conducted for at least a few years after a new construction specification has been introduced. Therefore, it is reasonable to assume that some pavements may have experienced premature failure, under one or both of the specifications, and were subsequently covered with a seal coat or an overlay. Regarding the older specification, if only "uncovered" pavements are included in an evaluation, the database may be unsatisfactorily small and will not represent all pavements placed using that

Table 15. Typical PMIS Data Obtained for Paired Pavements.

Pair	Eval. Year	Highway	Lane	From	To	Shallow Rut	Deep Rut	Patch	Failures	Block	Alligator	Longitudinal	Transverse
2-1A	1998	IH0820	R1	23.5	24.0	0	0	33	0	0	0	0	0
2-1A	1999	IH0820	R1	23.5	24.0	0	0	0	0	0	0	0	0
3-1B	1996	US0380	K1	471.5	472.0	0	0	0	0	0	0	4	3
3-1B	1998	US0380	K6	471.5	472.0	2	0	62	0	0	0	0	0
4-1A	1997	SL0171	K1	76.0	76.5	0	0	0	0	0	0	25	0
4-1A	1997	SL0171	K1	76.5	77.0	0	0	0	0	0	0	10	0
4-1A	1999	SL0171	K6	76.0	76.5	0	0	0	0	0	0	5	0
4-1A	1999	SL0171	K6	76.5	77.0	0	0	0	0	0	0	6	0
9-1A	1993	IH0035E	R	371.5	372.0	0	0	0	0	0	0	0	0
9-1A	1994	IH0035E	R	371.5	372.0	0	0	0	0	0	0	0	0
9-1A	1995	IH0035E	R	371.5	372.0	0	0	0	0	0	0	0	0
9-1A	1996	IH0035E	R	371.5	372.0	0	0	0	1	0	0	0	0
9-1A	1997	IH0035E	R	371.5	372.0	0	0	0	0	0	0	0	0
9-1A	1998	IH0035E	R	371.5	372.0	0	0	0	2	0	0	28	1
9-1A	1999	IH0035E	R	371.5	372.0	0	0	0	2	0	0	0	0
13-2A	1995	IH0010	L1	634.6	635.0	0	0	0	0	0	0	0	0
13-2A	1996	IH0010	L1	634.6	635.0	0	0	0	0	0	0	32	0
13-2A	1997	IH0010	L1	634.6	635.0	0	0	0	0	0	0	29	0
13-2A	1998	IH0010	L1	634.6	635.0	0	0	0	0	0	0	0	0
13-2A	1999	IH0010	L1	634.6	635.0	0	0	0	0	0	0	9	0

specification. Furthermore, considering only uncovered pavements would eliminate any poor performing pavements that were covered early in their service life and thus skew the analysis toward the poorer performing specification as being the most favorable. It presently appears, therefore, that some "covered" pavements will need to be included in comparative analyses, at least as an indicator of "time to first treatment." Evaluation of covered pavements will require total dependence on the pavement condition surveys (PMIS, district records, etc.) and, thus, may decrease the level of confidence in the analysis because some important data on the covered pavements may be unavailable.

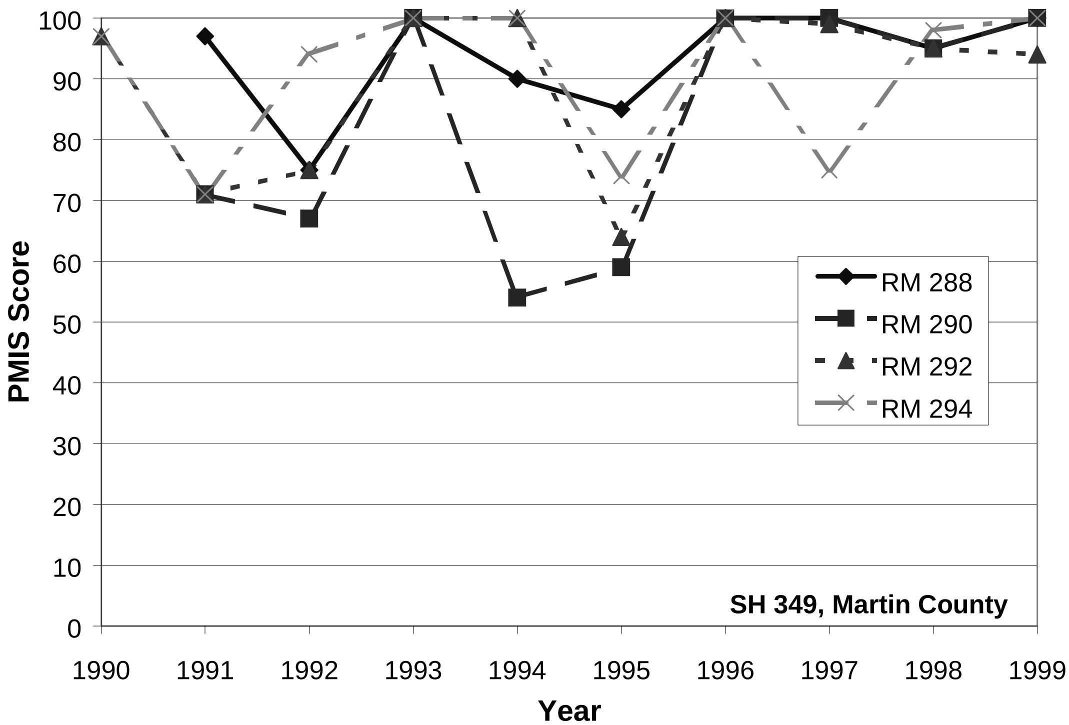

Figure 24. Example of Distress Score Complications.

All TxDOT districts did not uniformly adopt the QC/QA construction specification as soon as it became available. In fact, some districts used the Item 340 specification for several years after QC/QA specification was available, and some districts adopted QC/QA immediately and have not used the Item 340 specification for many years. Some have even used “hybrid” specifications which contain some Item 340 features and some QC/QA features. Such practices will, of course, disallow a blanket inclusion of virtually all pavements in a comparative analysis. Therefore, one can see the benefit of a methodology where specific pavements are selected for comparative analysis. Further, this demonstrates the importance of maintaining an accurate, consistent database on all facets of pavement design, construction, and performance.

CHANGES NEEDED TO PMIS TO ACCOMMODATE UTILITY OF THE MEASUREMENT STRATEGIES

SUMMARY

These recommendations are based on findings from this research study (Project 0-1877) and other TxDOT projects (0-1420, 0-1727, and 0-4186). These particular recommendations are directed primarily at the need for accurate, consistent data to support evaluation of differences in pavement performance. Most of the recommended changes are related to data, but a few are related to analysis of data.

PMIS CONDITION DATA

The current TxDOT PMIS has the capability to collect, store, and analyze the following four types of pavement condition data:

- visual distress data, which measures surface defects including patching and cracking (block, alligator, longitudinal, and transverse cracking);
- ride quality data, which measures pavement roughness and rutting (shallow and deep rutting);
- deflection data, which measures the overall pavement structural strength or stiffness, and
- skid data, which measures pavement surface friction resistance.

The visual distress data are primarily collected using trained observers/evaluators. In the past, TxDOT personnel collected most of these data but, recently, it has been collected using consultants. For inspections during the fall of 2000, TTI completed the quality control checks for TxDOT on the visual distress data. Pavement rutting is measured using automated methods based on sonic devices that determine the distance to the pavement at five points along a straight bar attached to the front of a vehicle. The measurements in the wheel paths and those in the non-wheel path locations are used to determine the rut depth. Distress data were historically collected on a cyclic basis, with annual collection on the interstate system but less frequently on other systems. However, with the change to consultant data collection, data is being collected on the entire network annually at the current time.

Except for shallow versus deep rutting, the TxDOT distress definitions do not define severity levels. This needs to be corrected. An approach that includes the severity of the distress type needs to be incorporated into the process. Cracking, for example, could include the width of the crack along with the length. It might also include whether there is a differential in elevation across the crack (e.g., faulting or tenting). Since rutting is measured, it could easily be reported as actual depth of the rut. This type of detailed information would be extremely valuable in subsequent evaluations of relative pavement or pavement overlay quality.

Ride quality is measured using Siometer devices that are vehicle mounted. As with distress data collection, historically only part of the network was surveyed annually, but since 100 percent of the distress data is being collected, the decision was made to collect 100 percent of the ride quality data.

Pavement surface deflection measurements are made using Dynatest falling weight deflectometers. This information was formerly collected on a cyclic basis, but the researchers now understand that many of the districts no longer collect deflection data on the entire system on a cyclic basis. This information could be critical for evaluation of an asphalt overlay. For example, a perfectly good overlay may exhibit premature failure if the deflections are excessive.

Pavement surface friction data are collected using TxDOT skid trailers. Currently, only a portion of the network is surveyed annually. This appears to be adequate. Although skid number vs. time information would be interesting and informative and may be useful for evaluating materials and improving aggregate specifications, these types of studies should probably be conducted as research projects separate from routine PMIS testing. If specific studies are desirable or if unacceptable skid values are suspected, a skid trailer can be quickly dispatched to the sites in question.

The primary change needed to improve the pavement condition data is the accuracy and reliability of the visual distress data. All agencies across the U.S. are having problems with this (Ref, PCI-Law Study for the Strategic Highway Research Program). These problems have driven the research efforts to develop automated equipment to record and interpret pavement distresses. TxDOT needs to pursue development of automated distress recording and interpreting equipment or purchase existing state-of-the-art equipment. TxDOT also needs to implement a sound QC/QA system for contracted distress data collection, whether it is visual or automated. During this study, the researchers found major contradictions in the PMIS database (e.g., pavement condition improved in a subsequent year with no recorded maintenance activities) which made reliable pavement performance comparisons impossible.

Data from a recent (2000) distress rater's training class illustrate some of the problems with the distress data collection process. As part of the training class, trainees were divided into five to eight groups containing three to five raters, who knew that they were being tested, and rated the same eleven pavement sections on the same day. The standard deviation of the distress score was slightly greater than 10 points. This is a high standard deviation for the number of groups and pavements inspected. During the annual condition survey, the average standard deviation between the annual and audit surveys was 13 points. This high degree of variation in distress score reduces the level of confidence in comparisons of pavement performance.

PMIS PAVEMENT LAYER DATA

Pavement layer thicknesses, as well as the types of materials used in the various layers and their properties, will obviously affect the performance of pavements. This is particularly true for HMA overlays, which comprise most of the pavement surfaces being evaluated for PMIS. PMIS contains a database structure that can store information on the pavement layer thicknesses, material types, and properties. However, that data is entered for very few sections of pavement in TxDOT's PMIS database. This information is critical for the type of evaluation attempted in this research project. Until the pavement layer database is populated, it will likely be impossible to achieve the goals of a research project of the type attempted herein.

PMIS TRAFFIC DATA

Paired analysis works only if all the pavement conditions (e.g., substrate, traffic, climate) are the same except for the overlay materials being studied. Since the sections to be compared are generally placed at different times, one of the most significant differences is the amount of traffic loadings. The TxDOT PMIS allows the storage of a traffic level, but that is a very generalized number. More accurate data regarding the traffic loads applied during the analysis period are needed.

In this study, each pavement pair selected was on the same roadway and in close proximity to one another to minimize any differences in traffic. However, if special circumstances exist (e.g., a major trucking operation on only one of the pavements in a pair), pavement pairs may experience significant differences in traffic volume and/or loads even though they are in mutually close proximity.

ENVIRONMENTAL DATA

Again, paired analysis works only if the conditions are the same. Since the sections are often placed at different times, one of the other significant differences may be environmental conditions. Generalized weather information can be captured from weather stations near the sites being studied. This would assist in determining unusual weather events that may have contributed to the performance of the pavement.

In this study, each pavement section in a given pair was in close proximity to one another in an attempt to neutralize the environmental factor.

DATA NEEDED FOR PAVEMENT STUDIES

Follow-up studies of relative pavement performance are often desirable for research (e.g., comparisons of performance under different specifications), forensics (e.g., attempts to explain poor performance), or possibly other reasons. The researchers learned, during this study, that several key items of information required for pavement performance comparisons were not available in the PMIS database.

The authors believe that the following data should be recorded in an automated database to accommodate comparative analyses of pavement performance:

- date(s) of pavement construction;
- periodic traffic loadings;
- data for all pavement layers;

- type of specification or special provisions used during construction;
- level of severity of any distress measured or observed;
- pavement design life, so that pavement quality as a function of percent of design life can be examined;
- degree of raveling and flushing;
- maintenance activities;
- data on failed pavements that have been covered by subsequent maintenance or rehabilitation;
- HMA mixture parameters from quality control tests (e.g., density, asphalt content, gradation, voids in mineral aggregate, voids filled with asphalt) and target (or mixture design) values; and
- name of contractor.

CONCLUSIONS AND RECOMMENDATIONS

Researchers developed a "measurement strategy" to evaluate comparative performance of asphalt overlays placed using either Item 340 or QC/QA specifications. The measurement strategy is described as a paired approach, wherein only selected pairs of pavements with specified attributes are evaluated. A second measurement strategy described as a general approach, wherein all data in a database can be evaluated, is described in Report 1877-6. Being the more robust of the two approaches, only the paired approach was evaluated using actual pavement data from PMIS and other district files. The researchers recognized that there would be much scatter in the data because pavement performance depends on many factors other than the construction specification. They assumed that, if the paired approach could not identify differences in pavement performance, the general approach would certainly not identify any differences.

Based on the findings of this study, the following conclusions and recommendations appear warranted.

CONCLUSIONS

- Attempts to evaluate relative performance of asphalt overlays placed using either Item 340 or QC/QA specifications were unsuccessful because the pavement distress ratings in the PMIS database were extremely inconsistent or the required data was not recorded.
- Much of the data required to compare relative performance of asphalt overlays placed using either Item 340 or QC/QA specifications are not available in the PMIS database but had to be obtained from other district records.
- TxDOT desires to have the ability to evaluate specification changes. Two measurement strategies were developed that have the potential to provide useful insight into the effects on HMA pavement quality resulting from changing the construction specification or any other factor that may affect pavement performance.

- The analysis programs or measurement strategies are versatile and can be used to compare other measures besides HMA performance from PMIS.

RECOMMENDATIONS

Based on the findings from this study, the researchers recommend that the following data be recorded in PMIS (or another automated database that interacts with PMIS) to accommodate pavement performance analyses:

- date(s) of pavement construction - required for comparative evaluations of performance as a function of time for pavements not constructed at the same time;
- periodic traffic loadings - required for comparative evaluations of performance as a function of traffic loads;
- layer data - can be used to compare pavement layer thicknesses and/or quality vs. performance, it is also needed to assess influence of substrate on performance observed at the surface;
- type of specification or special provisions used during construction - specification type cannot be evaluated unless it is known;
- level of severity of any distress measured or observed - this is needed to maximize the sensitivity of any pavement performance analysis;
- pavement design life - this will permit relative evaluation of pavement quality as a function of percent of design life (if design life of pavements is different, meaningful comparisons of performance must be related to design life);
- degree of raveling and flushing - these are important performance parameters which, alone, may be the cause for maintenance or rehabilitation;
- maintenance activities - without this unexplained improvements in pavement condition will appear in the database and confound any analysis attempts;

- data on failed pavements that have been covered by subsequent maintenance or rehabilitation - considering only uncovered pavements would eliminate many poor performing pavements that were covered early in their service life and thus skew any analysis toward the poorer performing specification as being the most favorable;
- HMA mixture parameters from quality control tests (e.g., density, asphalt content, gradation, voids in mineral aggregate, voids filled with asphalt) and target (or mixture design) values - this will assist in forensic analyses when trying to determine the source of a particular distress or performance issue; and
- identity of contractor(s) - construction quality is often associated with the expertise, equipment, and philosophy of the contractor.

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APPENDIX

Request for Information related to TxDOT Research Project 1877

Project 1877, "Analysis of the Effects of Construction Administration Changes to the Quality of HMAC Surface Courses," began about Dec. 1, 1998. The objective is to formulate and test a Measurement Strategy to compare differences in relative performance of similar surface course designs in which the only major difference is whether they were constructed using QC/QA or Item 340 specifications. The Measurement Strategy would be subsequently used by TxDOT to compare existing and future specifications. The Measurement Strategy will consist of the statistical process for comparing the performance of Item 340 and QC/QA pavements along with a pertinent database and appropriate normalization of the data (if necessary) to make valid comparisons in an automated format.

Rather than compare essentially all available Item 340 and QC/QA pavements, it appears most practical to select smaller sets of "paired" pavements from each district, collect the needed historical and performance data, and perform a detailed comparative analysis using the latest and most appropriate statistical methods. **A paired set of pavements is defined herein as an Item 340 pavement and a QC/QA pavement that have similar locations, substrates, thicknesses, mixture type, traffic, etc. but probably were constructed at different times.** This type of paired analysis would significantly reduce the required data set as well as minimize the effects of environmental factors such as substrate, traffic, and climate and thus provide the best opportunity to detect significant differences in performance.

Pavement quality will be evaluated by comparing pavement condition data (e.g., ride quality, rut depth, cracking severity, patching, etc.) versus time, useful service life as a function of design life, other factors, and combinations of factors. Pavement performance data will be obtained from the Department's PMIS database to the extent possible. Certain indispensable data is unavailable from PMIS database, (e.g., type of specification used, date of construction, project limits, design life, etc.) It will be necessary to request TxDOT district personnel to provide additional data to facilitate the analysis.

In order to determine the utility of this approach, a list of candidate pairs of projects, as defined above, is needed from each district. Acceptable paired sets of pavements would need to have enough performance data readily available in order to judge their relative performance. Please consider this in your response and supply the information requested on the following form. At this time, only the highway number, reference marker limits, date of construction of the section, and date of rehabilitation or reconstruction of the section is needed for each pair-associated section. This list will be screened later to determine which pairs have PMIS performance data available. Once the pairs without sufficient performance data are eliminated, the districts will be asked to help assemble the more detailed data required for each section.

Please identify the contact person in the district and how to get in touch with them. Please complete the attached form and send it to: Joe W. Button, P.E., Texas A&M University, Texas Transportation Institute, College Station, Texas 77843-3135 (or E-mail: J-Button@TAMU.EDU, Fax: 409/845-0278). If you have questions, call Button at 979/845-9965. Thank you.

Paired List of Candidate HMAC Projects for TxDOT Research Project 1877

Sect. #	Spec. Type 340 or QC/QA	Highway Name & Number	Beginning Reference Marker	Ending Reference Marker	Date of Initial Construction	Date of Rehab or Reconstruct
1(a)	340					
1(b)	QC/QA					
2(a)	340					
2(b)	QC/QA					
3(a)	340					
3(b)	QC/QA					
4(a)	340					
4(b)	QC/QA					
5(a)	340					
5(b)	QC/QA					
6(a)	340					
6(b)	QC/QA					
7(a)	340					
7(b)	QC/QA					
8(a)	340					
8(b)	QC/QA					
9(a)	340					
9(b)	QC/QA					
10(a)	340					
10(b)	QC/QA					
11(a)	340					
11(b)	QC/QA					
12(a)	340					
12(b)	QC/QA					
13(a)	340					
13(b)	QC/QA					
14(a)	340					
14(b)	QC/QA					
15(a)	340					
15(b)	QC/QA					

District Contact: **Name:** ______________________________

Phone: ______________________________

Fax: ______________________________

E-mail: ________________________________