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BASIC CONCEPTS, CURRENT PRACTICES, AND AVAILABLE RESOURCES FOR FORENSIC INVESTIGATIONS ON PAVEMENTS

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16. Abstract

The purpose of the project, entitled "Development of a Methodology for Identifying Pavement Design and Construction Data Needed to Support a Forensic Investigation," is to develop a database containing information useful in identifying the premature failure of pavements. The practice of forensic engineering is growing within the area of infrastructure management, as more and more areas become in need of repair or replacement. In terms of pavement facilities, the amount of money spent each year amounts to millions of dollars for new construction, maintenance, and rehabilitative efforts within the state of Texas alone. When a pavement's performance does not satisfy the criteria under which it was designed, whether it be in terms of reduced structural capacity, increased roughness, reduced surface friction, or any other possible number of unforeseen circumstances, a premature failure has resulted.

The creation of a forensic analysis system would provide forensic teams with easily accessible design, construction, and laboratory information for use to save time, should a forensic investigation need to be conducted on the project. It is also intended to provide managers with statewide graphics-based project information that can assist in the design process of a pavement. Information will be collected on all projects that a district constructs, as opposed to just the ones that undergo forensic investigations, so that a pavement that has failed can be compared to similar projects that are performing acceptably. This has the potential to help identify key elements of the failure as well as possibly predict potential pavement problems that could cause failure in the future.

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PROJECT ADVISORY COMMITTEE

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

The practice of forensic engineering within the field of infrastructure management has grown in response to the increasing number of facilities needing repair or replacement. In terms of pavement facilities, between $800 million and $1 billion is spent each year on new construction, maintenance, and rehabilitation efforts within the state of Texas alone. When a pavement deteriorates to a point where it no longer satisfies the criteria under which it was designed, whether it be in terms of reduced structural capacity, increased roughness, reduced surface friction, or other circumstances, premature failure may be involved.

Since the term *premature failure* may mean different things to different people, it is essential to clarify that not all premature failures constitute applicable situations for the work effort in this study. Pavement designers expect certain treatments to last a minimum amount of time. For example, a new continuously reinforced concrete pavement (CRCP) should last about 25 years or more before needing its first overlay; an asphalt concrete pavement (ACP) overlay should last 10 to 12 years; and a seal coat should last 5 to 8 years. Terminal serviceability may occur sooner (in years) than anticipated; but if the pavement has carried more traffic repetitions than specified in the design, this is not premature failure; rather, this constitutes a forecasting error (i.e., incorrectly forecasting the date when terminal serviceability would be reached).

The word *premature* implies that the actual number of years or traffic repetitions has fallen short of the anticipated design expectations. The term *failure* may imply more than just not satisfying the criteria under which the pavement was designed. Failure suggests that some event has occurred that affects the pavement's ability to perform its intended function of providing structural support for roadway traffic. Thus, pavement failure usually also requires some immediate, remedial action. An example of this distinction between definitions of failure is an interstate highway that was designed to function 8 years before its first overlay, but actually reached terminal serviceability in only 6 years. Although the design did not satisfy the criteria, the pavement could be viewed as not actually having failed because it could still carry traffic and did not necessarily require immediate remedial action to perform its intended function.

1.2 OBJECTIVES OF THE PROJECT

The purpose of this project, which got underway in September 1996, is to develop a database that contains information having the greatest applicability for identifying premature pavement failures. With such a database, the critical design, construction, and laboratory information would be easily and readily accessible for use should a forensic investigation be needed. This project addresses Tasks 8.1.2 and 8.1.3 of Goal 8 of the Long-range Research Plan of Research Management Committee 6.

For this effort, information on all projects constructed would be collected (as opposed to only those that undergo forensic investigations) so that a pavement that has failed can be compared with similar projects that are performing acceptably. This can potentially help identify key elements of the failure and can possibly predict potential pavement problems that could cause failure in the future. It is envisioned that the database would also be a repository for test section information that is too often lost or not presently shared. A geographic-information-system-based, computerized-forensic information and analysis system, ForenSys, is ultimately envisioned. The long-range vision for ForenSys is to provide district engineers and design engineers statewide with a graphics-based project information system for forensic analysis. Although ForenSys would initially be used by forensic team members and district pavement engineers, later versions will ultimately be used by district engineers as well. Such a system would allow others to benefit from the lessons learned. With all the information gained through the forensic investigation, it is envisioned that engineers will have better control over the crucial elements of their designs, and contractors will have better control over the crucial field factors, which together will create better, more reliable pavements.

1.3 SYSTEM CONSIDERATIONS

It should be stressed that the database needs to be both simple and flexible. Flexibility is important because it is envisioned that ForenSys will provide a means for storing all types of data—including video clips, digital photographs, memoranda, test data, and Excel graphs and charts—to support a forensic investigation. An important consideration is that the system should not greatly increase the workload of districts with regard to data collection (the expectation being that complex data collection systems will only impede implementation). Of course, enthusiasm at all levels of the department throughout the state is needed in order for the proposed system to be developed, implemented, and operated successfully. And what should be emphasized is the importance of a database in facilitating a timely forensic investigation. The researchers have considered and focused development of the ForenSys software based on TxDOT's current and future computer core architecture, so that the systems will be compatible.

1.4 MAJOR TASKS

The research approach adopted for this project has been divided into several major tasks, which are outlined in more detail in Figure 1.1.

1.4.1 Literature Review and Review of Past Work

As the first step in this overall effort, a comprehensive literature review was conducted in order to gather information on the current state of forensic engineering. While the primary focus was on pavement failures and analysis procedures used nationally and internationally, much material on general forensic practice was found as well. The procedure used to collect the information included library index searches using the Engineering Index (EI), Transportation Research Information Service Database (TRIS), and The University of Texas at Austin's on-line library catalog. Information was also gathered by the Federal Highway Administration (FHWA) regarding forensic efforts in other states.

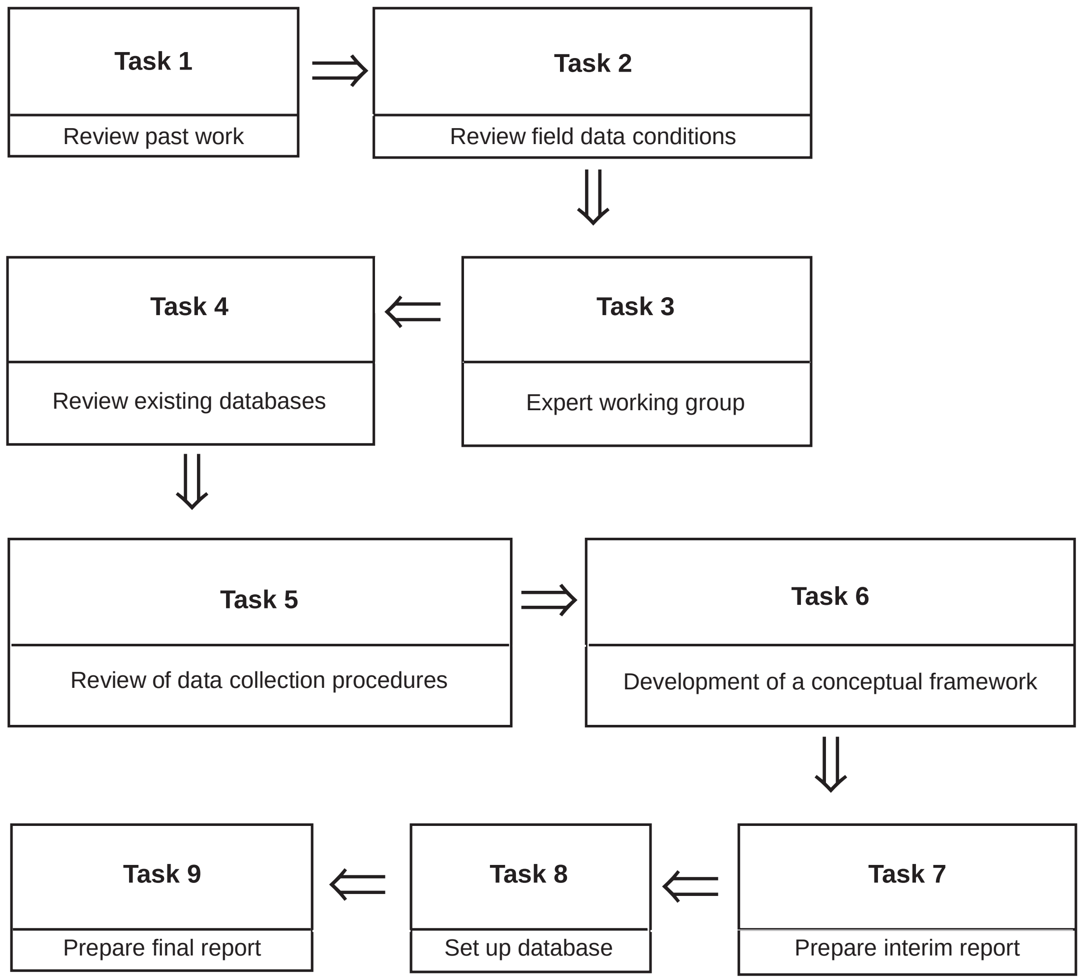

Figure 1.1 Official project tasks as outlined in the TxDOT project proposal

We reviewed design methods used by TxDOT for both flexible and rigid pavements in order to identify input into the design procedure (as such elements may prove to be critical in a pavement's performance). In addition to TxDOT Department Circular No. 19-93 that outlines forensic practices within the state, we reviewed several forensic reports prepared by TxDOT (obtained from the Design Division, Pavements Section) over the last several years. These were used to determine the general methodology that forensic investigations have followed in the past. Additionally, the types of data collected and tests performed were reviewed in order to identify information potentially useful in a forensic database.

1.4.2 Expert Working Group

A forensic expert task group meeting was held on December 12, 1996, at the Center for Transportation Research (CTR) in Austin, Texas. Members of the TxDOT Project Advisory Committee, as well as other knowledgeable individuals from academia and from the practicing pavement design community in TxDOT, gathered to provide valuable insight into important project issues. Some of these elements included the need to relate typical problems encountered in the field and the identification of critical design, construction, and materials information that would need to be stored in a database to support forensic investigations.

1.4.3 Review of Existing Databases and Data Collection Procedures

This project entails identifying the data items that should be collected, as well as justifying which items are reasonable to collect in case a forensic investigation should need to be performed. Factors to be considered in the final selection of data items for the database include how easily the item can be identified as well as that item's potential cost.

A review of existing TxDOT databases identified current data collection efforts within TxDOT. The TxDOT databases reviewed included the Pavement Management Information System (PMIS), Texas Reference Marker (TRM), Construction Management System (CMS), RoadLife, and the Maintenance Management Information System (MMIS). Research databases for the state of Texas were also reviewed, including the Flexible Pavement Database maintained by the Texas Transportation Institute (TTI) and the Rigid Pavement Database maintained by the Center for Transportation Research. Additional data collected by the department were reviewed in terms of their potential benefit to forensics. Such information included nondestructive testing and current record-keeping procedures.

1.4.4 Development of a Conceptual Framework

Work has been progressing on developing a conceptual framework illustrating the connections and flow of data between different parts of the forensic investigation system to various parts of the information system within TxDOT. Work will be completed once all the theoretical and practical details have been reviewed and properly compiled.

1.4.5 Establishment of Database

Once the conceptual format developed through previous project tasks (Phase 1) is approved, the next step is to move forward with the actual database set up (Phase 2). This task involves, first, the identification of the platform. Required next is the programming necessary to customize a suitable database from the Phase 1 concept. This involves either accessing and transferring data or setting up the necessary links in order to obtain the relevant data from the existing databases. A full administrative system may need to be implemented for additional data collection and storage; such a system will ensure that the database is maintained and populated with the data items critical for its successful operation. While many of the data items will be available from other sources, we expect that additional data will need to be collected. However, these additional collection efforts will be kept to an absolute minimum.

1.5 SCOPE AND ORGANIZATION OF REPORT

This chapter has presented the background, objectives, and basic research approach of the project. Chapters 2 and 3 introduce basic concepts of forensic engineering. Chapter 2, in particular, describes the procedures and steps required in conducting forensic engineering investigations. Focus is placed both on forensic investigations in general and on pavement investigations in particular. An overview of current forensic investigative practices is then presented in Chapter 3. There, more detailed discussion is given to current forensic investigative procedures practiced in Texas. Actual pavement forensic investigations that have been conducted in Texas and elsewhere are presented as examples.

Chapter 4 describes the expert task group meeting that identified key issues and concerns relevant to pavement forensic investigations. The main discussion items, comments made, and findings drawn from that meeting are presented.

In Chapter 5, we review some of TxDOT's existing databases. The databases are briefly discussed, and the approach used to compare the data items in these databases is explained. Finally, the results of the comparison are presented.

Chapter 6 discusses many of the possible data sources available within TxDOT for the forensics database. This work was conducted in an attempt to understand what types of data the department currently collects and in what formats. It is crucial that redundant efforts not waste time, money, or manpower, and that all existing data sources are fully utilized.

The need for identifying critical data items and the approach used to identify the critical data items are presented in Chapter 7. The critical data items for the forensic database identified to date are also presented.

Chapter 8 discusses the conceptual framework for the forensic database. Here, major components of the database framework are explained in detail. This chapter also discusses the advantages of using a GIS-based database system. Chapter 9 summarizes the research accomplished to date and discusses the future directions of the project.

CHAPTER 2. BASIC CONCEPTS AND PRINCIPLES OF FORENSICS ANALYSIS

2.1 FORENSIC ENGINEERING

A report prepared for the American Society of Civil Engineers (ASCE 86) defines forensic engineering as "the application of the engineering sciences to the investigation of failures or other performance problems." As this definition indicates, a failure is not necessarily a catastrophic event, such as the collapse of a building; rather, failure is said to occur when a structure does not perform as was originally intended. For pavements, a repairable failure is not considered catastrophic, though any failure that requires the total replacement of a pavement *might* be considered catastrophic. Other performance issues could include chronic pavement problems that a district is unable to address, including those associated with thermal cracking of an ACP surface layer or shrinkage cracking of treated base layers. While such performance problems may not cause failure in a pavement, they require attention insofar as they degrade overall pavement performance.

Forensic engineering has become increasingly important in recent years, given that the repair and replacement of a deteriorating infrastructure often depends on the skills and knowledge of forensic experts. Forensic engineering can be compared to forensic medicine in that forensic engineering identifies any departure from *healthy* values, which indicates that pavements are "ill" or not fully functional. "However, the same symptoms can indicate different 'illnesses' and demand different cures" (Metcalf 92). Forensic engineering attempts to find such cures and to uncover the causes of failures so that improved facilities can be engineered. Additional issues described in the ASCE report that are applicable to this study are described in the following paragraphs.

A forensic engineer is defined by the ASCE report as an acknowledged expert in the field who investigates construction-related failures and who claims and subsequently determines causation and, in some cases, responsibility. This definition should be expanded so that it does not imply that failures can occur only as a result of construction-related causes. The definition must also include failures that are ultimately the result of design problems or insufficient preliminary field testing. To be considered an expert in a field, an engineer must be thoroughly familiar with the nature and type of engineered facility being investigated, including design, materials, construction techniques, operations of the facility, building codes, test methods, contractual arrangements, and the economics of construction.

It is the responsibility of the forensic engineer to determine the cause of the failure. In order to do this the forensic engineer must extensively review all documents that were developed throughout the course of the project. Such documents include, but are not limited to, contract documents, the design analysis, construction change orders, engineering reports, correspondence, job memoranda, daily field reports, job progress photographs, and photographs taken at the time of failure.

According to the ASCE report, a forensic engineer seeking to develop an intuitive understanding of systems—how they actually behave and why they fail—must acquire capabilities in reasoning and analysis that go beyond building codes, specifications, and the simplistic models of engineering behavior used for design. However, reliance on past experience too early in the investigation is a common error a forensic engineer makes when trying to determine the probable cause of failure. Past experience is beneficial when it aids the investigator in recognizing failure symptoms, but not when it involves preconceptions that narrow the investigator's search.

For some failures, the forensic engineer must determine responsibility as well as causation. In order to properly address each situation, TxDOT forensic teams must determine if the failure is related to design, construction, materials or maintenance, or to some combination of these factors. A forensic team may be called on to identify whether TxDOT or the contractor is to blame for premature failure, and whether poor judgment, negligence, or unforeseen circumstances were involved. In more than one instance in the past, it was determined that the contractor had used improper construction procedures or used materials different from those specified in the plans, in which case the contractor was required to repair the failures at his expense.

In order for engineers to benefit from the experience of others, information of a forensic nature should be made available. Information such as case studies, errors in methods or procedures, and the types of a certain distress all provide necessary details that should be made available through some sort of information network. Fortunately, forensic engineers have begun to take an active role in coordinating the dissemination of information resulting from failure investigations, so that design and construction procedures might be improved. This, of course, is the motivation behind the current project.

A forensic investigation is the process by which the forensic engineering team gathers the necessary information to form the probable cause of the failure that has occurred. There is a methodology for investigative procedures that can be used when determining the cause of failure. The guidelines were developed to address a number of failures, ranging from serviceability problems to catastrophic failures to distressed structures that endanger lives. A thorough investigation must consider every aspect. There seldom can be a single cause of failure because failure is usually attributable to an interaction of components rather than to a single factor. Because the exact cause of failure is not always clear cut, conflicting opinions as to the true cause often exist, which leads to only the most probable cause being reported.

The tasks that comprise the critical steps of the investigative plan are as follows:

1) Planning the Investigation: The investigation should begin with the development of a logical investigative plan and establishment of project goals.
2) Client Interface/Project Schedule/Budget: Once the investigative plan has been decided upon, a conference with the client should be held to inform the client of the scope of the work required. The scope of work should be outlined in the form of a written proposal, though it should be made clear to the client that the scope of the investigation may change as the case builds and as new facts are discovered.
3) Identification of the Investigative Team: Often it is necessary to retain professional experts from other engineering disciplines so that each aspect of a

failure can be thoroughly investigated and understood. For example, the team could include photography and video experts.

4) Operations Planning: The forensic engineer who is the principal investigator is ultimately the one in charge of coordinating, analyzing, and integrating the work product of all the team members. Periodic meetings should be held in which intermediate results are reviewed, failure hypotheses discussed, and the investigative plan adjusted as needed.

5) Site Observations and Analysis: The goals of site visits are to conduct an overall visual examination, collect graphic and narrative records, obtain eyewitness accounts (if relevant), and perform testing programs (ASCE 86). The initial site visit is undertaken to evaluate the scope and nature of the failure in order craft an appropriate investigative plan. If possible, it is desirable that debris not be removed until the investigators have had an opportunity to photograph and study the debris in place, and to collect the necessary data and specimens (ASCE 86). As debris is removed to be stored in a protected environment where these materials can be tested, significant data, such as the orientation, should be recorded. An organized compilation of graphic and narrative records, such as sketches, verbal descriptions, photographs, and field notes, should be made so that information is easier to find and recall years later, and because such information may become evidence in a legal proceeding.

6) Document Search: This includes the acquisition and review of all available documents relating to the design and construction of the facility. These documents can include contract design drawings, as-built drawings, contract specifications, contract provisions, shop drawings, testing laboratory reports, field reports, inspection reports, field notes, project schedules, project correspondence, consultant reports (e.g., traffic and geotechnical studies), design analyses (e.g., calculations and studies prepared), and weather records. The condition and use of the facility at the time of failure, relative to maintenance and changes made, should be determined.

7) Literature Search: The collection and review of published works relating to the failure provides background data and assists in developing failure hypotheses.

8) Investigative Synthesis: As all of the above documents and results are collected it becomes necessary to synthesize the findings. A historical description, review of site and service conditions, and review of all the other documents must be made.

9) Development of Hypotheses: Based on the type of failure and the distresses observed, a checklist of possible causes can be compiled.

10) Test Hypotheses: Using the available information regarding this project, such as the results of the testing performed, each hypothesis is tested. The results of the tests used to justify or negate the hypotheses can be outlined in a matrix format, with the tests listed in the first column and the hypotheses listed across the top row. Symbols representing the types of results can then be filled in the

appropriate cells to show if the data support or negate each. This approach is a scientific way of expressing the test results in terms of which hypotheses they support and which ones they invalidate, so that nothing is overlooked.

11) Establish Most Probable Cause: After synthesizing all the information, the failure can be classified with respect to type and time, and a probable cause of the failure can be established.

It can clearly be seen that a comprehensive database as proposed in this research can greatly help accomplish the forensic investigation tasks outlined above.

2.2 FORENSIC METHODOLOGY FOR PAVEMENTS

A forensic investigation methodology compiled specifically for portland cement concrete (PCC) pavements was described by O'Kon (O'Kon 92). The methodology was developed for concrete pavements used on highways, airfields, parking lots, and on heavy-traffic areas around warehouses. The method follows the general methodology described earlier, with a few exceptions, and includes points specifically relating to pavements that are discussed below. Although this article discussed only concrete pavements, a similar methodology could be extended to include asphalt pavements.

Regarding the testing program of a pavement structure, O'Kon states: "The goals of the testing program include acquisition of data relative to material quality, workmanship, unstable materials, and exposure to deleterious substances or excessive wear. The testing program could include physical and chemical tests on materials of construction as well as other tests including electronics methods" (O'Kon 92). Tests for load-bearing capacity and durability are useful in determining the cause of some of the distress manifestation, and thus should also be considered in forensic investigations.

Typically some of the testing has to be conducted in the field, though the majority of the testing on samples obtained in the field is performed in the laboratory. In terms of soil tests, field testing shows in situ characteristics of the materials, thus providing a unique look at the interactions of the sample with its surroundings, which would otherwise be disturbed if the sample were extracted from the pavement and the ground below. In situ characteristics such as confining characteristics, moisture content, and suction values are more representative when comparing field and lab tests. Samples and borings should also be made by firms knowledgeable in geotechnical issues in order to evaluate the subgrade of the pavement.

There are three main field tests relating to concrete components. The first is the Swiss hammer, which provides an indication of the strength of the concrete. The second is ground penetrating radar, which is used to evaluate the density and location of voids in concrete and the quality of the subsurface as determined by the location of water and voids. The third is x-ray testing, which is used to determine the size and amount of reinforcing, the depth of the reinforcement of the concrete, and the quality of the concrete.

Commonly performed laboratory tests on concrete include moisture content tests, compressive strength tests, long-term creep tests, petrographic studies, long-term shrinkage/expansion tests, split tensile strength tests, aggregate matrix microcracking, air-content tests, and modulus of elasticity tests. Coring is an efficient way to determine the quality of concrete, type of base, and actual depths of layers through laboratory tests.

Several remedial measures have been developed for repairing and/or strengthening a failed pavement. One of the rehabilitative measures for PCC is the use of pavement overlays, which involves bonding new surfaces to the existing materials in order to take advantage of the structural capacity that the pavement still provides. An example of such a solution would be a fiber-reinforced concrete topping. If the pavement failure is a loss of structural capacity as a result of failed or weak subgrades, grouting can restore continuous support. Replacement of distressed elements, such as by removing and patching certain sections, may be required for other types of failures.

Table 2.1 presents the different types of distresses that are typically associated with a concrete pavement. It is important that forensic engineers be able to determine why and how certain types of distresses typically occur, so that in the analysis process, these scenarios can be effectively compared with what actually exists in the field. These different types of defects can be identified through a variety of methods. The majority of surface defects, joint defects, and some types of cracking can be evaluated by visual examination. Structural defects and some cases of cracking in the pavement require field and laboratory testing (O'Kon 92).

The design of a flexible pavement is influenced by the amount and character of the expected traffic, the subgrade strength properties, paving material properties, and the environment in which the pavement is to perform. Flexible pavements fail in two basic modes: (1) distortion (rutting, shoving, and corrugations), and (2) cracking (alligator, longitudinal, transverse, and block cracking) (TxDOT 93). The general failure areas in a typical flexible pavement include tensile stress failure of semirigid pavement layers, shear failures of surface and base courses, and compressive failures of the subgrade. Table 2.2 presents some of the different types of distresses that typically occur within a flexible pavement (Porter 94). Other typical flexible pavement distresses include block cracking, transverse cracking, longitudinal cracking, lateral shear failure, flushing or bleeding, and layer debonding.

Table 2.1 Different types of distresses on rigid pavements (O'Kon 92)

	Types of Distress	Description of Distress
Surface Defects	Delamination	Separation of surface layer from pavement.
	Polishing	Polished appearance owing to glazing of coarse aggregate.
	Aggregate Pop-outs	Breaking away of small portions of pavement surface owing to internal pressure.
	Spall	Flaking, fragmenting, or chipping of surface by impact, weather, or chemical attack.
	Scaling	Local flaking or peeling of mortar off the concrete surface.
	Cracking	Fine hairline cracks at the surface layer.
	Wheel Track Wear	Wearing of surface in wheel tracks.
Structural Defects	Faulting	Differential vertical displacement of abutting slabs.
	Settling	Displacement of pavement owing to displacement of subgrade.
	Pumping	The ejection of water or solid materials along joints or cracks in the pavement.
Joint Defects	Joint Creeping	Lateral movement of transverse joints.
	Joint Seal Loss	Joint seal squeezed or pulled out of the joint.
	Joint Sealant Bond Loss	Gap between joint and sealer and concrete.
	Joint Sealant Cohesion Failure	Rupture or crack in joint sealer.
	Joint Sealer Extruded	Removal of sealant from joint.
	Joint Separation	Widening of longitudinal joint between lane shoulder.
	Lane/Shoulder Drop-Off or Heave	Difference in elevation between the lane and shoulder in two adjacent lanes.
	Joint or Crack Spalling	Chipping or breaking of the slab edge at joints.
	Joint Failure	Severe breakdown of slab adjacent to transverse joint owing to volumetric change or subgrade failure.
Cracks	Longitudinal Cracks	Generally straight parallel to center line.
	Meandering Cracks	Serpentine cracks along the transverse joints.
	Corner Cracks	Cracks forming a triangle at edge of joint/pavement.
	D Cracking	Cracks paralleling edges and joints near corners.
	Transverse Cracks (single or multiple)	Cracks at right angles to center line.
	Diagonal Cracks	Angular cracks in pavement.
	Edge Cracks	Cracks extending from transverse joint to pavement edge.
	Punchout	Localized failure that breaks pavement into pieces. This is caused by closely spaced transverse cracks connected by longitudinal cracks.
	Map Cracking	Interconnected cracks forming network.
	Plastic Shrinkage Cracks	Shrinkage of concrete owing to a differential volume change in the plastic concrete that occurs when the moisture evaporates from the surface of freshly placed concrete faster than it is replaced by bleed water.
	Cracks Near Dowels	Cracks at transverse joint owing to local transfer.
Chemical Reactions	Alkali-Carbonate	Reaction between alkali, cement, and aggregate that results in random cracking.
	Alkali-Silica	Reaction between alkali, cement, and aggregate.

Table 2.2 Matrix of possible distresses and pavement type for flexible pavements

Distress	**Pavement Type**		
	Full-Depth Asphalt	Full-Depth Asphalt on Stabilized Subgrade	Full-Depth Asphalt and Open-Graded Asphalt
Roughness	X	x	x
Rutting	X	X	x
Alligator Cracking	X	X	x
Corrugations	X	X	x
Depressions	X	X	x
Raveling			x
Asphalt Concrete Stripping			x
Loss of Skid Resistance	X	X	

CHAPTER 3. REVIEW OF CURRENT PRACTICES

3.1 BACKGROUND

As the first step in the research, a comprehensive literature review was conducted in order to gather information on forensic engineering, with a focus on pavement failures and analysis procedures used nationally and internationally. This chapter presents an overview of these current forensics investigation practices. It covers the practices in Texas and in other states, with the more detailed discussion devoted to current forensic investigations in Texas.

Forensic investigation reports prepared by TxDOT over the last 6 years, along with the TxDOT Department Circular #19-93 that outlines forensic practices within the state, were obtained from TxDOT's Pavement Design Division. These were reviewed to determine the general methodology that forensic investigations have used in the past. Additionally, the types of data collected and tests performed were evaluated in order to determine common trends of information potentially useful to a forensic database.

3.2 CURRENT DEVELOPMENT OF PAVEMENT FORENSIC ENGINEERING AND RELATED ANALYSIS PROCEDURES

Part of the review of past work was aimed at finding information on the current state of forensic engineering and any existing forensic databases that are related to pavements. TxDOT currently conducts forensic engineering investigations on a case-by-case basis; that is, the agency does not have a formal procedure for conducting such an investigation because of the many variables involved. The procedures that do exist pertain to the arrangement of a forensic investigation to be conducted. In an attempt to learn more about the current status of forensic investigations within other states, the Austin Division of the Federal Highway Administration (FHWA) sent out an e-mail questionnaire to each division to determine the current status of forensic investigations within other states. Based on the responses, it was determined that the effort to develop a forensic analysis system is truly unique. It appears that while other states may have forensic activity practices, these are also conducted on a case-by-case basis, without the benefit of either a formal method or a database. Therefore, based on the information collected so far, it seems that the methodology for forensic engineering has not been well developed or implemented. It is anticipated that this project will be the first to develop a rational forensic methodology for pavement engineering.

Another area examined was procedures used for forensic analyses. Case studies of forensic investigations, both nationally and internationally, were reviewed to determine what kinds of information have been reported, and to determine the process through which conclusions have been made by the investigators. A review of case studies collected from other sources was important insofar as the studies presented different situations and methodologies used by other investigators.

These reports are presented on a case-by-case basis in order to maintain clarity of the important issues that were considered for each investigation. These cases provide good examples of the issues raised, and represent the broad range of factors considered in each investigation. One of the issues presented was that forensic engineering must deal with both new and rehabilitated pavements. Premature failure does not necessarily result from poor materials or workmanship, but can result from many other issues.

Case 1: Investigation of Postconstruction Failure of a Lightly Trafficked Road in Ghana (Attoh-Okine 92)

This article discussed an investigation that was undertaken to determine the cause of pavement failure of a major two-lane, low-volume road only 2 years after it had been constructed. The failure included excessive pavement distress in the form of settlement, cracking, differential subsidence, and outer-wheel path ruts. The study consisted of four parts: (1) desk studies of contract specifications and standards, (2) review of documentation of materials evaluations made during the project, (3) interviews with actual workers on the project, and (4) testing both in the laboratory and the field to evaluate the materials used.

First, a review of the contract specifications and standards identified the known data elements. Included were the following: an estimation of the daily traffic in vehicle standard axles for design purposes; CBR (California bearing ratio) value for the subgrade, subbase, and base materials; liquid limit (LL) for base material; plasticity index (PI) limits for base material; soaked CBR; maximum dry density; and grading limits in terms of the maximum particle size and percentage of fines. A review was made of the construction sequencing to see what impact such details may have had.

A general field survey and the field testing were undertaken next. Testing was done at three to six test locations every 10 km along the roadway and were specifically chosen to represent different types of distresses. A summary table of the pavement conditions at different stations was organized to track the exact station and the pavement conditions at that location (good, settlement, sides eroded, no settlement, etc.), as well as to assess the original land (whether the roadway was a cut, fill, embankment, riverbank, etc.). The field tests performed included the moisture content, analysis of field density using the sand replacement method to obtain comparative indicators of pavement strength at different locations, and the CBR. The field tests also allowed an examination of the actual layer thicknesses and determination of layer content. Atterberg limit tests, Proctor tests, a CBR test, and a classification test were performed on samples from the test hole. Other soil parameters that were considered included the field density, relative compaction, field moisture content, and optimum moisture content. Soil test results obtained during the investigation were compared with those documented by the contractor during construction.

It was revealed that this failure was caused partly by a lack of specialized geotechnical tests to determine reliable input parameters, and partly by poor construction practices for placing geosynthetics used on the project.

Case 2: Forensic Evaluation of the Cement-treated Base Failure on SH 36 in Houston, Texas (Bredenkamp and Scullion 95)

The cement-treated base (CTB) on SH 36 experienced rapid deterioration after only 3 years in service. The report presented the field and lab studies undertaken to identify the cause of the roadway's failure. The road had been constructed with an asphalt surface over two different layers of CTB.

The initial information determined about the failure was the thickness and structure (types of materials) of each layer and the average daily traffic (ADT), which was converted to a design 20-year number of 80 kN loads. It was apparent through visual inspection that pumping had occurred. The next information obtained was the type of distress. In this case, the distress involved transverse cracking and transverse depressions in the wheel paths. The frequency of occurrence (spacing), width, and depth of distress were also recorded.

Additional information important to a forensic investigation includes where the distress initially started, the characteristics of the initial distress, and the extent of the distress. Also, it should be determined whether the ride quality has been reduced. The initial hypothesis in the investigation was that the failure was a result of simple deterioration under wheel load. However, it was realized that other factors were involved in the deterioration that occurred throughout the upper CTB layer, after test results negated the original hypothesis. Therefore, additional tests were performed to find out more information. An analysis using ground penetrating radar showed that samples taken from badly distressed areas experienced changes in the moisture content and density of the top CTB layer. Specifically, there was a higher-than-normal level of moisture present. Laboratory analysis of the base material, which included a sieve and hydrometer analysis and an x-ray diffraction analysis of the clay layer, determined that the clay was an expansive type. (Expansion of these clays upon wetting could develop internal forces that can initiate or accelerate deterioration.)

Next, a test showed that the thermal coefficient of linear expansion of the two cement-treated base layers was substantially different. The measure was off by a factor of 2, which suggested that the materials had very different shrinkage and thermal expansion properties. A soak test determined that the suction properties of the cement-treated base absorbed water at a much greater rate than did sound soil samples. Also noted were signs of carbonation taking place, which is the process by which calcium hydroxide is lost from the cement matrix. Carbonation can lead to strength loss and layer disintegration.

The results of the investigation were as follows: The main cause of failure was carbonation, in which the calcium hydroxide was converted to calcium carbonate in the cement matrix, severely lowering the stabilized layer's strength. A second contributing factor was the substantial clay content that existed within the upper layer of the base, which caused high suction levels and thereby increased moisture levels within the CTB. A third factor was the pavement design, which placed together CTBs made of different aggregates that had substantially different shrinkage and thermal expansion properties, resulting in debonding of the layers.

Case 3:   Forensic Pavement Analysis (De Nicholas 90)

This report categorized the ability to assess the extent of heavy vehicle traffic on the state roadway system as essential to the pavement design process. Previous load data from standard loadometer tests may have been only rough estimates of the values, as more heavy traffic occurred at night, and overloaded vehicles may have taken alternate routes to avoid penalties. Thus, it was determined that it is more desirable to have more frequent data, and data from more points in order to more accurately assess the traffic mix, volumes and loads on the system. Such an endeavor requires large amounts of data collected over the entire system over full 24-hour time periods. The purpose of this study was to use portable Weigh-In-Motion (WIM) systems to collect sample truck data throughout Arizona in place of standard loadometer testing, in order to provide a large quantity of useful data for input into the pavement design process. The types of traffic data that were collected included speed, vehicle classification, axle spacing, length, axle weights, and gross weight with respect to time and date. It was concluded that an important consideration for pavement design purposes is average truck weight by route.

Case 4: Use of Microsurfacing in Highway Pavements (Smith et al. 94)

Microsurfacing is a complex of polymer-modified emulsified asphalt cement, crushed mineral aggregate, mineral filler, water, and other additives. It is normally used as a maintenance or surface treatment for an existing pavement that has an asphalt surface. It can be used for both preventative and corrective maintenance—primarily, for restoring skid resistance, filling ruts to restore transverse surface profile, and repairing weathering and raveling. However, there are cases, such as when the primary problem is cracking, when microsurfacing should not be used because the material is not strong enough to prevent the cracking from reflecting through relatively quickly. Microsurfacing mixtures that are applied in Texas should generally provide five to seven years' life if they are applied to pavements in the appropriate condition and in the correct manner. The skill of the crews operating the equipment is critical to obtaining a good final product. If microsurfacing lasts through construction and the first severe environmental cycle, then it typically will last for the desired five to seven years, which makes it easier to apply an end-result warranty to this type of material (compared with others). Many different factors, such as residual asphalt content, amount of mineral filler, specific conditions such as the presence of cracking, use of rut filling versus scratch course, traffic levels, and different surface conditions and the presence of fibers, affect the performance of the micro-surfacing. For the most part, the majority of problems dealing with materials, construction, or workmanship appear during construction.

A method of completing a forensic analysis of early failures of this material pertained to postconstruction problems was also summarized.. Typical issues that were considered in a forensic investigation of this material are described below in further detail.

1) Surface Loss/Delamination: This problem typically occurs some months after construction. The surface should be evaluated to determine where it is separating from the underlying pavement. If the surface loss occurs within the underlying pavement, the next step is to determine if the stripping is developing in the underlying asphalt concrete. If the delamination occurs between the underlying pavement and the microsurfacing, the next step is to determine if the underlying pavement is causing the problem, which may be a sign of structural inadequacy. If the pavement had substantial cracking in the wheel path prior to microsurfacing, there probably will be considerable vertical deflection in the wheel path if the flexure is too large for the treatment to withstand. Cores can be

taken to determine layer thicknesses and to determine the integrity of the existing pavement layers. The falling weight deflectometer can be used to determine the integrity of the existing pavement layers. An investigation of the existing conditions prior to treatment should be made by reviewing records such as TxDOT PMIS.

2) Rutting: This type of distress is a sign of problems in the existing pavement. If the ruts are caused by an unstable pavement layer material or structurally deficient pavement, the source of the rutting problem is not corrected by the microsurfacing treatment, and thus, the problems will return soon. The first step of this type of forensic investigation requires determining how long the original pavement was in use before rutting occurred, and determining the extent of the rutting. If the original surface was in use for many years and had only shallow rutting, the rutting was probably caused by consolidation within the lower pavement layers, and filling with microsurfacing should be all right. However, if the pavement was only in use for a short time before deep ruts developed, the pavement most likely had an unstable surface layer, and filling with microsurfacing would probably last only two to three years. If the existing pavement had significant alligator or other cracking in the wheel paths, then the pavement probably did not have adequate structural strength to prevent consolidation and possibly even shear failures in the subgrade. Cores can be taken both in the wheel path and in-between, and then tested for creep and structural characteristics to determine if the microsurfacing mixture was adequately stable. An investigation of the existing conditions prior to treatment should be made by reviewing records such as TxDOT PMIS.

3) Raveling: This type of failure occurs because of inadequate asphalt content or problems with aggregate segregation. The location and distribution of the raveling must be determined. If the raveling is widespread and covers the entire width of the affected lane, then low asphalt content is probably to blame. An extraction of several samples of the mixture should be completed to determine the residual asphalt content. If the raveling occurs sporadically, then segregation or construction problems are probably to blame. The application equipment or operator may have not kept a constant level of emulsion in the mixture. Segregation of aggregate and possibly different amounts of asphalt cement may have developed resulting in raveling along the edges of the application lanes. Extractions should be completed of several samples of the mixture both in and out of the raveled areas to determine the residual asphalt content.

3.3 FORENSIC ENGINEERING INVESTIGATIONS WITHIN TxDOT

The next step in reviewing procedures used for forensic investigations was to look at forensic investigative reports from TxDOT. The current TxDOT practice for pavement forensic investigations was reviewed through written documents and contact with individuals who worked on actual investigations. Materials, such as final reports including laboratory results and photographs, were also collected on various projects that had undergone official forensic investigations through the TxDOT Pavement Forensics Team within the past six years.

In July 1993, TxDOT issued "Administrative Circular No. 19-93" to district engineers and division directors. The purpose of this document was to establish procedures for requesting assistance from the Pavement Forensics Team and to document the responsibilities of the parties involved in such an investigation. As the document states, the Pavement Forensics Team was established "to provide technical assistance to the districts and divisions to determine the causes of, and recommend solutions to, premature pavement failures or chronic pavement distresses (TxDOT [2] 93)." In order to request that an investigation be conducted, the requesting division or district needs to send a memorandum to the Director of the Division of Highway Design. The memorandum should include such detailed information as:

1) the pavement history
2) the pavement structure
3) materials information
4) traffic information
5) description of the predominant distress or failure modes
6) construction records relevant to the problem
7) weather condition records
8) soil and geologic information.

If the request is granted, a project leader and other team members are assigned. This team then conducts a preliminary project meeting and performs an on-site investigation. From the information collected, an action plan is developed that includes details for materials sampling and testing. Final reports are produced after the data are analyzed and a most-likely cause of the problem determined. Once the investigation has been completed and any necessary rehabilitation steps taken, it is the responsibility of the requesting district or division to subsequently monitor the project in order to provide data to assess effectiveness. At the end of the pavement service life, a final analysis report of the performance should be produced by the district or division coordinator in order to further ascertain the effectiveness of the selected strategy for pavement improvement.

The reasoning behind conducting a formal investigation is that "forensic engineering can answer questions that may save a district money and headaches by identifying the source of a problem before various different repairs and rehabilitations are tried (Jones 91)." One important function that the forensics team has had, in addition to determining the causes, is to provide possible solutions for rehabilitation so that the problem can be fixed in the most effective manner. Another important reason for conducting a forensic investigation is to "identify, document and communicate causes of premature pavement failures so that they may be avoided in the future (TxDOT [2] 93)." It is only when all districts have improved information sources and actual field examples to refer to that they will be able to improve their problem-solving and design capabilities.

3.3.1 General Approach for a TxDOT Forensic Investigation

Through studying the reports obtained for previous forensic investigations, it can be seen that some common steps and procedures do exist in the methodology for conducting the investigations. Some of these common procedures are explained in the TxDOT administrative circular previously discussed, while others may be unique to certain projects. Only when certain details are uncovered in the investigative process, can the search be narrowed down. Extra samples or tests may provide information that is relevant only to a specific condition on a specific project. These different elements have been organized into a logical approach for conducting a forensic investigation, which is outlined as follows. Appendix B illustrates the frequency with which some of the tests discussed in the following sections have been used in actual forensic investigations.

1) Preliminary Meeting: An initial meeting is usually arranged between the coordinator of the project and the investigative team. The purpose of the preliminary meeting is to review the facts of the case and become familiar with specifics of the local area and project location.
2) Interviews. Interview with people familiar with the project under investigation usually can provide valuable information, such as their own professional opinion or facts that might not have been significant enough to report. Interviews generally have been arranged with the district construction engineer, the project engineer, the laboratory supervisor, and the project inspector.
3) Onsite Investigation. This is typically done by forensic team members in order to determine the condition of the existing pavement and obtain some firsthand visual information from which further analyses can be done. This allows the forensic team to be able to set up an effective test strategy that includes such details as the tests to be performed and the number of samples to be taken. The onsite investigation also gives the investigative team additional support in developing alternate rehabilitation strategies by considering the existing local conditions and restrictions that will influence the final decision.
4) Review of Project Records. Much of this recorded information may have been included in the original memorandum sent to the Pavement Forensics Team. It could include typical sections of the pavement structure, details on the pavement history (such as the date of initial construction; any rehabilitations, such as overlays; any reconstructions, such as widenings; etc.), the pavement materials information, a description of the predominant distress or failure modes, and any construction records relevant to the problem.

   Soil and geological records are important because the predominant soil types along the section of the project under investigation can be determined from an analysis of such records as the Soil Conservation Service Soil Survey. Core logs that are collected for bridge or retaining-wall foundation design purposes are very useful in providing information about subsurface soil and geologic conditions.

The results from earlier TxDOT geotechnical evaluations, such as Potential Vertical Rise of the soil, are also valuable reference data. They can indicate whether the design adequately compensated for the assumptions that were made, and whether the assumptions that were made are actually what occurred. They can also be used as a framework for interpreting the falling weight deflectometer and Dynaflect data. Such soil condition information provides insight for an analysis of the support strength of the subgrade. The subgrade soil study, along with environmental data, also provides information of the effects of the temperature and moisture on the specific soil types present.

Both historical data and future projections of traffic volume should be obtained from the Transportation Planning and Programming (TP&P) Division.

Temperature data, such as the average number of days with temperatures at or below 32°F (freezing), are important. It is also valuable to obtain the average number of days in a year at or above 90°F so that the typical fluctuations and stresses that a pavement must undergo are documented. Weather condition records such as the typical seasonal moisture patterns, may provide information regarding moisture damage.

It is important to keep track of damage that has occurred to the pavement as well. For example, a pavement may be damaged during snow removal efforts, which may lead to cracks or other structural failures depending on the nature and the severity of the occurrence.

5) Detailed Condition Survey. The testing procedure typically consists of several tests, which may include some of the following:

   a) Detailed Visual Evaluation

   b) Falling Weight Deflectometer (FWD). The falling weight deflectometer provides deflection measurements taken at seven different sensor locations. From these measured deflections moduli values can be back-calculated for the different layers that are present (e.g., for the surface, base, subbase, or subgrade). MODULUS is a typical computer program that is used for the back-calculation procedure. When the moduli values are generated, they can be plotted on the axis of station versus elastic modulus. This average data can be compared with typical modulus values that should result for the layer in order to determine its relative strength. These plots can also indicate the variability of the data and show weak points that exist within the layer. The actual sensor readings can be plotted on the axis of station versus sensor reading, and an average line can be drawn through the data. Certain known ranges of values can be drawn on the plot to show relatively weak, moderately strong, or relatively strong ranges, in order to indicate the relative strength at a certain location of the project. The layer strengths as determined by the FWD can be input into the Flexible Pavement Design Program to evaluate the pavement's structural capacity (TxDOT FPS -

Version 19). It is important to note that the FWD analysis indicates only the stiffness of a material in-place and does not give much information regarding the durability of a material, nor of the quality of other materials, such as aggregates. Thus, if the FWD values indicate that the material meets the minimum design considerations and thus does not cause the distress, additional tests should be made on the material quality and durability. Such additional tests may include soundness testing or Wet Ball Mill testing for an aggregate base. Another limitation of FWD testing is that the moduli for pavement layers less than three inches thick cannot be back-calculated accurately. Since many pavements in Texas have surface layers thinner than three inches, the ACP surface layer modulus is usually estimated by the analyst and fixed during the back-calculation process. The estimated modulus is based on knowledge about the relationship between ACP modulus and pavement temperature. This method, however, does not take into account potential problems, such as the reduction in modulus due to cracking or stripping of an existing ACP surface layer (among others), so the estimate can be inaccurate.

c) Dynaflect. The Dynaflect provides deflection measurements. The stiffness coefficients for each of the layers can be calculated based on the deflection data. These stiffness coefficients characterize the material strengths of the pavement layers and are used in the TxDOT Flexible Pavement Design equation (FPS - Version 11).

d) Dynamic Cone Penetration Tests. This test could be used to perform a subgrade evaluation. This test works on the principle that the rate of penetration is a function of the strength (stiffness) of each layer. The hammer is dropped from a fixed drop height, and the penetration of the cone in each layer is recorded. The DCP is also useful for determining pavement layer thickness, although it requires a lot of work to produce the results.

e) Ground Penetrating Radar (GPR). GPR can be used to perform a thickness survey of the existing pavement, and to provide certain information about the properties of the materials. One benefit of this testing equipment is that it can be performed at highway speeds so that no traffic control is needed. This test works by sending pulses of electromagnetic energy into the pavement and capturing the reflected energy from each layer interface. A plot is made of the time of arrival of the reflected incident wave versus the return voltage, since part of the incident wave may be transmitted at the layer interface instead of being reflected. Amplitudes and time delays between peaks are then used to estimate layer properties and thicknesses. The size of the reflected signal is a function of the dielectric properties of the pavement layers, which is strongly related to the moisture content of the layer. GPR data analysis can be used to determine only the presence of moisture, not moisture content.

f) TxDOT Profilometer. Using this piece of equipment, a roughness evaluation for the pavement can be completed.

g) Determination of the presence and location of the water table. The importance of this factor depends on the expansive nature of the soils (how sensitive they are to shrink-swell behavior).

h) Determination of the drainage condition on the roadway.

i) Other condition survey procedures that may be used include the Spectral Analysis of Surface Waves and the Multi-Functional Vehicle (MFV). TxDOT no longer operates the Automatic Road Analyzer (ARAN), but instead has built its own equivalent piece of equipment, known as the MFV. Another device that could be used in forensic investigations, especially for measuring the stiffness of thin layers, is the Portable Seismic Pavement Analyzer (PSPA).

6) Materials Sampling and Laboratory Testing. The testing procedure typically consists of several tests, which may include of some of the following:

a) Coring (Core Rig). The analysis of pavement cores typically includes determining the layer thicknesses for the materials involved. Pavement cores verify the presence or actual thicknesses of the layers in relation to those documented in the pavement design and rehabilitation records. For example, in some cases involving an asphalt pavement, the absence of an asphalt surface layer might be attributed to milling operations on the roadway under previous maintenance contracts. Coring is beneficial in that it can prove whether two layers were appropriately bonded to one another. Coring provides information as to whether each of the layers was in good condition, or whether it was somehow damaged, or crushed. The moisture levels of the soil, when the core and other samples are being obtained, are important. However, since water is typically used to cool the core barrel during coring operations, it may be difficult (or even impossible) to obtain accurate information about the moisture content of the pavement or subgrade layers. The thermal coefficient of the existing base indicates the temperature susceptibility of the material. On one project the magnesium sulfate soundness test was run on the base material, which gave an indication of its relative strength (soundness) at various depths. This is relevant because soft bases can sometimes undergo degradation during material handling and compaction, which leads to more fines and a gradation that is not as coarse. The density of asphalt materials can be determined in order to compare the actual values to the maximum theoretical density. The density values might also be important when comparing one section to another. An example of this would be density in the wheel path versus density out of the wheel path. The density can be determined in terms of bulk gravity (Ga), average bulk gravity, rice gravity, or average relative density (%). The average air voids (%) and asphalt or asphalt cement content (%) of the AC can also be tested. The tensile strength (psi) and average tensile strength can be determined. A sieve analysis can be performed on the core material with the resulting percentage passing each sieve reported in order to determine the gradation of the ACP. Additional tests that can be performed on the extracted AC include viscosity (@ 140°F, Poises), the ductility (@ 77°F, cm) and the penetration test (@ 77°F, dmm). A gas chromatograph (GC) analysis was performed on the cores of one project that exhibited a strong diesel odor to determine the presence of this substance. In concrete cores the placement of rebar and tiebar steel are important. Coring also allows determination of whether corrosion of the bars is occurring. The pavement samples can be tested for alkali-silica reactivity (ASR), in which water causes a reaction between the alkali portion of the cement and the silica portion of the aggregate, resulting in expansion of the concrete and, often causing cracking.

b) Trenching. Trenching is carried out in order to take samples of any pavement layer. These samples are then taken back to the laboratory for testing. Trenching is sometimes performed to verify the thickness and condition of bound or unbound layers, or to determine which layer(s) are rutting. Since the trench is difficult to repair and requires closing down a traffic lane, trenching is used only in critical situations.

c) Subsurface Investigations. A subsurface materials analysis can be performed to identify and classify subgrade materials. The materials can be classified by soil type and the types of stabilizing materials, such as cements is all they contain. The presence of sulfates is important to concrete pavements because if such sulfates as gypsum come in direct contact with concrete, cracking problems can result. The existing subgrade can be tested for its triaxial class value, which indicates relative strength; its plasticity index (PI), which can indicate a potentially reactive soil (shrink/swell potential); and its liquid limit, which indicates the soil's susceptibility to moisture damage.

7) Analyze Data and Identify the Most Likely Cause of the Problem. This step involves reviewing all of the evidence relating to the project in order to come up with the most reasonable explanation for the failure that occurred. This process is ongoing throughout the project in the respect that, as test results are complied, the lines of thinking can become better defined. However, even after all of the testing has been completed, uncertainties often remain. Then, through a combination of previous experience and engineering principles, the most likely cause of the problem must be determined.

8) Produce a Final Report that Documents in Detail the Entire Forensic Investigation. Upon completion of the investigation, two reports must be developed: 1) a detailed, confidential report, and 2) a generic report for statewide distribution. Reports should include such items as the project history and background, a description of pavement structure, and a description of material types. A detailed description of the pavement condition, the types of distress involved, and the failure modes should also be included. Environmental conditions, soil conditions, traffic history data, and traffic projections must be included. A summary of the evaluation and testing strategies used for the investigation, as well as the findings of these tests, should also be presented. Finally, a prioritized summary of possible corrective strategies and their associated costs should be included.

3.4 FLEXIBLE PAVEMENT CASE STUDIES

Several forensic investigation reports prepared for cases examined by the Pavement Forensics Team during the past few years were reviewed in an attempt to determine common types of pavement failures that were occurring throughout the state. The first section focuses specifically upon forensic investigations of flexible pavements. The goal of this process of classification by distress type is to examine, and ultimately determine, common trends between similar failures. These trends may include the types or amounts of materials used, the construction procedures, or even the geographic location. Thus, information on pavement locations and specific pavement structure was included. Additional, relevant details of these reports, such as the types of tests performed and the reasoning behind such an investigative methodology, were included as available. These case studies, detailed in Cases 1 to 13, can be found in Appendix A.

3.5 CONCRETE PAVEMENT CASE STUDIES

This section focuses specifically upon forensic investigations of rigid pavements conducted by TxDOT. The case studies are summarized in the same manner as in the previous section, in an attempt to determine common types of pavement failures occurring throughout the state. These are detailed in Cases 14 to 16 in Appendix A.

Through investigating the details of the above forensic case studies, as well as by applying the general methodology for a forensic investigation, much information has been obtained on the current status of forensic engineering within the state of Texas. The reports detailing the case studies are very informative and provide new lines of thinking, but they were difficult to obtain. If they are not properly filed or referenced when such a pavement failure does occur, all of this valuable information may be simply lost, or limited to those who are directly familiar with the project. Thus, it appears even more crucial that an effective means of forensic investigation information dissemination be established.

CHAPTER 4. THE EXPERT TASK GROUP (ETG) MEETING

4.1 BACKGROUND

An expert task group (ETG), formed to advise this project, met for the first time on December 12, 1996. The meeting allowed members of the Project Advisory Committee and other select members of the academic and practicing pavement design community in TxDOT to provide valuable insight concerning critical elements of the project. Some of these elements included relating typical problems encountered in the field and identifying the critical design, construction, and materials information that would need to be stored in a database to support forensic investigations. This directly supports the purpose of this project—to develop a database that contains pertinent information having the greatest applicability for identifying premature failure. It is anticipated that the ETG will meet periodically to offer further input as the research progresses.

This chapter summarizes discussion items and comments made at the first ETG meeting. The most important issues stemming from the discussion have been condensed, but an expanded version of all the comments made during the discussion can be found in Appendix C. The group discussion focused upon two main areas: (1) common/chronic pavement distresses or premature failures that have been observed, and (2) types of information that would help district pavement designers and forensic investigation team members, including corresponding formats for such information. Outlined in the following sections are the construction-related, materials-related, and design-related problems discussed. Also outlined are issues of data collection and storage, the challenges of data collection, critical data items, and future project initiatives.

4.2 CONSTRUCTION-RELATED PROBLEMS

In terms of construction-related problems, it was established that there is a difference between chronic and forensic failures. Catastrophic failures are one-time, sudden occurrences (not chronic), and it is often debatable whether they are construction- or design-related. There is also a difference between failures where the specifications were not followed and failures where the specifications were followed but the pavement still failed.

There is often incompatibility among the design, materials selection, and actual construction processes. An important point was that the curing conditions during construction could influence the pavement performance. Proper documentation of weather conditions is required, especially for construction under adverse weather conditions.

Another construction-related problem is inexperience and/or inadequate testing and inspection in the field. The quality of testing may be a factor, because less testing means that a lot of variability in the materials is not being caught. Finally, specific types of construction-related problem were discussed, including such distresses as thermal cracking, debonding of the surface from the base, stabilization problems, contaminated materials, and that actual timing in adding curing compound.

4.3 MATERIALS-RELATED PROBLEMS

Variability of materials is a leading cause of materials-related problems. Another consideration is that material properties often change over time owing to temperature and moisture effects. The fact that material location and function may vary over a project can be another source of problems. A key issue in materials problems is improper testing. A material may have satisfactory performance in the lab, but there is no assurance that it will perform the same way on an actual highway where conditions differ.

The issue of compatibility of materials arises with certain applications or uses. Owing to the depletion of good materials, marginal materials are often used. The definition of a good material is based on application. Recycled materials have been used to address the depletion problem, but there may be a lack of experience with these new materials, and so they may not be used properly. A problem may occur when mixing and blending of material from different sources occurs. Additionally, there are currently changing needs for materials as they are exposed to such situations as new types of trucks with different loading configurations.

4.4 DESIGN-RELATED PROBLEMS

One design-related problem is that site inspection or investigation needs to be done prior to design, and this does not always occur. Additionally, the designer needs sufficient information on existing conditions. There is often a lack of sufficient knowledge about what the pavement structure is and what condition it is in. The designer also needs information on constraints that directly affect the particular pavement being designed.

A problem can occur when the selection of strategy is done before the actual design process. A question can arise as to whether the designer had enough information about the site and designed accordingly, or whether he just went out and did what is always done. The pavement engineer may not be free to design, because the budget can strongly limit control. In some cases, the designer can only design what the district can afford and, therefore, not be designing for the pavement variables but for the budget. A pavement engineer should be part of the planning process and should get his or her program out ahead in order to function proactively instead of reactively. Currently a lack of long-term planning exists.

Important aspects of design that were identified include the design of the drainage facilities and the projection of traffic into the future. Essential traffic projections include load and ESALs (equivalent single axle loads), rather than just volumes. Material design must also be an integral part of the pavement design. The surface often receives too much emphasis. It is important to note that other components of the pavement structure, such as the base and subgrade, need to be considered also. These other components could lead to significant improvements if they were better designed.

There exists a cycle of *new* ideas. In some cases, the same idea may have been tried 7 to 10 years ago. It is crucial to obtain feedback from experimental test sections. Frequently TxDOT spends a lot of money on a test, but loses what has been learned from it. Additionally, districts don’t know what other districts have already tried. Unique results should be made available to the districts, and if something does work, then the news should be shared. The forensic database should capture the data from such trials, both good and bad.

4.5 DATA COLLECTION AND STORAGE

The ability to look for trends should be included as a function of the forensic database. To accomplish this, it is necessary to consider not only failures, but also successes. Currently there is more of an emphasis on failures, which means that feedback on pavements performing well is not being collected, although this information is essential for model calibration. When premature failure occurs, the forensic team needs to consider whether the pavement really was built as designed, and whether the materials specified were actually used. The challenge of some previous forensic investigations was simply to get the data needed. The data required for storage is tied to the problems observed. The forensic system needs to contain the information necessary to determine the cause of failure. Additionally, the system needs to be flexible so that it can accommodate every possible type of information or data element. It was recommended that these data be classified according to the following four priority levels: 1) critical or absolutely required, 2) highly desired, 3) possible/desired, and 4) optional.

It is important for the forensic system to make full use of existing databases in order to ensure cost effectiveness. At the time of this meeting, it was noted that an important step that needed to be taken as part of the future research work was to review existing databases and determine how they could best be used. ForenSys could then go through existing TxDOT databases like a *search engine* to obtain the required data from other databases without duplicating efforts. Suggested databases include RoadLife, CMS (Construction Management System), and PMIS (Pavement Management Information System).

The issue of accessibility could be satisfied with a client/server system. ForenSys needs to be accessible to several people and places at one time, not just on a single PC. It is important to recognize the TxDOT short- and long-range system environment when making decisions about database accessibility.

4.6 THE CHALLENGES OF DATA COLLECTION

A major challenge of data collection is that there is never enough lead time to conduct a forensic investigation. Forensic investigations of pavements are often performed to determine the question of whether the *problem* can be left in place or not. A tremendous workload results from undertaking forensic studies; thus, there is never a good time—and there is often not enough time—to conduct a full-scale forensic investigation. Most importantly, what was done wrong needs to be determined so that it will not be done again.

It is necessary to look at established causes of certain distresses in order to determine what kinds of factors might have been involved in the failure (i.e., *critical factors*). This will allow the needed data to be determined based on the distress type observed. Eventually a forensic plan should be produced that would set up an input format in which the symptoms of a pavement failure could be filled out. In the future, an interactive expert system, to be used as a tool to diagnose problems based on distress and observations, could help districts by identifying possible causes and by following decision rules to determine a solution.

4.7 CRITICAL DATA ITEMS

After a daylong exchange of ideas, the experts decided on the data items that are the most important to identify during the investigation. These are contained in the following list. Some of these essential items would need to be derived from prior information, while others might be determined during the course of the forensic investigation.

A. Physical Description
   1) Location of the project
   2) Typical section (possibly lane, by lane because there will often be varying thicknesses and materials used)
      a) Include ditches (design and current)
      b) Design and actual thickness
      c) Previously existing layers

B. Construction History
   1) Specifications
   2) Date of construction of each layer
   3) Description of each layer
      a) Materials
      b) Mix design
   4) Weather
   5) Construction diary

C. Traffic History
   1) ADT
   2) ESALs

D. Performance History
   1) FWD
   2) Serviceability (last three years)
   3) Distress modes
   4) Results of coring
   5) Observations of current material

E. Observations
   1) Inspector interview
   2) Opinion of maintenance personnel

4.8 FUTURE DIRECTION

Also discussed was the direction that should be taken in establishing the architecture of the forensic database. The database should include information on either: 1) every project built—including the selected critical data (conditional on the availability in Road Life of certain elements) for all roadways, or 2) every project upon which a forensic investigation is conducted, including selected critical data only when there are problems with the pavement and a forensic investigation is performed.

The group decided that this issue must be resolved during the first year of the project, and that the course of this project probably should include information on all projects. Thus, if a forensic investigation should need to be performed, the information and project goal would be readily available. Because it is impossible to predict which roadways might eventually require a forensic investigation, it would be similarly impossible to collect additional information critical to a forensic investigation without collecting it for every single roadway. Information may be collected and stored in the forensic database, but links to existing databases would also be established so that when a forensic investigation is required, the information could easily be gathered from other databases via the links. Also, the decision to collect information on every project built would assist in the goal of being able to identify roads that are performing well, in order to learn from them.

CHAPTER 5. REVIEW OF EXISTING DATABASES IN TXDOT

5.1 APPROACH FOR THE REVIEW OF DATABASES

This chapter describes several of the existing and proposed pavement-related databases at TxDOT. The following information includes data that might ultimately be required for the forensic database and that are already being collected and recorded (or will be in the future) for other purposes, such as for contract management and pavement management. The role of the forensic database is seen as assisting in codifying and accessing this data. TxDOT currently has several databases associated with pavement design and performance; and although these sources do not have all the information required for pavement forensic analysis, using existing data would eliminate redundant data collection and data-entry efforts. Thus, a review was made to identify what types of data-collection activities were already underway that might prove to be important elements in characterizing the performance of a pavement, and that might be included in the forensics database.

The approach used to compare the data items in these databases consisted of a matrix that was set up to indicate what data elements, relevant to a forensic database, were or will be contained in which database. This included data that were currently being, or anticipated to be, collected within the department. Initially, the summary matrix included only the PMIS data elements, but was quickly expanded as different databases were identified that contained related, though different, data items. The original information came from data dictionaries obtained from TxDOT. After the information was compiled, TxDOT personnel responsible for each specific database then checked it for accuracy. The research team attempted to look at a wide variety of issues regarding the data. The first consideration was how data are referenced and stored within the database. It is important to identify duplication, overlap, direct linking, and mismatch between the items of the databases, because if the systems do not overlap properly, it may be difficult to merge the data into a single database. Other key items included the actual existence of data and the extent of the database population. The time dimension of the data input is also a consideration—for example, whether the data are collected at the time of construction or annually. Another aspect of this is how frequently data are updated in the database (daily or annually). The amount of sampling and repeatability are considerations, as is the reliability of the quality of the data. The units the data are stored in must be looked at as well. Also, the current status of the database—in terms of what it is used for and what was its original purpose—is a further consideration.

It is important that the overall information system within TxDOT be integrated among the various systems, divisions, and districts so that the full potential of all its data assets is utilized. Investigating the types of data collection activities already underway and making use of these resources can help ensure that redundant effort is eliminated. Eventually, part of the project will entail work on database information codifying and accessing, in order to avoid redundancy of efforts should data be integrated from one system to another.

5.2 PAVEMENT MANAGEMENT INFORMATION SYSTEM (PMIS)

TxDOT implemented the Pavement Evaluation System (PES) in August 1982. Because this system was a network-level management tool, its effectiveness at the project-management level was quite limited. The purpose of this system was to provide information concerning the present condition of the highway system, monitor changes in the condition of the highways, and determine the funding levels required to meet district and statewide pavement maintenance and rehabilitation needs. The PES no longer exists. It has been replaced by the Pavement Management Information System (PMIS). Thus, the PES data have been converted to PMIS format. PES data were collected from 1983–1993, and the conversion to PMIS took place in 1993.

Currently TxDOT performs pavement evaluation surveys on all of its roadways. A 100 percent sample of interstates is required annually; otherwise, a 50 percent sample of all TxDOT roads (except those under construction) is made every year. When conducting a visual rating on a PMIS section, only the lane that shows the most distress on each roadbed is rated; PMIS accepts a two-digit code for the roadbed and lane rated. Information collected includes values of surface roughness, a value of distress, a value of deflection, types of visual distress, and other important distress information, such as the existence and degree of cracking. Visual distress, ride quality, and skid data are collected on flexible and rigid pavements, while structural strength data are collected only on flexible pavements.

The Pavement Management Information System (PMIS) is an automated system that TxDOT uses for "storing, retrieving, analyzing, and reporting information to help with pavement-related decision making processes (TxDOT 94)." The program has been in use since May 7, 1993. The PMIS was created in response to the Federal Highway Administration policy that required all states to create a pavement management system. Pavement management can be defined as the process of providing, evaluating, and maintaining pavements in a serviceable condition according to the most cost-effective strategy (TxDOT 94). The purpose of a PMIS is to serve as an analysis tool that will support decision-making and provide a means for estimating future needs and determining the consequences of different funding levels on network-level pavement conditions. This program allows districts to identify deficient highway segments and develop economical design procedures. The primary elements and products of PMIS are: (1) an inventory of pavements in the network, (2) a database of past and current pavement conditions, (3) budget requirements, and (4) methods for optimizing and prioritizing projects. Of these four items, the first two are the most relevant for our purposes. The system stores roadway inventory, condition, and traffic data, all of which may be crucial factors in the forensics database. Some of the data items within PMIS are created in, and obtained from, other automated systems. These items are updated from the other systems within the department (Texas Reference Marker System, Road Life System, and Maintenance Management Information System) once a year. The two main files of the PMIS are the inventory and data files.

When analyzing and selecting projects, a management section for a roadway is created; this is a pavement segment of similar structure that is intended to be treated and maintained uniformly (i.e., it may be thought of as a candidate project). Data collection sections are used for the PMIS to summarize and report data on specified portions of the roadway; these are typically 0.5 mile, but can range from 0.1 to 1.0 mile in length. In the future, when TxDOT converts to the metric system, most sections will be 1 kilometer long. PMIS sections are identified by reference markers, though they may not begin or end exactly at a reference marker. The future direction of data collection seems to be that the physical characteristics of the road will be measured with automated equipment where they occur; however, it appears that analysis will continue to be undertaken in terms of sections.

The PMIS combines two operating/mainframe environments. The first is the Customer Information and Control System (CICS), which is an on-line environment. The second is the Remote Operating Systems Conversational On-Line Environment (ROSCOE), which is a batch-operating environment. The Arbiter Data Transfer Facility is used when it is necessary to download the Section List Files used in the portable data-collection computers and to upload the resulting data that are collected as part of the automated data collection and storage process. In terms of the existence of actual data and overall database size, the PMIS contained approximately 180,000 sections in 1995, which, when combined, make up the entire network of state-maintained highways. The PMIS system is operational and has been used by TxDOT to produce annual reports on pavement conditions and needs. The PMIS is a 20-year database, so in August of 2003, the system administrators will need to make a tape or other backup of the first-year data.

5.3 MAINTENANCE MANAGEMENT INFORMATION SYSTEM (MMIS)

The Maintenance Management Information System keeps track of all of the maintenance activities performed on all of the highways within TxDOT. The Construction and Maintenance Division maintains this database. The information is organized according to district, county, highway, and reference marker. We would be interested in using the actual reference marker and offset where the work is actually being performed, not the beginning or ending reference marker. All of the records dealing with the information on the roadways are kept for a 2-year period. The records deal with both contract maintenance work and noncontract maintenance work.

Each record contains cost information, the amount of work performed (the area data field that contains the corresponding amount of units), man-hour information, and material usage information for the specific highway location. The work performed is classified into categories known as function codes. The data-collection process takes place in two steps. First, the maintenance section crew fills out a form logging the work performed in the field; then the office secretary enters it into the system after they return. Thus, the transaction file is updated on-line during each working day, and gives the exact date the work is performed. The master file may not include the exact date; thus, for end-of-the-month activities, the work may be added to the next month instead, which would serve as an approximation of the date the work was performed.

The MMIS system is composed of the audit file, the master file, the transaction file, and the FIMS-ENC41 file (which provides additional information on the contracts). Full data collection began on September 1, 1989 (FY 1990). All the data are tracked in 1-mile increments. Thus, even if only 10 feet were worked on, whole-mile increments are close enough for maintenance purposes. The data also are currently not handled by roadbed. This is in the process of being changed, but it will take a couple of years to convert all of the files.

5.4 TEXAS REFERENCE MARKER SYSTEM (TRM)

The TRM database is designed to represent an inventory of current conditions, which means that districts are supposed to update the information immediately. The system is not designed to perform historical tracking. Information (data) does exist for all on-system routes statewide. The information is available on-line within TxDOT, and anyone with a login privileges may access the information.

The TRM database is a mainframe database that contains network data and feature data in a total of nine files. These consist of eight feature files plus one administration file. The Transportation Planning and Programming (TP&P) Division of TxDOT maintains the TRM system. All twenty-five districts are involved in the on-line update process, and they are responsible for initiating the route-establishment process by contacting the TP&P Reference Marker Coordinator in order to obtain the marker number.

The data within the database are presented in terms of control sections, not projects. The network data include such items as the reference markers. The roadbed's beginning and ending points are listed in terms of reference markers, but the file also contains the geographic coordinates for the reference markers. Reference markers increase north to south and west to east, depending on the highway's general direction. Exceptions to the above rule are interstates, where numbers increase south to north. The numbers are continuous from the beginning to the end of the route.

The feature data include the existence of bridges, information on shoulders, information on pavement sections and layers, the length of pavement type, and geometric features such as the PC and PT of curves, among other things. There are two levels of data—roadbed features and centerline features. The centerline information includes the geometric file, the mileage, and some administration file information (on the county and district level). It is possible for different numbers of lanes and even different pavement types to be tracked using this system. The reason for this is that every lane is given a different code representation, for which information on all of the roadbed details is entered.

Administrative data exist for every piece of roadway on the system in order to assist in determining the parties responsible for a specific piece of roadway. The TP&P Division that maintains the TRM system updates the administration file. The traffic information eventually will be loaded once a year from the traffic database numbers according to reference marker, but it has not been updated since the inception of the database because some details are still being worked out. In terms of the existence of actual data, the database has been completed for the highways for which TxDOT is responsible. The system is operational and is capable of reporting lane miles of roadway to comply with government reporting requirements.

5.5 ROAD LIFE DATABASE

Road Life began within the Traffic Programming and Planning (TP&P) Division of TxDOT in the early 1990s. In November 1995, the Design (DES) Division took control. The database was needed for performance of pavement and rehabilitation design, life-cycle cost, and preventative maintenance.

The Road Life Database was set up as an attempt to offer an immediate solution to the district's data collection needs. It was completed in June 1996 and is a mainframe database that is linked to TRM. The main features of the reference system consist of control sections and reference markers. The system was designed as a prototype, and its use so far has been completely voluntary; to date, only two or three districts have tested this database. Eventually it is envisioned that all districts will be responsible for updating the database daily as changes take place and new data are collected. The data most likely will be obtained when a new project is constructed, which means starting at this point in time and moving forward.

This review revealed the breakdown of data categories, as well as the data elements contained within each category that characterize the level of data collection proposed for this database. A new record is stored for each new pavement-layer entry. There are seven different types of pavement layers, and up to nine different entries can be made for a pavement layer on the same Control-Section-Job (CSJ).

Owing to the lack of actual data at this point, it will be difficult to predict the role of Road Life in the forensics database until its use becomes more widespread. The progress of the Road Life Database is being closely monitored. A contract was written in January 1997 for the imagery of RL-2 files. The contract for scanning these old log files is scheduled for release at the end of August 1997; therefore, the data should be available on CD format in approximately 6 months. Research Project 1779, relating to the development of guidelines for the data elements and population of the database, including researching new technology to determine pavement layers, will begin in September 1997. Districts working on the layer database include Brownwood, Austin, Houston, and Fort Worth.

The possibilities for future development of this database include: (1) becoming part of PMIS (the two databases will most likely become one system, with the Road Life system as one or two files within the PMIS instead of a separate database), (2) entering current and future projects in order to populate the database (start now and move forward), (3) developing a client/server application, (4) using CMS/Site Manager to update the database, and (5) possibly implementing with a Geographic Information System (GIS).

5.6 CONSTRUCTION MANAGEMENT SYSTEM (CMS)

The American Association of State Highway and Transportation Officials (AASHTO) is currently developing a Construction Management System (CMS). Within TxDOT, this system is also referred to as *Site Manager*. CMS-AASHTO is a FHWA-sponsored project that was intended to provide DOTs with a database management system for storing and managing construction-related information during the course of a project. The five major functional areas on which the CMS is focusing are as follows: (1) daily work reports and project records, (2) materials management, (3) contractor payments and progress monitoring, (4) civil rights requirements, and (5) administrative support. The proposed system would allow daily inputting of the results of thirty different field tests directly into the system while in the field. Thus, the system would provide a means for storing daily work reports, material test reports, change orders (reason for change and description of change), and inspector diary information. This would help eliminate redundant efforts, reduce lost records, and identify any deficiencies. In terms of materials management, important information may include: (1) how much actually was tested versus testing requirements, and (2) design values vs. specified requirements. It is also envisioned that this system may be used to document pavement material performance (especially for SuperPave).

It was originally thought that TxDOT would be testing the system during the spring and summer of 1997; however, development of this system is still underway. According to the current schedule, alpha testing will take place during September and October 1997 with the developers in Atlanta. Beta testing will take place in the San Antonio and Waco districts from November 1997 to April 1998. September 1998 is the target date for full implementation of the system, though it is still uncertain whether this will take place system-wide or in phases.

5.7 RIGID PAVEMENT DATABASE

The Texas Rigid Pavement Database is made up of the continuously reinforced concrete pavement (CRCP) and jointed concrete pavement (JCP) databases. This is a research database that has been maintained by the Center for Transportation Research (CTR) since 1974. It contains samples of rigid pavements across the state, which are continually monitored and updated by condition surveys. The test sections that make up the database are typically 1,000 feet in length and are in the outside lanes. The database contains geometric, environmental, construction, traffic, and inventory variables. The data elements contained for each pavement type reflect the different distress types and design considerations associated with that particular type of pavement. The database is increased as pavement designs change over time. The historical pavement performance data can be used in analysis and design model development to improve pavement design procedures and to assist in pavement management and administrative decisions.

5.8 TEXAS FLEXIBLE PAVEMENT DATABASE

The Texas Transportation Institute (TTI) has maintained the Texas Flexible Pavement Database since 1972. This is a research database that includes detailed information on 350 sections of pavement that were originally selected as a stratified random sample of the state's pavements proportional to the total mileage of each class of roadway. The Flexible Pavement Database has been dormant for several years, but funding has been requested to revitalize this database. In the past, the Flexible Pavement Database has been used to develop or validate design equations for the Flexible Pavement Design Procedure (FPS).

The original system was created on the mainframe computer using a database system written in SAS. In 1986, a study created a new system that would preserve the data but restructure it for ease of access and newer computer technology. Thus, the current system is a microcomputer database management system that provides flexible storage, reporting, and modeling of the data. The database also needed to be enlarged to include additional distress- and serviceability-index data to improve the predictive equations that the database supports. Data collection was enhanced by taking core samples and measuring the layer thickness instead of relying on as-built plan information dating from when the roadways were designed. According to the report, data need to be collected on an annual basis. The system was designed to easily add new monitoring sections to the system in order to be compatible with the SHRP Long-Term Pavement Performance system and to provide a long-term means of monitoring experimental pavements.

The inputs for the storage system developed in this project include: (1) the PES annual Master file, (2) maintenance and rehabilitation information from Road Life STrip maps and district maintenance records, and (3) information on roadway characteristics, particularly traffic levels (AADT) from the Roadway Information File.

5.9 DATABASE SUMMARY

Appendix D presents the compiled summary of information on these databases. Owing to the nature of this compilation, every effort has been made to ensure accuracy. Its contents have undergone several rounds of checking by the research team and by TxDOT personnel familiar with the database. However, the research team welcomes any suggestions or comments on the validity of particular items, if it is thought that an error has been made. It should be kept in mind that there may be slight discrepancies, so potential users should be cautious.

CHAPTER 6. DATA SOURCES AND DATA COLLECTION PROCEDURES

6.1 BACKGROUND

It appears that some of the data ultimately required for the forensic database is already being collected, or will be collected in the future, for other purposes. These purposes include contract management, pavement management, and general record keeping. A review was made to identify what types of data-collection activities are already underway, focusing on elements that were considered to be important to the performance of a pavement and a forensic investigation that might have to be conducted upon it. A review was also made of the design procedures used within TxDOT for both flexible and rigid pavements in order to identify the input into the design procedure, as such elements may also prove to be critical to a pavement's performance. The potential data resources discussed in this section may provide some of the information required for conducting a forensic investigation. While the exact definition and format of the information remains to be determined should data be used, the sources examined helped the research team better understand what kinds of data records exist within the department.

6.2 GEOGRAPHIC DATA

TxDOT has created 1:24,000 scale highway maps in digital format for every Texas county. These files were originally digitized from USGS 7.5-minute quadrangles. Updates on these files are made periodically using TxDOT highway construction plans, aerial photographs, official city maps, and field inventory data. These files contain most of the features found on 7.5-minute quadrangles, except for such items as contour lines, fence lines, jeep trails, electrical transmission lines, oil pipelines, and control-data monuments. Given the USGS-stated positional accuracy of plus-or-minus 40 feet for its 7.5-minute quadrangles, and given the inadvertent positional shifts that may have been introduced during the process of digitizing, it is estimated that the positional accuracy for most of the features included in these files will be plus-or-minus 50 feet. All the files are based on the Texas Statewide Mapping System (NAD 27) map projection.

6.3 CONDITION SURVEY

The annual PMIS pavement condition survey is not collected on all roadways. Each year, 100 percent of the interstate highway system and approximately 50 percent of the remaining mileage is sampled, so that *all* of the roadways are sampled every 2 years. Information collected includes ride quality, various types of distress, and in some districts, deflection and skid data. Such information most likely would be valuable to a forensic investigation by helping investigators (1) determine when and why problems would occur (since the data involve the present condition of the highway system), (2) monitor changes in the condition of the highways, and (3) acquire the needed funds to improve the system.

6.4 NONDESTRUCTIVE TESTING METHODS USED BY TxDOT

Several nondestructive testing methods are currently being used within TxDOT, while others are in the testing phase to determine their capabilities. Such tests have a very important role as a potential data resource for forensic investigations. The first of these methods is the Dynamic Cone Pentrometer (DCP). This test is particularly useful for checking thicknesses, determining the presence of a stabilized layer, and testing granular bases. Ground penetrating radar (GPR) can be used to determine layer thicknesses, determine changes in section, determine the moisture content of the base, and identify defects in the hot mix of a flexible pavement such as stripping. The falling weight deflectometer (FWD) can be used to determine the quality and stiffness of the base and subgrade.

6.5 INVENTORY DATA

The Log Record of Project Construction and Retirements (RL2 paper files) exist for every highway section. These files document many details, including: the scope of the work, the county name, the control number, the section number, the highway number, the width, the type of materials used, the type of surface (code), the date completed, the type of shoulders, the depth of the base and surface, and the total cost spent on the project. Additionally, there is a plan view of the roadway, which indicates the location of drains, county lines, etc. The main problem with this is that the data are not easily accessible. TxDOT is currently undertaking a project to image each sheet in order to have better access to all of the information contained in these files. Problems of accessing and referencing the proper sections will have to be worked out if this information is to be used.

Information on the original design of the pavement in terms of intended pavement thickness, slab length, type of reinforcement (if any), and load transfer devices could be extracted from design plans (Huerta 94). These plan sheets are referenced by control section job number. One drawback is that there are no sheets for overlay, only for original construction and major reconstructions, which means that the entire pavement history is not documented here. Another major limitation is that, unless the project was built recently enough that the plans would still be in the district office where the project was located, these files would be managed by the General Services Division (GSD) in the large construction plan storehouse on Metropolitan Drive in Austin, which means that the information would not be easily accessible. Before storage by the GSD, TxDOT’s Equipment and Procurement Division, Records Management Section handled the storage of these plans.

The Texas Reference Marker System (see Chapter 5) does provide inventory information on shoulders, pavement sections (layers), and other items. This information has the advantage of already being in database format.

6.6 MATERIALS INFORMATION—PAPER FILES

The coarse aggregate type could be obtained for every project using the Material Testing Reports and Core Test Reports, which are included in Folder #5 of the Project Correspondence (Huerta 94). These files are also stored in the Records Management Section in D-4 and are customarily stored on microfilm, except for recently built projects, whose files may still be found in paper form. A limitation of this process is that, before a project is built, contractors usually submit more than one type of coarse aggregate to the Materials and Test Division for certification and approval. This results in several Material Test Reports, which is why it is so critical to document what was actually used during the construction process.

6.7 TRAFFIC INFORMATION

Traffic data are available for the major roadways in Texas. The Traffic Planning and Programming Division collects this information. Actual load information that has been collected since the pavement was designed and constructed is not available, owing to such factors as different truck configurations and different tire pressures. Instead, estimates are made in terms of 18-kip equivalent single axle loads (ESALs). An ideal requirement would be the original value of traffic predicted by the TP&P Division for the roadway for which the pavement engineer designs the pavement.

6.8 TxDOT PAVEMENT DESIGN METHODS AND PROCEDURES

A review of pavement design methods used by TxDOT was made in order to identify the inputs. It has been suggested that, under certain circumstances, important design factors may not be considered in the current design procedures. Establishing what elements are accounted for in the design may ultimately lead to the discovery of certain elements that prove to be critical in a pavement's performance, but that are being overlooked by simplified design models or procedures. Since forensic investigations may lead to the identification of such critical design elements, they could potentially lead to improved pavement designs.

6.8.1 Design Methods for Flexible Pavements

Several design methods have been used by TxDOT since the formal design procedure was introduced. These methods are discussed and the main input variables for each are described in the following section.

1) The Texas Triaxial Design System. The Texas Triaxial Design System was the only system used from the late 1940s through the early 1960s. This method is still used to determine wheel-load capacity for load-zoned roads, to perform the design of low-volume pavements where the current design procedure (the Flexible Pavement Design Procedure, or FPS) is out of range, and to check all FPS designs. Typically the FPS provides accurate results for design loading ranging from 0.5 million to 20 million 18-kip ESALs. However, when the roadway has less than 0.5 million ESALs, a bearing capacity failure or a shear failure may occur. There is currently a modified version of the system used as a check on the FPS for adequate thickness for the other roadways it predicts (TxDOT 93).

   The inputs required for the Texas Triaxial Design System include:

   a) The subgrade triaxial value
   b) The average of ten heaviest wheel loads daily (ATHWLD) for traffic
   c) The percentage of truck tandem axles
   d) The cohesiometer value for bound materials

The ATHWLD or the legal wheel load limit (10,000 lb) is used for the analysis. If the percentage of tandem axles is greater than 50 percent, the ATHWLD is multiplied by a factor of 1.3. A chart is used to determine the pavement thickness required to prevent subgrade compression failure. A separate chart is used to determine the allowable thickness reduction for bound layers based on the cohesiometer value.

2) The Flexible Pavement Design Procedure (FPS). The Flexible Pavement Design Procedure (FPS), which was developed in the 1960s and 1970s, is TxDOT's primary design procedure for both new flexible pavements and pavement rehabilitations. After many revisions from the original computer program, FPS is still in use today. The two versions of this design method that are currently being used are Versions 11 and 19. Stiffness coefficients obtained through deflection testing with the Dynaflect machine characterize the stiffnesses of soil and paving materials for FPS 11. FPS Version 19 is a newer method that uses strength values calculated using a falling weight deflectometer instead of the Dynaflect. Thus, Version 19 converted the FPS methodology to a linear elastic system using elastic moduli as strength inputs that were representative of pavement layer strengths. Different versions of FPS are briefly summarized on the following pages.

FPS—Version 3: This was the first published version. It represented changes made to FPS 1, the first computer program (Haas and Hudson 78).

Category of Variables Used as Inputs	Description of Variable
1. Program Controls	These are required to control the operation of the program.
2. Unit Costs	These are the economic inputs required for the computation of the costs of each pavement design.
3. Material properties	These define the characteristics of each material.
4. Environmental Factor	A district temperature constant based on the mean temperature of the area where the pavement is to be constructed, and used in predicting of the behavior of each pavement design.
5. Serviceability Index Values	Used to predict the life of an initial design or an overlay by determining the serviceability level of the pavement after initial construction and after overlay construction and the minimum value of serviceability that will be allowed during the analysis period.
6. Seal Coat Schedule	These variables describe the restraints imposed on seal coats by the designer and are used in the determination of a seal coat schedule for each pavement design.
7. Constraints	Variables that are important in controlling the design and management scheme produced by the program.
8. Traffic Demand Inputs	Describe the expected traffic that the pavement must serve during its lifetime.
9. Traffic Control Inputs	Used in the computation of user costs to determine how traffic will be handled during overlay construction.
10. Miscellaneous Parameters	Variables that do not fit into any other group.

FPS—Version 11: Twelve categories of variables are needed as inputs.

Category of Variables Used as Inputs	Description of Variable
1. Project Identification	
2. Project Comments	
3. Basic Design Criteria	Design period (in years) for calculation of performance period. It is strongly related to the functional classification of the facility being designed.
4. Program Controls and Constraints	These may be financial variables, such as the maximum funds available per square yard for initial construction; or physical variables, such as the maximum total thickness of initial construction, maximum total thickness of all overlays or existing structures.
5. Traffic Data	Average Daily Traffic (ADT in vehicles per day) at each end (present and future) of twenty-year evaluation period. The directional distribution is used to calculate the ADT for the most heavily traveled direction, but this calculation is done manually and is not input. The estimated number of *__18-kip equivalent single axle loadings (18-kip ESALs)__ for the given structural number (SN) from the AASHTO Design Procedure. Percent trucks in ADT. The following traffic inputs are used primarily to determine the traffic delay costs based on the optional detour layouts. These consist of the average approach speed to overlay zone, the average speed in the overlay direction, the average speed in the nonoverlay direction, and the percent ADT/hour of construction.
6. Environment and Subgrade	The District ***Temperature Constant** (in • F) is taken from the FPS User's Manual. ***Swelling Clay Properties** - The effects of swelling clays may require Potential Vertical Rise and swelling rate constant if no other information is available. However, adding extra pavement thickness and stiffness to the pavement structure will not prevent or even significantly reduce swelling clay effects on pavement structures. Pavement designs are typically done both with and without the introduction of swelling clays into the design so the effects of swelling clays can be determined.
7. Construction and Maintenance Cost Data	Initial serviceability index and serviceability after overlaying. Minimum overlay thickness. Materials cost input items are in units of dollars per cubic yard compacted in place. Maintenance costs include first-year cost of routine maintenance and annual incremental increase in maintenance cost. The total cost concept considers maintenance costs and user-delay costs, which means that the lowest initial cost pavement is not always the most economical over the total analysis period.
8. Detour Design Information	Used to determine the best rehabilitation strategy. Detour model during overlays, total number of lanes, number of open lanes in work and nonwork directions, distance traffic is slowed in the work and non-work directions and the detour distance.
9. Engineering Properties	
10. Proposed Paving Material Information	This information is provided for new pavements. For each layer proposed it is necessary to provide the in-place cost in dollars per cubic yard. Also the minimum and maximum allowable thicknesses of each layer are important. Stiffness coefficients of each proposed pavement layer are also input.

Category of Variables Used as Inputs	Description of Variable
11. Existing Pavement and Proposed Overlay Materials	**Materials Stiffness Coefficients (or Surface Curvature Index, in inches)** The Surface Curvature Index (SCI) of the existing pavement is a measure of the strength of the existing pavement. The standard deviation of the SCI represents the variation in the strength of the existing pavement structure. Also, information on the materials of the overlay layer are included.
12. Serviceability Index Related Items	These items include ***initial serviceability (index)**: a function of surfacing type and construction procedures, and construction quality; ***serviceability after overlay**: a function of the actual terminal serviceability index (actual roughness) of the existing pavement at the time of overlay; the amount of ACP overlay; the surfacing type; construction procedures such as the number of lifts for placement of overlay and construction quality; and ***terminal serviceability (index)**: level of serviceability which will be allowed before initiating rehabilitation.

Levels of importance for the inputs are dependent upon whether the variables appear in the FPS performance equation. The performance equation inputs will have the largest effect on the pavement designs generated by FPS. Inputs for the performance equation are indicated in the table above by being boldface and having an asterisk (*). One important consideration to note is that this procedure does not consider frost heave or strength of materials.

FPS—Version 19: The inputs into the computer program are almost identical. The main difference between Version 19 and Version 11 is that instead of layer stiffness coefficients, layer moduli are used in FPS—Version 19 (TxDOT 96).

6.8.2 Design Methods for Rigid Pavements

TxDOT currently uses the 1993 American Association of State Highway and Transportation Officials (AASHTO) Rigid Pavement Design Procedure to design new rigid pavements and pavement rehabilitations. Previous to this design method, the 1986 American Association of State Highway and Transportation Officials (AASHTO) Rigid Pavement Design Procedures were used. The 1972 Interim Guide for the Design of Pavement Structures written by the American Association of State Highway Officials (AASHO) was used prior to the 1986 AASHTO method. TxDOT periodically issues design specifications that directly relate to the above-mentioned design procedures for the purpose of giving additional information to the districts on the procedures.

1) The 1993 AASHTO Rigid Pavement Design Procedure

- JCP/JRCP: Jointed Concrete Pavements (JCP)/Jointed Reinforce Concrete Pavements (JRCP). Five categories of variables are needed as inputs for this version.

Category of Variables Used as Inputs	Description of Variable
1. Design Variables	• Time Constraints Performance period (years) Analysis period (years) • Traffic (cumulative expected 18-kip ESALs— must factor traffic by direction and number of lanes) • Reliability – reliability level from state AASHTO range Standard deviation for traffic = 0.35 for rigid • Environmental Impacts – cumulative serviceability loss due to following two factors (0 to 1.0): Roadbed swelling (should be considered) Frost heave (should be considered)
2. Performance Criteria	• Serviceability – Present Serviceability Index (0 to 5) Initial serviceability level & terminal serviceability level
3. Material Properties for Structural Design	• Effective modulus of subgrade reaction (pci) • Pavement layer material characterization (PCC = E_C, base = E_{BS}, subbase = E_{SB}) • PCC modulus of rupture (psi) •
4. Pavement Structural Characteristics	• Drainage, coefficient of drainage :C_d=0.7 – 1.25 • Load transfer - jointed pavements (3.6 – 4.2) • Load transfer - tied shoulders or widened outside lanes (should be considered) (2.5 – 3.1) • Loss of support (values range from 0.0 to 3.0) •
5. Reinforcement Variables	• Jointed pavements Slab length, L (feet) between untied transverse joints Steel working stress, f_S (psi) Friction factor, F (0.9 – 2.2)

- **CRCP: Continuously Reinforced Concrete Pavements (CRCP)**

Category of Variables Used as Inputs	Description of Variable
1. Design Variables	**(same as JCP/JRCP) – see previous table**
2. Performance Criteria	**(same as JCP/JRCP) – see previous table**
3. Material Properties for Structural Design	**(same as JCP/JRCP) – see previous table**
4. Pavement Structural Characteristics	• Load transfer – continuous pavements • Load transfer – tied shoulders or widened outside lanes (should be considered) • Loss of support
5. Reinforcement Variables	• Concrete tensile strength from indirect tensile test (psi) • Concrete shrinkage (in./in.) • Concrete Thermal Coefficient (10^{-6}in./in./• F) • Bar or wire diameter, inches • Steel Thermal Coefficient (5 x 10^{-6}in./in./• F) • Design temperature drop, • F • Friction factor, F (0.9 – 2.2)

2) **Computer Version of Rigid Pavement Design Procedure:** A computer program based on the 1986 Design Procedure for slab thickness is used by TxDOT. It requires the following inputs:

Input Variable	Units
1. Mean concrete modulus of rupture	psi
2. Concrete elastic modulus	psi
3. Effective modulus of subbase/subgrade reaction	psi
4. Initial serviceability index	N.NN
5. Terminal serviceability index	N.NN
6. Load transfer coefficient	N.NN
7. Drainage coefficient	N.NN
8. Overall standard deviation (log repetitions)	N.NNN
9. Desired Level of Reliability	%
10. Design traffic	18 kip ESAL

Although the research team has reviewed the design procedures, at this point it is difficult to tell which design variable is the most critical to a forensic investigation. As discussed earlier, eventually design methods may change, but since this is such a complicated issue, currently not much can be done if the design is wrong.

6.9 SUMMARY OF DATA SOURCES AND DATA COLLECTION

As shown, TxDOT does have quite a few existing data assets. However, not all of these may be useable for the forensics database. The amount of labor required to input all of the information contained in paper files stored in warehouses into the forensics database would be enormous. While it is important to use these resources should a forensic investigation be required, it does not seem feasible to go back and enter in all of these data simply because a forensic investigation might be required. Thus, in many cases it seems that efforts need to start at the present and continue into the future in terms of collecting all the information required for the database. The task for the research team is to make the most efficient use of the existing data resources, so that the database will be as complete and accurate as possible.

CHAPTER 7. CRITICAL DATA ITEMS FOR THE FORENSICS DATABASE

7.1 IDENTIFICATION OF CRITICAL DATA ITEMS

Critical data items must be identified, since both time and resources for gathering data are limited. While at a project-management level it may seem ideal to maintain every detail regarding a project, it is impossible because it would require too much time and money, given the testing procedures, validation, and data entry that would be required. At the network-management level, it would be overwhelming for a district to fill in a long list of blank fields in the database, some of which may have only a minor impact on the project's performance. Additionally, it would be inefficient for a forensic investigator to have to sort through large quantities of data when he or she needed only the most critical elements. It has been recognized that pavement distress manifestations are affected by a number of factors besides pavement age. Since it is not possible to collect information on all of these factors, only the factors most important for use in predicting the performance of the pavement structure should be included (Chou 88). Thus, it would be much more practical for only the absolutely critical data items to be required to be collected, with the recommended elements for the other levels of data collection listed and the space available to contain such details. In order for the database to fully meet its objectives, it would need to include the ability and space for districts to create any type of data field to store the value of any test that may have been performed because it seemed pertinent to the forensic investigation.

7.2 APPROACH USED TO IDENTIFY CRITICAL DATA ITEMS

Mandatory pieces of information should be defined as essential items without which the investigator could not perform a forensic investigation. For example, an engineer needs to know the structure of the pavement before it can be overlaid. Critical data items, on the other hand, could be defined as items that were necessary because the investigator would not be able to determine the cause of failure without access to this information. Critical data items may be obscure items that would be difficult to define. For example, in a real investigation it was determined, by using the absum recovery test to assess the quality of asphalt, that the asphalt was damaged. However, the question of how it happened remained unanswered. Possibly it was a problem with poor-quality asphalt or with burned asphalt. Because the district in question happened to collect stack temperature as part of its inspections (information that most other districts probably do not collect), it was able to answer the question.

Critical data items could also be defined as data items that the Department has only one chance to collect. For example, the distance between the roller and the laydown machine is important to SuperPave. Another example: The Odessa District has identified the density of the base as a very important factor, which means that inspectors collect three times the regularly required number of samples to ensure good quality. Properties that change with time and can only be captured during construction likewise could be considered critical. For example, questions have arisen during past forensic investigations about the asphalt cement

(AC) grade (viscosity, pen number, and/or performance grade) at the time of construction. There may be a suspicion that the contractor burned the AC, used a different grade AC than specified, or used an AC tainted with diesel or some other deleterious materials. However, no as-built information existed, and there was no way of going back to determine it through some other sort of testing; thus, the issue could not be resolved.

Another approach to determining important data items would be to identify which are relatively inexpensive to collect during construction but expensive to collect later. Other types of data, which may be critical to understanding pavement performance and which could be collected anytime and are just as inexpensive to collect now as later, may be downgraded in importance to *important* or *desirable.*

The approach used to identify the critical data items included several considerations. The first was to determine what factors were influential to the performance of a pavement. This included reviews of previous work that offered rankings based on the number of times a variable appeared in a model. Other sources used AASHTO equations, empirical models, mechanistic models, and field survey studies to determine which data elements were the most important to the performance of a certain type of pavement. Information used to form a summary sheet was compiled from various sources on important distresses (and their causes) for different types of pavement. The second aspect included reviewing data elements critical to forensic pavement investigation. The sources of such information included previous TTI research projects and actual data elements and tests used in past Texas forensic investigations. Appendix E presents a compilation of required information from those sources on distress types and required information for failure investigations of flexible pavements. The third aspect was to determine the types of data elements other management systems collect, and to ascertain whether major categories of elements were being overlooked. The following portion of this chapter includes sections relating to the information found and previous research done to support the inclusion of certain data elements.

After the critical data items were identified, this information was compiled into a minimum list of required elements for forensic analysis. This list was put into a matrix of different rows based on level of importance for the different data items. The list includes the reason for including an item. (e.g., ETG = expert task group meeting; CW = conventional wisdom; PDF = primary design factor.)

While the precise definition and importance level of some of the information still needs to be determined, a good understanding of the data items most critical to the database has been obtained. Although significant work has already led to a preliminary list of the most critical data elements, such a list will need to be periodically reviewed and modified by knowledgeable engineers. A meeting has been proposed in which the participants would work together to compile the final list.

Table 7.1 Variables considered in the significance analysis of pavement performance for CRCP (Chou 88)

I. Design/ Construction Factors	**II. Environmental Factors**
A. Concrete layer properties 1. Concrete aggregate type 2. Type of steel (bar mats or welded-wire fabric) 3. Amount of transverse and longitudinal steel 4. Thickness *** **B. Subbase layer properties** 1. Coarse aggregate type *** 2. Type and amount of stabilization (if any) *** 3. Surface coating (if any) 4. Type of grading (cut or fill) **C. Roadbed layer properties (subgrade)** 1. Type of stabilization (if any) 2. Stabilization thickness 3. Type of grading (cut or fill) ***	**A. Moisture** 1. Rainfall *** 2. Humidity 3. Evaporation 4. Transpiration **B. Temperature** 1. Solar radiation 2. Thermal fatigue (number of annual freezing and thawing cycles) 3. Annual lowest temperature*** **C. Clay activity** (shrink/well characteristics) ***
D. Shoulder 1. Surface layer a) type of material (concrete cement, asphalt cement) b) Thickness	**III. Traffic Volume** **A. Accumulated 18-kip ESALs** **B. Annual Average Daily Traffic (AADT)** **C. Directional distribution factor (D)**
2. Base layer a) type of coarse aggregate b) type of stabilization (if any) c) thickness	**IV. Pavement Age (in months) *****

Selected Experimental Parameters (indicated by *** above):

1. Slab thickness
2. Coarse aggregate type
3. Subbase type (cement-treated, asphalt-treated, lime-treated, crushed stone)
4. Roadbed soil (swelling, nonswelling)
5. Average annual rainfall (high, medium, low)
6. Average annual lowest temperature (high, low)
7. Age
8. Roadbed grading type (cut, fill, at grade, transition)

Table 7.2 Overall ranking of variables that influence performance of rigid pavements (Gräter 96)

1. Strength
2. Thickness
3. Subgrade modulus
4. Subbase type
5. Concrete modulus
6. Subgrade type
7. Placement time
8. Thermal coefficient
9. Coarse aggregate type
10. Load transfer
11. Drainage
12. Drying shrinkage
13. Curing
14. Strength variance
15. Overall variance
16. Seal type
17. Pumping
18. Initial serviceability
19. Swelling
20. Dowel support modulus
21. D-cracking
22. Percent steel
23. Air content
24. Crack width
25. Fine aggregate durability
26. Ion levels
27. Macro texture
28. Permeability
29. Water-cement ratio

Table 7.3 Other variables influencing performance for rigid pavements as identified by TQI workgroup (Gräter 96) and which need to be considered

1. Depth to cover of reinforcing
2. Mortar (paste) density
3. Time of opening to traffic
4. Unit weight of concrete
5. Abrasion resistance of concrete
6. Cement type
7. Clay and other undesirable materials in aggregates
8. Concrete density
9. Achievable allowable variance in construction parameters
10. Initial pavement condition survey (early distress manifestations)
11. Joint movements
12. Larger allowable maximum size coarse aggregate
13. Load-deflection characteristics of the pavement
14. Traffic noise levels
15. Polish value as a test for lasting skid resistance instead of acid insolubility
16. Subbase layer levels
17. Quality-control practices
18. Reduced method specification for curing

There are nine main categories of the critical data items: (1) physical section description, (2) geometric information, (3) design information, (4) construction information/records, (5) traffic data, (6) environment-related data, (7) maintenance and rehabilitation information, (8) performance and condition information, and (9) autopsy data. These categories closely match the data categories suggested for a forensic investigation by the TxDOT Administrative Circular, as well as the Critical Data Items identified by the Expert Task Group meeting in December. The four categories for the data elements include: (1) absolutely required, (2) highly desired, (3) desired, and (4) hopeful. This summary of database elements can be found in Appendix E.

CHAPTER 8. THE CONCEPTUAL FRAMEWORK

8.1 A CONCEPTUAL FRAMEWORK OF THE COMPUTERIZED FORENSIC INFORMATION AND ANALYSIS SYSTEM

Ultimately this project will lead to a computerized forensic analysis procedure for use in Texas. Of course, the decisions about, and processes of, such a procedure will need to be approved by the TxDOT staff, but the present concept is illustrated here for clarity. Minor aspects can be or have been adjusted based on the research done during the data and information specification process. We believe that this framework will produce a user-friendly, flexible tool that, when finalized, will reduce the amount of time required to collect and analyze forensic data. In addition, the results of the forensic investigations conducted will be more accessible to the districts and divisions than they were in the past.

The purpose of the conceptual framework is to highlight the major components of the computerized forensic information and analysis system (ForenSys) and to configure the logical data flow paths among these components. In other words, conceptual framework design is intended to provide a blueprint for developing the proposed system. The conceptual framework has to accommodate the following three important factors:

1) TxDOT is in the process of establishing its GIS architecture.
2) TxDOT will soon be retooling its computation environment to use Windows NT as the Operating System and SYBASE as the primary database.
3) The system will have to handle a wide variety of digital data and information in such formats as texts, numbers, images, video, and audio.

Considering the nature of the data required for forensic investigations and the three important factors listed above, a GIS-orientated forensic information and analysis system (ForenSys) is the best choice for TxDOT. Using the results of research conducted by Zhang at The University of Texas at Austin (Zhang 96), a conceptual framework for such a system has been developed. The system is illustrated in Figure 8.1.

ForenSys is intended to operate under the state-of-the-art Multiple Document Interface (MDI) environment for easy data analysis, manipulation, and operation. There it would be able to handle a wide variety of data and information visually, analyze them spatially, and present the results graphically. An expert system might eventually be included to help investigators conduct better forensic analyses and to train new forensic engineers. Important issues and components involved with the conceptual framework are discussed below in the following section.

8.1.1 General Considerations of Forensic Information Database

The database is the central feature and most important component of a computerized forensic information and analysis system. The quality of the data maintained by the database directly affects the value of the system. From the perspective of database design and development, certain mechanisms must be included to preserve the four basic characteristics a database must have. These required characteristics include integrity, accuracy, validity, and documentation.

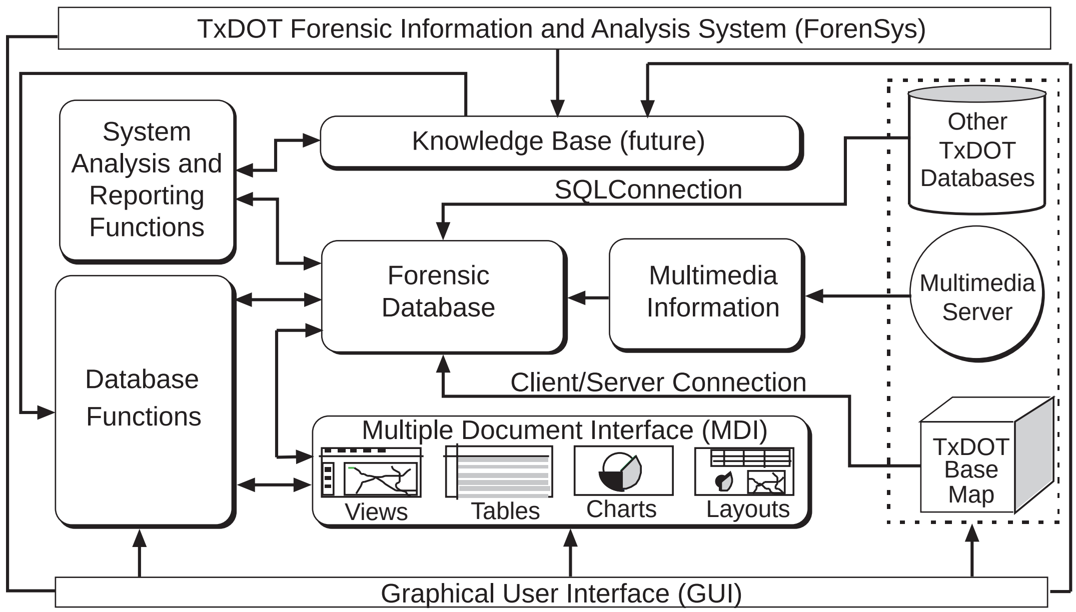

Figure 8.1 Conceptual framework design for TxDOT forensic information and analysis system (ForenSys) (Zhang 96)

8.1.2 Database Management, Data Manipulation, and Results Presentation

Forensic investigations should be based on scientific analysis of data and information. A good forensic information and analysis system should allow users to maintain their database easily, manipulate their data effectively, and present their results visually. The following explanations further describe these concepts.

1) *Database maintenance:* The database portion of ForenSys will include two databases: (1) the attribute database, and (2) the geographic database. Database maintenance in the system is intended to provide all kinds of database management capabilities, such as creating a new database, modifying an existing database, adding/deleting data fields, updating data values, etc.

2) *Multimedia data support*: Most of the information related to forensic engineering often exists in different formats (e.g., tabular data, spatial data, drawings, videos, images, etc.). The system is designed to include a multimedia interface and related capabilities to support all kinds of multimedia data, such as videos, sounds, images, pictures, and numbers.

3) *Data query*: Data query means that data records in a data table or geographic features on a map theme can be selected by a defined set of query conditions based on their attribute values and relations. Through user-friendly data query graphical user interfaces (GUIs), rather than through complex programming, the user should be able to conduct a wide spectrum of sophisticated data queries to support forensic analysis.
4) *Data manipulation*: Data manipulation is a necessary routine for conducting forensic analysis. The system should allow the user to perform a wide variety of data manipulation operations on the records of any data type, including number, string, date, and Boolean. The results from such manipulation can be used either to create a new data field or to replace the values of an existing field.
5) *Results presentation*: A good forensic information and analysis system should be able not only to conduct sophisticated analysis, but also to produce presentation-quality reports. These reports may be produced in various formats, including, but not limited to, tables, maps, spreadsheets, graphic charts, or a combination of these. The user should be given the flexibility of defining and/or customizing the reports based on his/her own needs.

8.1.3 Geographic Database

The geographic database is a database management system that organized a collection of spatial data and related descriptive data for efficient storage and retrieval using a georelational and topological data model. The georelational data model combines closely related physical geographic features into a set of independently defined layers, themes, or coverages consisting of points, lines, or polygons. For example, pavement network and unusual climatic or subgrade soil conditions can be represented by separate coverages.

8.1.4 Attribute Database

The attribute database is a relational database management system (RDBMS) for the storage and retrieval of tabular data. The attribute database can be either a part of the geographic database or a separate relational database that is SQL (sequential query language) compliant.

8.1.5 Graphical User Interface (GUI) Design

A user interface is the boundary across which the user interacts with the system. A well designed, user-friendly graphical user interface (GUI) not only greatly decreases the user learning curve, but also increases the chances of successfully implementing the system.

8.1.6 Multimedia Server

Multimedia data such as videos and sound files usually require a large amount of disk space if they are stored on the computer disk. Sometimes it simply may not be feasible to do so because of the disk-capacity limitation of microcomputers. One of the solutions for multimedia data storage and retrieval is to use the laser compact disk (CD) as the storage media if a writeable CD driver is available. But the best solution would be to set up a special multimedia server where the same multimedia data could be accessed simultaneously by many users through network connections.

8.2 ADVANTAGES OF A GIS-BASED DATABASE SYSTEM

As stated earlier, considering the nature of the data required for forensic investigations and the three important factors regarding system structure within TxDOT, a GIS-orientated forensic information and analysis system (ForenSys) would be the best choice for TxDOT. The advantages of a GIS-based system include the following:

1) A GIS-based system can improve information reporting using graphics rather than tabular data. This is particularly important to pavement engineers, who must relate soil, climate, traffic, and pavement condition data to identify complex engineering relationships and performance trends. A GIS can help identify trends in pavement failures and represent them visually. Visual representations often give insight into the causes of problems because they help represent trends that would not be distinguishable by just looking at the data alone.

2) A GIS-based system can improve efficiency by linking together several data sources more effectively. Using several sources, information can be combined in a GIS to create analyses and representations of the results that incorporate data from all these sources. This is an important feature of ForenSys because it will allow the data stored in other TxDOT databases to be accessible to the forensics system without needing to be copied or stored in the forensic system.

3) A GIS-based decision support tool can help pavement managers determine which roads need treatment now and which can wait. In terms of the forensic system, similar features would include the ability to search for pavements similar to one that underwent a forensic investigation. Then, based on various critical characteristics of the failure, similar problems and imminent failures could be located so that corrective actions could be made or so that the appropriate funding levels for rehabilitation could be determined.

4) A GIS-based system can make better use of scarce labor and financial resources. The use of the ForenSys, and the collection of data on pavements that perform well and poorly, will provide pavement engineers with the ability to find pavements with exact or similar characteristics within a certain tolerable range through the analysis capabilities of a GIS. When these results are represented graphically, the analysis process should become more efficient, resulting in the most beneficial use of financial resources. In terms of scarce labor, ForenSys should help lighten the workload of forensic engineers by making the analysis and data collection process of a forensic investigation easier and less time consuming.

Additionally, even though manpower may be scarce, the ability to make use of the previous experience and results of other forensic and pavement engineers in a GIS-based analysis format should help not only to ensure that knowledge gained over the years will be put to use, but that past mistakes will not be repeated.

CHAPTER 9. PAST AND FUTURE DIRECTIONS

The past several chapters have dealt with the types of data that currently exist, as well as data the forensic system ideally would need to contain. With the actual development of the forensic investigation system (ForenSys), the researchers will be able to combine these aspects into an operating system that will enhance knowledge gained from a premature failure. This chapter summarizes the research accomplished so far and describes the future direction of the project. It also presents researchers' suggestions about potential ways to improve the system that is being developed for forensic investigations.

9.1 RESEARCH ACCOMPLISHED

The following list is a summary of the main accomplishments of the investigative effort to date.

1) The research team has gained a solid understanding of the forensic field and the requirements for a forensic investigation. The methodology used for a forensic investigation provides insight into processes that will typically be used to form a probable cause of failure. It also provides information about types of information that may be collected in such an investigation and that would, thus, need to be stored in the forensic database.
2) The research team has extensively reviewed numerous forensic investigation reports. These reports provided information on the types of factors and failure hypotheses investigators have considered in the past. The reports also illustrated the types of data the investigator frequently ends up collecting owing to a certain hypothesis being proven correct or incorrect.
3) The research team has compiled and reviewed a summary of TxDOT databases. The research team has also reviewed other existing sources of TxDOT data that may provide additional information for the forensic database. The information regarding all the potential sources will be used to maximize the use of TxDOT's existing data. The data may be related to a project in general, or may include specific details that provide insight into the cause of a failure. Preparation of this database summary, as well as the list of other sources, ensures that the same data item will not be collected or entered in more than one location.
4) The research team has completed a compilation of data elements required for a forensic investigation. This list provides the backbone for the database and begins to illustrate the manner in which the fields ultimately will be linked within ForenSys. The team is in the process of obtaining feedback from experts in the field of pavement performance in order to perfect the list and to focus on only the most critical data elements that will be used for the pilot system.

9.2 FUTURE DIRECTION OF THE PROJECT

Although much work has already been accomplished on this project, much still remains to be done in order to ensure the success of a functional forensic system. The tasks listed below describe the steps that the research team will take to complete the project. These tasks relate to the short-term future as defined by the project completion date of August 1998.

Most of the project will involve the actual development of the ForenSys software. The research team will need to keep current with the changing data environment within the Department and adapt the forensic system as is necessary and as possible. This will include continuing efforts to monitor the development of existing and future TxDOT databases. Many details within the Department still need to be worked out, such as which database will be responsible for storing certain types of information, how all of the databases will be linked, and where some of the data collected in certain systems will be permanently stored. It is still uncertain within the TxDOT organization exactly which data will be organizational records that all areas can use, and which will be departmental records to which access is restricted. TxDOT has created a specific group, the Information Systems Division (ISD), that has this task as part of its mission. Eventually, part of the project will entail critical database issues in order to avoid redundancy of data-collection efforts.

TASK 1: Finalize the Conceptual Design of ForenSys — Although a preliminary conceptual design for the ForenSys system was proposed in the original project proposal, efforts by the research team are needed to further examine, improve, and finalize the conceptual design. Work is progressing on the development of a conceptual framework illustrating the connections and flow of data between different parts of the forensic system and various parts of the information system within TxDOT. This process also includes the selection of programming software, data structure of the database, and issues related to GIS integration. Work will be completed once all the theoretical and practical details have been reviewed and properly configured.

TASK 2: Finalize the Critical Data Items — Although considerable effort has gone into developing the first draft of the critical data items to be included in the ForenSys database, the research team needs to further analyze and finalize the identified data items, along with their proposed levels of priority. The approach required to accomplish this is to initiate a number of small Expert Task Group (ETG) meetings. There, participants could go through the draft version of the critical data items one category at a time in order to come up with a group consensus on the critical data items required for a forensic investigation.

TASK 3: Develop the Prototype System of ForenSys — A prototype system will be developed that is based on the finalized conceptual design discussed in Task 1 and the critical data items. The prototype system is intended to include all the major features of ForenSys and will use samples of real data and/or near-to-real data.

TASK 4: Develop the Deliverable ForenSys Software — Most of the efforts will concentrate on the development of the deliverable ForenSys software in FY 1998. Development of the database system is considered to be Phase II of the project. This task requires actual programming and setting up of the required information database. The prototype developed in Task 3 will be used as the basis for the deliverable software development.

TASK 5: Preparations for Pilot Implementation — Preparations for the pilot implementation will be conducted a couple of months ahead of the target date for the software completion in order to ensure that all important considerations have been made and all the details are in order. Thus, once the software reaches completion, it will be possible to actually begin the pilot implementation.

TASK 6: Pilot Implementation — The next step will be to assist in the pilot implementation of the database, which is also an extremely important part of this project. Special attention will be given to this task to ensure overall success of the project. Two districts, Odessa and Fort Worth, have already agreed to conduct the pilot implementation. After the system has been tested through actual use at the test sites, feedback will be given on ways to improve the system—such as data elements to incorporate—before statewide implementation takes place.

TASK 7: Prepare Reports — All the reports and software manuals for the system as outlined in the original project proposal or as warranted for actual use of the system will be prepared by the research team.

9.3 PROPOSED AREAS FOR FUTURE IMPROVEMENT

It is important to stress the need for further improvement of ForenSys even after the pilot implementation has been completed. The results of the pilot implementation need to be evaluated carefully in order to determine the potential use of the system statewide and to make any improvements before full implementation. Once the system begins to be used, feedback from users will be crucial in evaluating the true value of the system and determining the need for improvements. At present, the research team has identified three possible areas for the long-term future direction of the forensic investigation system.

1) A formal forensic investigation procedure should be developed that directly entails the use of the ForenSys within TxDOT. Envisioned is a consistent, effective procedure that will be able to streamline the current forensic investigative process that entails requesting a forensic investigation team from the state's design division.
2) The second recommendation is to improve the system by adding more features. A key feature of this system's development and long-term value is its degree of flexibility. After districts become accustomed to using the system and begin to gain from it, the possibility of expanding the system should be explored. Also, additional analysis features could be added as recommended by users. A potential link between this database and the Materials Performance Database (TxDOT Research Project 0-1785) should be considered.
3) Another possibility for the future direction of pavement forensic investigations would be to add an expert system to the analysis capabilities of the database. This would help engineers reach preliminary analysis results based on the knowledge of experts in the field, and would serve to train new engineers more effectively. Such a system would ensure that knowledge and information are not lost with personnel turnover within the department.

9.4 CONCLUSION

The potential value of a forensic database analysis tool is obvious. Such a system will provide forensic investigators throughout the state of Texas with an information source that will eliminate unnecessary, time-intensive searches for information. In the past, project information has been stored to varying extents. The forensic database would prevent information stored in different locations from being lost or misfiled; in other cases it would house information that was simply never recorded. The forensic database would also serve as a tremendous resource to district engineers and design engineers for design procedures and methods used. It would also allow TxDOT to identify pavement sections that may be subject to certain types of probable failure. Finally, the database information would allow users to compare a wide range of alternatives and, based on that comparison, to design and maintain the best pavements possible for Texas.

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APPENDIX A:

TXDOT PAVEMENT FAILURE CASE STUDIES

FLEXIBLE PAVEMENT CASE STUDIES

Case 1.

Distress Types	Severe Block Cracking (but little structural damage = rutting or cracking)
Location	US 82 - District 1, Grayson County
Structure	3.81 cm (1 ½”) surfacing, 21.59 cm (8 ½”) black base, 15.24 cm (6”) granular subbase
Details	The major problem with the highway was shrinking and swelling of the subgrade.

Case 2.

Distress Types	Major Block Cracking/Alligator Cracking
Location	State Highway 158 - Odessa District, Midland County
Structure	4.45 cm (1.75”) ACP surface, 25.4 cm (10”) crushed limestone flexible base
Details	Testing indicated that the base and subgrade were in good condition. The laboratory results indicated that the viscosity of the residual asphalt was unusually high. Penetration test results indicated a very stiff asphalt that might be prone to cracking.

Case 3.

Distress Types	Block Cracking/Alligator Cracking/Rutting/Flushing/Raveling (all predominantly in outside lane)
Location	US 77 - Pharr District, Cameron County
Structure	3.81 cm (1.5”) ACP overlay, 13.97 cm (5.5”) ACP, 33.02 cm (13.0”) caliche, 15.24 (6.0”) lime-treated subgrade
Details	Pumping of fines had occurred through some cracks, which therefore indicated that some cracks extended through the ACP layers. This was verified by full-depth cracking found in cores. The cores also indicated stripping and disintegration of lower ACP layers. The FWD data indicated a relatively weak ACP surface layer, which was attributed to the cracking and stripping in the surface. The FWD data indicated weak base layers but strong, stabilized subgrade layers overall. Both showed considerable variability. The FWD indicated that the subgrade was relatively weak. The conclusions made were that the weak ACP moduli values reflected the cracking and stripping that was occurring in the ACP layers. In terms of overall stiffness, the right outside lane was considerably weaker than the left lane, causing the apparent difference in distress magnitudes.

Case 4.

Distress Types	Extensive Alligator Cracking
Location	US 290 - Austin District, Lee County
Structure	The base was made up of 30.48 cm (12”) of foundation course on the far western end of the project to 20.32 cm (8”) of flexible base in the central portion to 30.48 cm (12”) of flexible base on the eastern end. The base also varied from the original pit-run, river-gravel material to limestone-aggregate, flexible material. 1.02–13.97 cm (0.4–5.5”) of ACP surface in eastbound direction/6.35–15.24 cm (2.5–6.0”) in westbound direction.
Details	No pumping of base fines was occurring. The cores contradicted the information available in the plans at times, and indicated that several successive seal coats and ACP overlays had been placed. Through analysis of the FWD data with the MODULUS back-calculation program, it was concluded that the pavement structure had basically exhausted its fatigue life, causing the ACP surface to crack.

Case 5.

Distress Types	Alligator Cracking and Pumping of Flexible Base Fines in the Wheel Paths (predominately in the outside lane)
Location	RM 2222 - Austin District, Travis County
Structure	39.37 cm (15.5”) flexible base, 2.54 cm (1”) ACP Type D layer, 3.81 cm (1.5”) ACP Type C surface course.
Details	It was hypothesized that the cracking may have been due to improper use of the vibratory roller on the Type D ACP. If the vibratory roller had been operated in the high-impact, low-frequency mode, damage could have occurred. The air void contents were tested from the cores taken, revealing the air voids to be 8–13 percent, which is too high for ACP surface courses because it may be such a permeable layer that it lets in water to the underlying layers. The FWD data indicated that the modulus (material stiffness) values of the ACP were weak in many areas. The base also had a few existing weak areas but was in good condition overall. The Ground Penetrating Radar (GPR) indicated that a significant amount of moisture was present at the interface between the ACP surface and the flexible base, which supported the hypothesis that the ACP surface—which had a high void content—was absorbing water. The moisture can cause the base to weaken, resulting in the distress present on the roadway.

Case 6.

Distress Types	Rutting
Location	IH-35 - Laredo District
Structure	This roadway included both concrete and asphalt-surfaced pavements. Asphalt structure (the critical one): 5.08 cm (2”) asphalt surface, 15.24 cm (6”) asphalt base, 30.48 cm (12”) flexible base, 20.32 cm (8”) stabilized subgrade
Details	The primary distress mode was rutting in the asphalt pavement. Other distresses included shoving, pumping, and flushing of the asphalt cement. The conclusion was reached that the roadway had simply reached the end of its service life. It was determined that the amount of traffic, in terms of 18 kip ESALs that was originally projected for the sections, was underestimated by a factor of three. The additional traffic led to excessive consolidation in the asphaltic pavement layers and, thus, to the subsequent pavement failure. The pavement deterioration was aggravated by the saturation of the soils and moisture intrusion of the pavement surface due to a faulty sprinkler system. However, deflection testing indicated that the base and subgrade layers part are still providing adequate support for the most part, and thus, would be acceptable to use for any rehabilitation strategy with only minor revitalizations of a few weak areas.

Case 7.

Distress Types	Intermittent Surface Rutting and/or Shoving in Localized Areas
Location	US 183 - Brownwood District, Lampasas County
Structure	None given.
Details	The localized areas of distress ranged in length from 3.048 m to a couple of hundred meters (ten to several hundred feet) and were randomly spaced. The material appeared to be shoving laterally along with some vertical consolidation. A potential problem source was a new pavement structure built over an older pavement structure but FWD data indicated that the pavement structure had sufficient strength (material stiffness). The focus of the investigation turned to material quality and durability. It was concluded, through additional testing with the Magnesium Soundness Test and the Wet-Ball Mill Test, that the aggregate base near the surface was not of sufficient quality to perform as a base layer near the surface because it could easily be crushed under load.

Case 8.

Distress Types	Regular Transverse Cracking at 30- to 50-foot intervals with Associated Longitudinal Cracking in the wheel paths
Location	IH-27 - Amarillo District
Structure	10.16 cm (4”) hot-mix asphalt surfacing, 12.7 cm (5”) asphalt stabilized base, 17.78 cm (7”) gravel base, 10.16–12.7 cm (4–5”) caliche subbase, weak clay subgrade
Details	Some of the longitudinal cracks were exhibiting pumping. Disintegrations of the surface mix were occurring primarily in the left wheel path of the outside (truck) lane. The pavement had no evidence of chemical stabilization even though the alignment crossed the outskirts of playa lakes. The existing clay subgrade was very weak (as indicated by the Triaxial class), was potentially reactive (as indicated by plasticity index), and was susceptible to moisture damage (as indicated by the liquid limit). The drainage on this project was poor to inadequate. The existing gravel base on this project was extremely temperature-susceptible (as indicated by the high thermal coefficient) and was historically susceptible to moisture damage over time. The asphalt-stabilized base and hot-mix asphalt were temperature-susceptible and historically susceptible to moisture damage. The case presented was that of the pavement failing from the bottom up.

Case 9.

Distress Types	Swelling Clay Problems
Location	Proposed US 183 - District 13, Gonzales County
Structure	None given; information based on memo regarding lime stabilization (not a full forensic report).
Details	The proposed 40.64 cm (16”) deep lime-treated subgrade in problem areas on the project seemed to be the most effective solution for the swelling clay problems. There are tests available for determining the amount of lime needed for effective lime stabilization. Such a test should be implemented because the optimal solution may be greater than the proposed 4 percent.

Case 10.

Distress Types	Longitudinal and Transverse Cracking
Location	East-West Freeway/US 67 - San Angelo District, Tom Green County
Structure	Subgrade was caliche and other native soils of low to moderate plasticity. The moderate to highly plastic clays were stabilized with 2 percent lime.
Details	The limestone base material was progressively softer/weaker at depth with increasingly higher soundness losses. As the aggregate breaks, additional fines are created which are conducive to shrinkage cracking of the base material. The shrink/swell potential of plastic soils is directly related to the plasticity, density, and moisture content of the soils. These conditions hold for the compacted subgrade, which means a high swell potential. The base construction practices were determined to be a major cause of the pavement distress. The contractor used excessive water in the construction process, which caused the base material to become desiccated. Thus, the base material achieved the density requirement without additional mechanical compaction, by the volume decrease due to the desiccation. It was hypothesized that the large magnitude of volumetric shrinkage caused premature cracking in the base material, which reflected through the overlying asphalt concrete surface.

Case 11.

Distress Types	Flushed Areas
Location	IH-10 - Odessa District, Pecos County
Structure	None given; information based on memo regarding completed core testing (not a full forensic report).
Details	There was a significant difference between the density of the cores in the wheel path and between the wheel path. A softer AC was determined to exist in the flushed areas. The penetration values are much lower than those that typically exist for a pavement that has been in service for only a few months. A gas chromatograph analysis confirmed that diesel fuel is present in the mix where flushing is heavily evident. The conclusion was that, since diesel was used on the roller wheels of the compactor to prevent sticking of the HMAC, localized overspilling on the fresh pavement may have caused the asphalt to soften up and move to the surface.

Case 12.

Distress Types	Surface Irregularities such as Surface Popping and Excessive Rutting of the Surface
Location	Follett-Lipscomb County Airport - Amarillo District, Lipscomb County
Structure	Original : three-course surface treatment, 15.24 cm (6”) crushed caliche base, compacted brown sandy clay subgrade. Apron expansion: 3.81 cm (1.5”) hot-mix asphaltic concrete (HMAC), 15.24 cm (6”) crushed caliche base, compacted brown sandy clay subgrade. 3.048m (10’) widening: three-course surface treatment, 20.32 cm (8”) compacted crushed caliche base, compacted brown sandy clay subgrade. 3.048 m (10’) widening was reconstructed and appeared to experience base failure. The surface appeared to be very soft and delaminated from the base material.
Details	The surface irregularities were the result of surface materials separating from the supporting base layer. The possible causes of this distress were chemical incompatibility of the materials used, or lack of bonding of the surface treatment at the base interface due to conditions of the base interface. The excessive rutting resulted from the surfacing material conforming to the shape of its supporting base material layer. The rutting appeared almost block-like, which indicated problems with the materials within the top 5.08–15.24 cm (2–6”) of the pavement. This may have been caused by weak or over crushed base or very soft asphalt cement. Coring determined that the base material was crushed within the top 2.54–3.81 cm (1.0–1.5”) of the 15.24 cm (6.0”) base layer. Longitudinal cracking was limited to the area immediately adjacent to the block-like rutting, as well as to the extreme edges of the pavement. Longitudinal cracking at the edges of the pavement is common due to the reduced lateral support provided. The FWD and back-calculations indicate that the subgrade moduli values vary between poor and fair, and the subbase moduli are in the good to very good range. The modulus values for the top 5.08 cm (2”) of the base are in the very poor range, which indicates that they may have been over-rolled or rolled with an inappropriate roller type during construction.

Case 13.

Distress Types	Fatigue Cracking and other Structural Disintegration (within a few weeks of being opened to traffic)
Location	US 287 - Childress District, Childress County
Structure	6.99 cm (2.75”) Asphalt Concrete (300 #/yd^2), 40.64 cm (16”) flexible base (sand and gravel), crack and seat 9-6-9 concrete pavement subbase. Widened with: 6.99 cm (2.75”) Asphalt Concrete (358#/m^2; 300 #/yd^2), 40.64 cm (16”) flexible base (sand and gravel), 45.72 cm (18”) lime-treated materials
Details	The FWD data indicated that the modulus (material stiffness) values of the base and subbase were weak in many areas. On the day of testing there was water standing in ditches, even though it had not rained within three to four days prior; thus, water lying in both the median and outside ditches could possibly have migrated into the unstabilized sand/gravel base layer. Cores were taken, revealing high air voids that may have allowed moisture penetration through the ACP, thus, contributing either partially or wholly to the saturation of the base and subgrade. The penetration grade of the asphalt cement was low, which would have increased the chances for fatigue cracking in the cold winter months; there also existed gap grading of the aggregate mix. Another possible explanation is that the lime-treated subgrade material extends below the bottom of the concrete pavement and thus could possibly trap moisture under the concrete slab. It is feasible that moisture trapped under the slab could be pumped up into the base under the action of traffic. The construction of this project took place late in the season and before completion a winter storm produced rain, snow, and 5.08–10.16 cm (2–4 in.) of ice on the roadway surface. It was concluded that weak/wet base and weak/wet subgrade resulted in poor support for the ACP surface. The combination of a stiff, brittle mix and heavy trucks resulted in the accelerated fatigue cracking and failures experienced.

RIGID PAVEMENT CASE STUDIES

Case 14.

Distress Types	Rutting/Shoving/Cracking (load and nonload related)/Loss of Ride Quality
Location	Kemp Street - Wichita County
Structure	15.24 cm (6”) jointed plain concrete pavement (JPCP) with 11.43–17.78 cm (4.5–7.0”) asphalt concrete overlay in two lifts
Details	The main distresses were rutting of up to 5.08–7.62 cm (2–3”) in the wheel path and reflective cracking at 30–40 percent of the transverse joints. Transverse, longitudinal, and random cracking were present, which indicated that some underlying slabs may require repair or replacement due to some of these cracks reflecting through the overlay. The concrete moduli values indicated that the concrete strength was good to very good. The difference between the back-calculated and measured values was thought to be due to the presence of voids under the concrete slabs, in addition to the cracking. Poor subgrade support values existed along the entire length of the project. It was concluded that, with repairs to the slab and sealing of the voids, the structural integrity—and thus, the load-carrying capacity of the slab pavement—should improve.

Case 15.

Distress Types	Extensive Transverse and Longitudinal Cracking
Location	IH-40 - District 25, Wheeler County
Structure	20.32 cm (8”) continuously reinforced concrete pavement (CRCP) with an asphalt concrete pavement (ACP) shoulder, 15.24 cm (6”) asphalt stabilized base
Details	The ride quality was still very good, and there were no signs of pumping of the subbase or subgrade material either from beneath the pavement or at the pavement edge. It was determined that there was no alkali-silica reactivity within the concrete. The subgrade on the project had a low shrink-swell potential and moderate permeability. The roadway was built in the early 1960s and seems to have exceeded it design life in terms of truck traffic.

Case 16.

Distress Types	Uncontrolled Longitudinal Cracking
Location	IH-20 and Loop 288 - Dallas District; Denton, Dallas and Kaufman Counties
Structure	Concrete pavement (contained tiebar steel). No other details given.
Details	Examination of the cores indicated that, of the majority of the cores taken at the joint, the joint did not crack as expected, which seemed to explain the majority of the longitudinal cracking. Gypsum (which is soluble in water), was found in the clay subgrade underneath the pavement, which could have been a potential problem if the gypsum had been removed due to water percolation through the subgrade. The presence of gypsum also could cause cracking problems because it is a sulfate compound, and if sulfates come in direct contact with concrete, cracking problems may occur. The clay subgrade was found to be particularly moist, which may also explain the cracking in that area, the clay subgrades in the project location are subject to shrinking and swelling due to moisture variations.

APPENDIX B: TESTING PROCEDURES USED FOR TXDOT FORENSIC INVESTIGATIONS

APPENDIX B: Testing Procedure Used for TxDOT Forensic Cases

	Case Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Location																
• Detailed map showing project beginning and ending		X														
Climate During Construction																
• Climatic factors = description													X			
• Avg. annual daily max temp.													X			
• Avg. annual daily min temp.													X			
• Avg. summer temp. (July)														X		
• Avg. winter temp. (Jan)														X		
• Avg. annual precipitation													X	X	X	
Section Information																
• Typical cross sections – plan sheet = thickness, materials used	X						X						X	X		
Pavement structure from District info–plans						X										
• Number of lanes	X															
• Lanes = divided or undivided	X															
Visual Inspection / Site Visit ➔ distress manifestations							X		X				X	X		
Photographs of pavement condition	X		X									X			X	
Interviews district construction engineer, project engineer, laboratory supervisor, and project inspector									X							
Structural Evaluation																
• Dynaflect	X	X				X	X					X		X		
• FWD	X	X	X	X	X	X	X					X	X	X		
• MODULUS back-calculation of elastic moduli values			X	X	X							X		X		
Roughness Evaluation																
• TxDOT profilometer	X															
• Ground Penetrating Radar (as thickness survey, can detect the presence of moisture in pavement layers)	X	X			X								X			
Subgrade Evaluation																
• Dynamic Cone Penetration Tests (subgrade evaluation)	X	X														
• Potential Vertical Rise – results from TxDOT geotechnical eval.	X															

Materials Sampling	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
• Presence of reinforcing steel/load transfer devices / placement of														X		X
• Existence of voids under concrete slabs														X		
Cores	X		X	X	X	X		X		X		X	X	X	X	X
• Stripping			X													
• Disintegration			X													
• In-place densities			X													
• Core density						X										
• AC content in the mix, %			X										X			
• Bulk gravity/avg. bulk gravity			X													
• Rice gravity			X										X			
• Avg. relative density			X													
• Relative density of top layer										X						
• Avg. air voids/air void content			X		X								X			
• Tensile strength/avg. tensile strength			X										X	X		
• Modulus (psi)														X		
• Sieve analysis = aggregate gradation													X			
• Thickness/layer thicknesses					X	X										
• # of overlays														X		
• Corrosion of rebars															X	
Extractions from Road Samples																
• Penetration on residual asphalt			X							X			X			
• Viscosity on residual asphalt			X										X			
• Ductility on residual asphalt			X													
• Gas Chromotograph (GC) analysis										X						
• Alkali-silica reactivity of concrete pavement samples															X	
Lanes Trenched																
• Materials sampling: surface, base, subbase, subgrade						X										
• Subsurface investigation: materials identification						X										
• Subsurface investigation: stabilization						X										
Laboratory Testing																
Materials sampled: base/aggregate base							X	X				X				
Magnesium Soundness Test							X		X			X				
Wetball Mill Test							X					X				
Temperature Susceptibility (thermal coefficient)								X								
Stabilization agent												X				

Materials Sampling (cont.)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Sieve analysis												X				
Atterberg limits												X				
Surface-to-base stiffness ratio													X			
Materials sampled: existing subgrade								X							X	X
Type of material								X							X	
Triaxial class								X								
Plasticity Index (PI)								X								
Liquid Limit (LL)								X								
Stabilization?								X								
Shrink–swell potential															X	
Degree of permeability															X	
Presence of sulfates/gypsum																X
Core Records							X									
Lab Records							X									
Materials Sampling (cont.)																
Predominant Soil Types – detailed description of each soil type as taken from the Soil Conservation Service Soil Survey/engineering properties of soils													X	X		
Observations on the Presence/Existence of Pumping (at cracks, pvmt-shldr edge)			X	X				X							X	
Extent of pumping								X								
Saturation of the soil – moisture level						X										
Molded laboratory specimens – moisture density curve												X				
Quality of Drainage (adequate, inadequate, poor, etc.)								X								
Traffic Data														X		
level of truck traffic/% heavy trucks				X									X		X	
AADT/ADT	X												X			
Twenty-year design – 18 kip ESALs	X					X										
Project Construction Records									X							
Construction Records: milling, sealcoats, overlays, etc.				X												
Pavement history from district info.						X										
Construction plans: maintenance activities				X												
Construction observations													X			
Additives/modifiers to seal coats and hot mixes	X															
Standard Specifications					X											
Specifications for cracking and sealing													X			
Mix Design															X	

APPENDIX C: SUMMARY OF MAIN COMMENTS AND DISCUSSION ITEMS FROM THE FIRST EXPERT TASK GROUP MEETING

CONSTRUCTION-RELATED PROBLEMS

1. There is a difference between chronic and forensic failures. Catastrophic failures are one-time, sudden occurrences (not chronic), and it is often debatable whether they are construction or design related. There is also a difference between failures in which the specification was not followed and failures in which the specification was followed and the pavement still failed.
2. There is often incompatibility among design/construction and materials selection.
3. Proper documentation of weather conditions is required, especially for construction in adverse weather conditions. Sudden weather changes during construction affect possible failures and, thus, should be recorded.
4. The roadway's initial serviceability (roughness) is an important consideration after construction.
5. The curing conditions during construction can influence the pavement's performance.
6. There is a problem with inexperience and/or inadequate testing and inspection in the field. The quality of testing may be a factor because less testing means that more variability in the materials is not being caught. There has been a migration of expertise from the department to private contractors, which often means that the inspectors are inexperienced. There may be a lack of pride in TxDOT or a lack of responsibility. Inexperience inspectors often are afraid of conflict because they want to see things pass and to see have the construction go smoothly. Partnering may be being pushed too far.
7. Sometimes encounter untrained contractor workers or contractors not experienced in quality control. Need to show them what is desired and what the consequences are. Additionally, a better mechanism for feedback from the contractor needs to be established.
8. The sequence of construction and the effect of construction traffic can cause not only inconvenience but also damage to the new pavement. An example of this involves building the frontage roads first and then transferring the traffic to the frontage roads as the main lanes are constructed. In such a case, the pavement may be overloaded before construction is even completed.
9. It is necessary to establish acceptable drainage throughout the pavement life. This includes the time during construction as well as after construction.
10. An important consideration is what time of day the construction occurred (noon, night, etc.).
11. Often the issue of the availability or nonavailability of construction documents arises. The actual layer thickness may not be equal to the design depth. Need to

determine if a substitution occurred during construction through such documentation as field changes or extra work orders. If a contractor asks for a different thickness or for different materials, the request may be handled through letters or conversation and, therefore, does not necessarily get properly documented.

12. Often problems arise due to poorly-worded, misunderstood, or vague specifications. It is difficult to express an idea in writing so that others understand it.
13. There may be a problem with the adequacy of construction equipment. Issues include: equipment breakdown and malfunction, worn-out or improperly functioning equipment, or even on-site substitution of the wrong equipment. Failures can sometimes be traced to improper calibration, which should have been caught when the equipment was inspected prior to its use.
14. Problems can arise from inadequate construction practice.
    a) Example: The contractor did not prime before construction.
    b) Example: The contractor saturated the soil and put it in too wet, and then allowed it to dry back to optimum, which later caused problems.
15. Construction-related problem: thermal cracking.
16. Construction-related problem: debonding of surface from base.
17. Construction-related problem: low density/high air voids. This distress may be caused by rolling too late.
18. Construction-related problems: stabilization problems.
    a) Improper lime stabilization (leaching)
    b) Excessive deterioration of cement-stabilized bases (in Houston)
    c) Reflective cracking from stabilized bases
19. Construction-related problem: inadequate or improper surface preparation.
20. Construction-related problem: inadequate embankment materials.
21. Construction-related problem: contaminated materials; for example, mudballs in concrete (see Section III materials).

ASPHALT

22. Construction-related problem: HMA segregation that leads to other distresses, such as raveling.
23. Construction-related problem: over-asphalting.
24. Construction-related problem: wrong asphalt used.

25. Construction-related problem: plant damage to HMA, for example; burned hot mix.
26. Production-related issues for HMA arise. For example, improper production causes problems with performance.
    a) Periodic/sporadic contamination may occur.
    b) Need plant and equipment inspection and calibration.
27. Need adequate compaction along longitudinal joints in hot mix; poor longitudinal joints may cause cracking.

CONCRETE

28. Production-related issues for PCC arise. For example, improper production causes problems with performance.
29. Spalling, as related to the construction paving direction, is a construction-related problem.
30. Construction-related problem: timing when adding curing compound.
31. Construction-related problem: water-to-cement ratio including when the water is actually added.
32. Need proper timing for the sawing of joints.
33. Need to ensure proper reinforcement placement, especially dowel bar placement in jointed pavements.

MATERIALS-RELATED PROBLEMS

1. The following types of variability in materials exist:
    a) There is variability in the subgrade.
    b) Soil properties change constantly as moisture changes.
    c) Rehabilitation may change the materials in certain areas but not in others.
    d) Timing variability causes variability in materials to exist. For example, if only a section of a roadway is built each year, different materials may be used. Additionally, there may be changes in the mixes used. For example, if the predominant material were right at limits now but the specs were tightened in the future, the material would be limited.
2. Material properties often change over time. Examples of changing properties include:

a) Lime stabilization.

b) Effects due to temperature.

c) Effects due to moisture.

d) Adhesive properties of aggregate change with time.

3. The material location and function may vary throughout a project. For example, all different types of materials are encountered up and down hills.
4. Problems may arise with the relationship between different layer stiffnesses. Interdependency of layers may occur.
5. Modulus and material properties change due to moisture effects. A change in values can occur throughout the year due to freezing and thawing cycles.
6. There may be competing qualities within materials. Materials are expected to perform so many different tasks and meet so many different criteria that, at times, these may cause direct complications. An example is the conflicting aggregate properties of soundness versus skid resistance. A designer must understand such trade-offs. The conflict may be one of economics versus performance.
7. The issue of compatibility of materials arises with certain applications or uses. Today designers are combining materials that no one has experience using, so the full potential and history of the materials are not known. An example of this compatibility issue is alkali-silica reactivity and sulfate attack.
8. Due to the depletion of good materials, marginal materials are often used. Examples include:

   a) Districts that need to bring in acceptable materials for use on their projects.

   b) The use of iron ore gravel, which was the best material available.
9. The definition of a good material is based on application.
10. Recycled materials have been used to solve the depletion problem. Properties advertised do not match test results. There is a lack of experience with new materials; need to learn how to use properly. There is political pressure to use recycled materials of which we do not have adequate knowledge. An understanding of the future impacts of recycled/by-product materials is needed.
11. The needs for materials are changing. Additionally, in most cases the future design requirements are not known. Examples of changing needs include:

    a) New types of trucks with different loading configurations.

    b) New air pressures in tires but with the same materials used.
12. An analysis basis for stabilized materials is needed.
13. Materials-related problem: aggregate soundness.
14. Variability of asphalt binder in HMAC is an issue. Variability occurs in the following forms:

a) Type (SHRP grading -modified; how to test what we get on the road).

b) Quality: Binder quality is an important factor.

15. An important issue is the ability to determine the current materials' properties. It is essential to have an understanding of what the test results actually mean. Often, current tests are indicators, not true measures, of the properties.

16. A key issue in materials problems is improper testing. Laboratory and field tests are often very different than the actual material quality in the field. A material may have satisfactory performance in the lab (where materials are tested at optimum conditions), but it may not perform the same way on the actual highway because field conditions are different. Lab tests must represent the current or expected worst field conditions. It may be necessary to consider testing at nonoptimum conditions. Representation of test method for actual field material is more critical toward the end of the pavement's life. That is when traffic is at its highest but material is at its worst strength.

17. The applicability of performance-graded asphalt in hot-mix asphalt concrete (HMACs) needs to be understood better. Key issues include how well the material holds up to environmental conditions and its design for dense-graded mixes.

18. The quality of fine aggregate in HMAC is a type of materials-related problem, particularly as measured by sand-equivalent testing.

19. Rutting can be a materials-related problem. However, rutting most often is also related to the stability or strength of layers underneath.

20. Stripping is another type of materials-related problem.

21. Raveling can be a materials-related problem. This distress may be related either to mineralogy, because this distress is more prevalent with certain aggregate mineralogies, or to the mix design used.

22. Ryolites may be a materials-related problem because they can cut the asphalt content (AC) by 1 percent. Mix design is based on mineral type. When measuring absorption with water, ryolite has been shown to be an absorptive aggregate, but with asphalt it is not as absorptive.

23. A problem will arise if the inspector does not know what material is actually being used versus what he or she is told is being used. Sometimes the question arises of whether the pre-tested, pre-approved material is actually used in the project. This, in part, is caused by the time lag between approval testing and actual construction.

24. Material degradation during handling, transportation, and construction is a potential problem.

25. The use of nonspecified material may occur.

a) Was the specified material actually available?

b) The wrong material may have been delivered. For example, AC 10 may have been used instead of AC 20; or Type I base may have been requested and Type III used instead.

26. More material sampling may be needed to determine the proper amounts or types of materials used. The philosophy that *more is better* is not necessarily true in design and construction. For example:

    4 percent stabilization versus 6 percent, or higher concrete strengths used with no justification.

    By the time problems show up months later, there is often no material available for testing.

27. Chemical analysis is a testing procedure that can be used to determine a material-related problem. For example, the wrong material (flume ash instead of fly ash) was used, and it was only discovered through this test.

28. Problems with seal coats can be materials-related problems. Traffic can add dust, and dusty aggregate then will not properly stick to other materials present.

29. The debonding of hot rubber seals on concrete, such as when it steams off of the pavement, can be a materials-related problem.

30. Quality control of PCC can be a materials problem. This can lead to plastic shrinkage or air voids problems.

31. A problem may occur when mixing and blending material from different sources. This approach is used to try to improve the quality of the material. Often, specifications can be met for blended material, but overall quality is usually inferior because there is a wide range of variability in such properties as absorption and soundness. Increased pressure may exist from producers who want to blend.

32. Aggregate problems may be site-specific or site-particular. For example, a particular aggregate was used that had a coating and did not fail any test but, over time, picked up water, expanded and destroyed itself.

33. There may be a problem with the use of information—for example, the proper way to use and interpret construction control charts.

34. Material problems with caliche may occur. One percent lime stabilization may make the material look like concrete at first, but after several years' exposure to water, it will look more like sand.

DESIGN-RELATED PROBLEMS

1. There may be problems in the selection of strategy before the actual design process. Did the designer have enough information about the site, or did he or she

just go out and do what is always done? Site inspection/investigation needs to be done prior to design. For example, more core drilling is needed to identify underground streams and pockets of water. Additionally, Ground Penetrating Radar can be used to find old mine shafts. The designer needs to have enough information about existing conditions. There is often insufficient knowledge about what the pavement structure is and what condition it is in. The designer also needs information about constraints that directly affect the particular pavement. For example, right-of-way (ROW) constraints may limit ditch depth, or the height of existing guardrails may limit overlay thickness. Such constraints should be included as part of the pavement design reports and engineering documentation.

2. Detailed subsurface investigations provide detailed data, such as moisture effects and moisture migration, which should be stored for forensics. One source of such information is county soil surveys, which can generally provide such information on soil properties as gradation, plasticity, and the depth of various soils. Bridge logs may be another useful source.

3. Did the designer only design what the district could afford to do? In such a case, the engineer would be designing not for the pavement variables but for the budget. The pavement engineer may not be free to design, because the budget can be very limiting. The choice must be made between providing improvements to all areas at lower quality, and to providing improvements of higher quality to fewer areas (quality versus quantity). Economic constraints often point to *quick-fix, short-term* solutions that provide a functional, rather than a structural fix. For example, overlays are placed that are too thin. Money should be spent money more wisely, such as in the use of stabilized materials. Additionally, there is often political pressure to divide funding into so many projects that it can not be applied adequately.

4. A lack of long-term planning exists. A pavement engineer should be part of the planning process and should get his or her program out ahead in order to function proactively instead of reactively. For example, a seal coat should be added or microsurfacing should be redone every five to ten years. Current efforts are just *band-aiding* the situation.

5. An issue was raised with the FPS-19 modulus-based design. The modulus is not known during construction and is not checked after construction. There is no way to ever improve these values unless data is collected and a comparison is made.

6. In theory, design occurs at the wrong time because, ideally, the designer would like to know which contractor has what material so that the contract can be awarded based on these factors, instead of the design taking place first and not knowing exactly what materials will be used.

7. Design of the drainage facilities is an important aspect of design. It is important to ensure that adequate depth is provided. For example, pavements have become thicker, but ditches have not become deeper. It is also important to conduct

maintenance of the drainage, including the removal of silt as it builds up over the years.

8. A design problem for CRCP is separation of the shoulder from the CRCP because of a longitudinal joint or gap. At the joints separation allows moisture penetration to an increased number of lanes.
9. The design process should include checking the maintenance records. Talking with the maintenance foreman may help identify the types of major problems with which he or she has been dealing.
10. Another problem may be the use of rules-of-thumb for construction processes in the field without any actual testing. An example of such a *cookbook* approach might be always using 4 percent lime stabilization, whether it is for sands or a high plasticity index.
11. An important design consideration is the projection of traffic into the future. Site visits should be used to make traffic projections. The essential projections include load and ESALs rather than just volumes. In terms of traffic-related design failures, it was observed that the engineer will never miss the traffic for which they are designing the pavement, yet they will miss the year at which it will occur.
12. *Pavements* are overly simplified, but the complexity of the pavement structure needs to be recognized and considered as engineering structures. Another problem is that the definition of failure differs across the state.
13. Material design must be an integral part of the pavement design. The surface often receives too much emphasis. Consideration of other components, such as the base and subgrade, could lead to significant improvements in design. For example, a pavement engineer could make an average aggregate base into a better aggregate base by considering compaction.
14. An envelope for the design of properties like cohesion, friction, and modulus should perhaps be used instead of the material’s class for design. It was suggested that the modulus needs to simulate more of the performance. Another important issue is the in-service condition of the subgrade or subbase.
15. The improper use of product is a design problem. For example, a plant mix seal is not a seal, but rather, an open-graded friction coarse that allows water to pass through. It is used to provide skid resistance, not moisture resistance, as would a typical seal. Another example would be the improper use of microsurfacing.
16. Stripping may be design related. Stripping may be caused by precoated aggregate, which causes dilation of the aggregate. The state of stress will then predict performance. Stripping may be caused by emulsion penetration.
17. Texas Triaxial and Resilient Modulus (M_R) Tests are moisture sensitive.
18. Better models for stabilized layers are needed.
19. The selection of wearing course is a design issue.

20. There exists a cycle of *new* ideas that are tried exists. In some cases the same idea may have been tried seven to ten years ago. It is crucial to obtain feedback from experimental test sections. Frequently TxDOT spends a lot of money on a test, but loses what has been learned from it. Additionally, districts don't know what other districts have already tried. If something does work then the news should be shared! Also, unique results should be made available to the districts. The forensic database should capture the data from such trials, both good and bad!

DATA COLLECTION AND STORAGE

1. The ability to look for trends should be included as a function of the forensic database. To accomplish this, it is necessary to consider not only failures, but also successes. Currently there is more emphasis on failures, which means that feedback on pavements performing well is not being collected, although this information is essential for model calibration. An issue to consider is how *exceptionally good* pavement performance can be stored in the database.
2. When premature failure occurs, the forensic team needs to consider whether the pavement was built as designed and whether the materials specified were actually used.
3. The challenge of some previous forensic investigations was to get the needed data.
4. Required data are tied to the problems observed.
5. The forensic system should contain the information needed to determine the cause of failure, including whether failure was construction- or design-related.
6. The system needs to be flexible enough to accommodate every possible type of information or data element. This data should be sorted according to four priority levels: 1) critical or absolutely required, 2) highly desired, 3) possible/desired, and 4) optional.
7. If data inputs for the forensics database are obtained from FPS, it will be necessary to specify which FPS design method was used.
8. Background on the Construction Management System (CMS), as well as its interaction with the forensic database, was discussed.
9. It was suggested that the forensics database should operate as a geographically-based interactive data management system. The Information Systems Division (ISD) within TxDOT is the team on database management that eventually may need to coordinate this work.
10. ForenSys should contain an automated system or procedure that would allow it to search for similar projects across the state and provide a series of case studies of previous forensic investigations as output.

11. The data format for the forensic database was discussed. First, it must be easy to use. Uniformity of data must exist. In order to maintain consistent formats, a list of choices for data fields from which the user can choose from should be provided.
12. It is important for the forensic system to make full use of existing databases in order to ensure cost-effectiveness. An important step that needs to be taken is to review existing databases and determine how they could best be used. ForenSys could then go through existing TxDOT databases like a *search engine* to obtain the required data from other databases without duplication. Suggested databases include RoadLife, CMS, and PMIS.
13. It is important to look for extension to existing projects (such as CMS, etc.).
14. A forensic system built in GIS will have the capability to look at information geographically.
15. The issue of accessibility could be satisfied with a client/server system. ForenSys needs to be accessible to several people and places at one time, not just on a single PC.
16. It is important to recognize the TxDOT short- and long-range system environment when making decisions about database accessibility. The proposed environment includes Windows NT, Client/Server architecture, and SyBASE database structure.
17. It is critical to verify stored information on as-builts for example with what actually exists in the field, by using some sort of data-verification procedure.
18. The log of maintenance activities should be examined. However, information is often lost in the field. This can happen because maintenance activities, such as a seal coat application, are not always recorded.
19. An issue raised was how to actually fill the database. The idea of hiring an independent contractor to populate the database was suggested.
20. It is important to recognize that certain attributes of a road, such as the alignment, change over time, which means that data values may not always be accurate.
21. The LTPP database demo provided a useful example. There was more information from picture of distress than from columns/data fields, which means that graphical objects and information need to be considered.
22. The type of information and how it is collected is an important issue. ForenSys will probably want to deal with the pavement on a lane-by-lane basis because on interstates and state highways there are no clear records, and there is no set pavement structure or alignment. A 3-D description of the management section could be considered.

THE CHALLENGES OF DATA COLLECTION

1. There is never enough lead time to conduct a forensic investigation. Forensic investigations of pavements often are performed to determine the question of whether the *problem* can be left in place or not. More importantly, what was done wrong needs to be determined so that it won't be done again.
2. There is never a good time, and there is often not enough time, to conduct a full-scale forensic investigation. A tremendous workload results in undertaking forensic studies.
3. With any failure it is important to learn from it and then correct it. It is important to learn from mistakes and not repeat them. Eventually, problems will be corrected with better specifications.
4. It is important to obtain the information in a timely fashion.
5. Sometime problems arise over as-designed versus as-built information. For example, it is necessary to determine if the thickness designed was actually built; this may be resolved with as-built testing.
6. It is necessary to conduct data verification when a team goes in the field, in order to compare what they actually found with what the records said.
7. Variability in data collection exists, due to factors such as the use of different contractors, different experience, and different standards of reference.
8. There is a difference between rehabilitation work for a normal, scheduled failure, and forensic investigations for premature failure.
9. There is also a difference between a reconstruction/rehabilitation condition survey and a true forensic investigation. In the first instance, the pavement is expected to fail after having serving its intended lifecycle, whereas a forensic investigation is conducted because the pavement failed prematurely.
10. There should be a person responsible for forensics in each district.
11. It is essential to look at established causes of certain distresses in order to determine what kinds of factors might have been involved in the failure (i.e., *critical factors*). This will allow the necessary data to be determined based on the distress type observed.
12. The expertise of a knowledgeable person(s) should be used to help conduct a forensic investigation. Pavement engineers from other districts or states could be used but may be difficult to fund.
13. Eventually, feedback from forensic investigations may be used to fix specifications.
14. The forensic team eventually may want to write a capture program to collect data inputs directly from FPS (the departmental design procedure for flexible pavements). It would be necessary to capture only things that cannot be changed.

For example, designs often are overridden because they are too expensive; thus, it would not be beneficial to contain information that is not pertinent.

15. Eventually, a forensic plan should be produced that would set up the input format in which the symptoms of a pavement failure could be filled out. Then the system would produce the answer.
16. In the future an interactive expert system, to be used as a tool to diagnose problems based on distress and observations, could help districts. Such a system would be able to: 1) identify possible causes and, 2) follow decision rules to determine a solution.
17. One challenge of data collection is coordinating with the district traffic control in order to obtain accurate data for the time period needed.
18. The design strength of TxDOT is that it performs decentralized design; therefore, it might be better to conduct decentralized forensic investigations as well. The districts would try to sort out their own problems instead of calling on the forensic team, but would store all the information in the database for others to use.
19. The forensic system must provide a useful format for generating reports.
20. An issue was raised regarding Ground Penetrating Radar (GPR) data integration. The person conducting the data collection should also be familiar with the materials used and soil conditions present. The reason for this is to better understand any abnormalities and, thus, to understand what the results of the data really mean.
21. It will be necessary for the research team to evaluate tools for investigation. For example, a statewide photo log of images maintained over a period of time would serve the purpose of describing the problem to others immediately.

APPENDIX D: DATABASE SUMMARY

Appendix D. DATABASE SUMMARY

Pavement Type and Characteristics Data	PMIS	TRM	MMIS	CMS	ROAD LIFE	RIGID PVMT D.B.	FLEXIBLE PVMT D.B.
1. Roadbed Pavement Type	√						
• Continuously Reinforced Concrete Pavement (CRCP)	√ 1 type Actually populated Some very accurate; depends on district.				√		
• Jointed Concrete Pavement (JCP)	√ 2 types Actually populated Some very accurate; depends on district.				√		
• Flexible (Asphaltic Concrete Pavement (ACP))	√ 7 types Actually populated Some very accurate; depends on district.				√		Type of Pavement Code (28 types) Includes info on: Type of base, surface thickness & surface seal.
2. Number of Lanes (thru-lanes)	√ ###	√				√ (each direction) JCP , CRCP	√ (one direction)
Lane Identification							√ (L or R)
3. Left Shoulder							
Type	√ ###	8 types Original information from Road Inventory files in 1995. Since then, transferred to district responsibility. ∴may or may not be valid.					
Width	√ ###	√ Original information from Road Inventory files in 1995. Since then, transferred to district responsibility.					

Appendix D. (cont.) DATABASE SUMMARY

Pavement Type and Characteristics Data (cont.)	PMIS	TRM	MMIS	CMS	ROAD LIFE	RIGID PVMT D.B.	FLEXIBLE PVMT D.B.
4. Right Shoulder Type Width	 √ ### √ ###	 8 types Original information from Road Inventory files in 1995. Since then, transferred to district responsibility. ∴may or may not be valid. √ Original information from Road Inventory files in 1995. Since then, transferred to district responsibility.					
Outside Shoulder Width							(left or right ?) √
Shoulder Surface Type						Shoulder type (left or right?) √ JCP	√
Shoulder Surface Thickness							√
Shoulder Base Type							√
Shoulder Base Thickness							√
5. Curb Type		5 types					
6. Median Type		5 types					
Coefficient of Drainage						√ CRCP, JCP	
Cut/Fill Position Roadbed Type (cut, fill, transition, at grade)						√ CRCP 4 types : √ JCP	
Curve (Y or N) Horizontal Curve (Y or N)						√ CRCP √ JCP	
7. Roadway Surface Width (total)	√ ###	√				Width of lanes ⊗	lane width: one-way

LEGEND: *** = not populated; from RoadLife (pavement type detail codes are from RoadLife).
= item used in PMIS; is updated and maintained in TRM.

Cross-section Data - AS CONSTRUCTED	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Inspector							
Location of Layer Information					3 types		
Layer Number					Order of construction		√
1. Original Surface					Layer ID = OS		Original surface = layer description
Date	√***				Date completed (month & year)	Construction date = CRCP Project completion date (years) = JCP	Job completed date (month & year)
Type (materials used)	√***	15 types			5 types	Code - CRCP 2 pvmt types → plain or reinforced = JCP	Material type classification code = 11 types.
Thickness (actual)	√***				√ (nearest 0.1")	Pvmt thickness (in.) - CRCP, JCP	Layer thickness across the road 3^{rd}, 2^{nd}, and 1^{st} positions from center Also center = distance and thickness (in.)
Width	√***				√ (of pavement layer)		
Aggregate type					Optional	Coarse agg type code -5 Types = CRCP, 4 types = JCP	
Aggregate Application Rate (S.Y./ C.Y.)							√
Aggregate grade					Optional (for ACP or ST)		
Polish value (numeric)					Optional (for ACP — Average, High & Low Values from construction records) — or ST);		
Asphalt binder type					Optional (for ACP)		
% Air Content					Optional (for ACP); Average, High & Low Values from cores & construction records (total = 6)		
-- Date %AC cores taken					Optional (for ACP)		
% RAP					Optional (for ACP)		
% Air Voids					Optional (for ACP); Average, High & Low Values from cores & construction records (total = 6)		
-- Date %AV cores taken					Optional (for ACP)		
Asphalt viscosity					Optional (for ACP); Average, High & Low Values from cores (total=3)		
-- date AV cores taken					Optional (for ACP)		
% Passing #200 Sieve					Optional (for ACP); Average, High & Low Values from construction records (total=3)		
Asphalt Application Rate							√ (Gal/S.Y.)

Cross-section Data - AS CONSTRUCTED (cont.)	PMIS	TRM	MMIS	CMS	ROAD LIFE	RIGID PVMT D.B.	FLEXIBLE PVMT D.B.
Coarse aggregate grade					Optional (for CRCP, PJC, or RJC)		
Cement type					Optional (for CRCP, PJC, or RJC)		
Fly ash (numeric 0 to 99.9)					Optional (for CRCP, PJC, or RJC)		
Presence of load transfer devices (dowels)						√ JCP	
Joint Spacings						√ JCP	
Admixture Types							√
Admixture %							√
Pit ID number				Producer/ supplier	Optional		
Precoated (Y or N)					Optional (for ST)		
2. Base					Layer ID = BS		Base layer = layer description
Type (materials used)	√ ***	7 types			9 types		Material type classification code = 6 types
Thickness (actual)	√ ***				√ (nearest 0.1")		Layer thickness across the road 3rd, 2nd, and 1st positions from center Also center = distance and thickness (in.)
Width (actual)	√ ***				√		
Stabilization type					7 types		
Drainable					4 types		
Pit ID number					Optional		
3. Subbase					Layer ID = SB		Subbase layer = layer description
Type (materials used) (code)	√ ***				9 types	SBT code – 4 types = CRCP & JCP	Material type classification code = 3 types
Thickness (actual)	√ ***				√ (nearest 0.1")		Layer thickness across the road 3rd, 2nd, and 1st positions from center Also center = distance and thickness (in.)
Width (actual)	√ ***				√		
Swelling potential	√ ***				√	SOIL (Y or N) - CRCP, JCP	
Stabilization type					7 types		

Appendix D. (cont.) DATABASE SUMMARY

Cross-section Data - AS CONSTRUCTED (cont.)	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Drainable					4 types		
Pit ID number					Optional		
4. Subgrade					Layer ID = SG		Subgrade = layer description
Type (materials used)	√ - approximated from avg W7 of FWD				16 types		Material type classification code = 5 types
Stabilization type (code)	√ ***				7 types		
Stabilization thickness/depth	√ ***				√		
Triaxial class (Texas Triaxial Field Test)	√ ***				Optional		√
% Passing #200 Sieve							√
Plasticity Index							√
Liquid Limit							√
Permeability Index							√
5. Milled Layer					Layer ID = ML		Partially milled surface = layer description
6. Last Overlay					Last? Layer ID = OV		Overlay = layer description
Type (materials used) (code) -last	√***				5 types		
Date - last overlay	√*** (month & year)				√	Date of last 4 overlays (OV1-OV4) = CRCP Date of last 3 overlays (OV1-OV3) = JCP	
Thickness - last overlay					√	Thickness of last 3 overlays (in.) (OVT1-OVT3) = JCP	Layer thickness across the road 3rd, 2nd, and 1st positions from center Also center = distance and thickness (in.)
Total overlay thickness	√***						
Width - last overlay	√***				√		
Aggregate type					Optional		
Aggregate grade					Optional (for ACP or ST)		
Polish value (numeric)					Optional (for ACP (Average, High & Low Values from construction records) or ST);		
Asphalt binder type					Optional (for ACP)		

Appendix D. (cont.) DATABASE SUMMARY

Cross-section Data - AS CONSTRUCTED (cont.)	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
% Air Content					Optional (for ACP); Average, High & Low Values from cores & construction records (total=6)		
-- Date %AC cores taken					Optional (for ACP)		
% RAP					Optional (for ACP)		
% Air Voids					Optional (for ACP); Average, High & Low Values from cores & construction records (total=6)		
-- Date %AV cores taken					Optional (for ACP)		
Asphalt viscosity					Optional (for ACP); Average, High & Low Values from cores (total=3)		
-- Date AV cores taken					Optional (for ACP)		
% Passing #200 Sieve					Optional (for ACP); Average, High & Low Values from construction records (total=3)		
Coarse aggregate grade					Optional (for CRCP, PJC, or RJC)		
Cement type					Optional (for CRCP, PJC, or RJC)		
Fly ash (numeric 0 to 99.9)					Optional (for CRCP, PJC, or RJC)		
Pit ID number					Optional		
Precoated (y or n)					Optional (for ST)		
7. Last Seal Coat					Last Layer ID = SC		Seal coat = layer description
Type (materials used) (code) - last	√				7 types		
Date - last seal coat	√*** (month & year)				√		
Aggregate type					Optional		
Aggregate grade					optional (for AMT)		
Pit ID number					Optional		
Precoated (y or n)					optional (for AMT)		
Polish value (numeric)					optional (for AMT)		
Interlayer							Interlayer = layer description
Porous Friction Course							Porous friction course = layer description
HMAC Layer							HMAC layer = layer description
Surface Treatment							Surface treatment = layer description
Embankment (Fill)							Embankment = layer description
Recycle Surface							Recycle surface = layer description
Fabric							Fabric = layer description

LEGEND: *** not populated - from RoadLife
construr = Construction Records, %AC = % Air Content, %AV = % Air Voids

Appendix D. (cont.) DATABASE SUMMARY

AV = Asphalt Viscosity
% RAP = Percentage Recycled Asphalt Pavement
ACP = Asphalt Concrete Pavement
CRCP = Continuously Reinforced Concrete Pavement
PJC = Plain Jointed Concrete
RJC = Reinforced Jointed Concrete
ST = Surface Treatment
AMT = All Material Types

Climatic Data	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Weather							
1. Average annual rainfall	√ (by county) - constant values					√CRCP √ (in.) JCP	Precipitation - mean
Precipitation - standard deviation							√
Precipitation - no. of years averaged							√
2. Average annual number of freeze-thaw cycles	√ (by county) - constant values						Total freeze thaw cycle - mean
Total freeze thaw cycle - standard deviation							√
Total freeze thaw cycle - no. of years averaged							√
Wet Freeze thaw cycle - mean							√
Wet Freeze thaw cycle - standard deviation							√
Wet Freeze thaw cycle - no. of years averaged							√
Average Lowest Temperature (°F)						√ JCP	
Average Highest Temperature (°F)						√ JCP	
Yearly temperature range						√ (°F) - CRCP	District Temperature Constant
Maximum Temperature - mean							√
Maximum Temperature - standard deviation							√
Maximum Temperature - no. of years averaged							√
Averaged Temperature - mean							√
Averaged Temperature - standard deviation							√

Appendix D. (cont.) DATABASE SUMMARY

Climatic Data (cont.)	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Averaged Temperature - no. of years averaged							√ (for a county)
Environmental Data							
Thornthwaite Index - mean							√
Thornthwaite Index - standard deviation							√
Thornthwaite Index - no. of years averaged							√

Comment: Once GIS system is implemented, the data can be referenced spatially and by soil types, which will increase the accuracy of the above info.

Location Data	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
1. District	√ ###	√	√		√		√
2. County (number)	√ ###	√	√	√	√	county name - CRCP, JCP	√
3. Responsible Maintenance Section	√ ###	√ Maintenance district	√				
Maintenance Section ID	√ ###	√	√				
4. Highway Designations (Signed Highway Key)	√ ###	hw-system (21), hw-number, hw-suffix	hw-system, hw-number, hw-suffix		TRM hw-system, hw-number, hw-suffix	hw designation - CRCP, JCP	Highway Identification (HW number)
PMIS Highway System	6 - 7 types: Further combines the 21 systems as defined in TRM to facilitate searches.						
5. Beginning Reference Marker and Displacement	√ ### √	ref marker # ref marker displacement ref marker suffix	√ (limits)		√ √	√ JCP	
6. Ending Reference Marker and Displacement	√ ### √	ref marker # ref marker displacement ref marker suffix	√ (limits)		√ √	√ JCP	
Actual Reference Marker			√				

Appendix D. (cont.) DATABASE SUMMARY

Location Data (cont.)	PMIS	TRM	MMIS	CMS	ROAD LIFE	RIGID PVMT D.B.	FLEXIBLE PVMT D.B.
Mileposts (Beginning to End)						√ beginning; end - CRCP, JCP	√ NNN+NN to NNN+NN
Milepoint (Beginning to End)							NN.NNN to NN.NNN
Section Length						√ (miles) - CRCP	
Direction						√ ⊗	
7. Roadbed ID (type of roadway)	√ ###	13 types			9 types	√ y = main lane N = shoulder or access rd. CRCP	
8. Control-Section	Can grab, but the system doesn't retain them.	Control-Section			Control-Section-Job-Number	TxDOT Control # - CRCP, JCP TxDOT Section # - CRCP, JCP	√ (# / #)
9. Contract Number			√ (for maintenance)	√		TxDOT Construction Job # - CRCP, JCP TxDOT subsequent job #'s - CRCP	
Fiscal Year			√				
Prime Contractor				√			
Elevation measure		√ No data; will be several years before it is collected.					
Latitude measure		√ No data; will be several years before it is collected.					
Longitude measure		√ No data; will be several years before it is collected.					

Appendix D. (cont.) DATABASE SUMMARY

Location Data (cont.)	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Functional system	√ ###	√				√	√ Functional classification (7 types)
Urban Rural Design Standard	√ ***				√	Rural/urban	
Under Construction Flag	Empty - from Contract Info. System (CIS) - pay $ to contractor (month & year) - after final payment know the road is open. Also linked to RoadLife.	√ Highway Status Code 7 types			√		
Widening Flag							√ code (3 types)
Widening Date							(month & year)
CFTR (center for transp. research) #						√ CRCP, JCP	
SID (Section Identification #)							√

LEGEND: *** not populated; from RoadLife
= Item used in PMIS is updated and maintained in TRM.

Traffic Data	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Number of points averaged						√ CRCP	
1. Average Daily Traffic (ADT) AADT current year & year itself Estimated AADT achieved at end of design year Growth rate/factor (%) Cumulative ADT since original Surface date	[(ADT) ###] √ AADT ## √ √ (calculated field) √ (QTY) - only if original surface date ∴ empty	 √ AADT √ Periodic group. AADT history & AADT history year - up to 19 previous years. Periodic group. Didn't pull historical data fields from MPRME ∴fields 2 to 19 are currently zero.				√ CRCP √ JCP √ year of observation- CRCP √ CRCP	 AADT √

Appendix D. (cont.) DATABASE SUMMARY

Traffic Data (cont.)	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Cumulative ADT since last Overlay date	√ (QTY) - only if last overlay date ∴ empty						
Design Hourly Volume		√					
Directional Distribution						√ JCP	
2. Truck Traffic	[18-kip ESALs ###]						
Current 18-kip Measure = 20-year projected 18-kip equivalent single axle load (ESAL) (20 year projected - not every year. TxDOT does not collect annual kip data)	√ ##	√ FLEX18 kip - holding one numeric value. Not a periodic group. Rigid 18 kip - holding one numeric value. Not a periodic group.					Annual cumulative 18 kip ESALs - one way
Cumulative 18-kip ESAL since original surface date	√ (QTY)					Yearly ESALs, Both directions = CRCP Cumulative 18-kip ESALs (estimated) dating from initial project constru = JCP	
Cumulative 18-kip ESAL Since last overlay date	√ (QTY)						
Percent trucks	√ AADT ###	√				√ CRCP, JCP	√
Percent tandem axles						√ CRCP, JCP	
Average ten heaviest wheel loads (ATHWL)	√ (100 lbs). ###	√				√ CRCP, JCP	

LEGEND: ### = Item used in PMIS is updated and maintained in TRM.

For TRM = original data from automated merge of MPRME file - originally loaded in 1995. Have been working on that file and thus have not reloaded any new/updated information since. For TRM will eventually role the periodic group data to history tape (archive) vs. Tracking File that keeps a log of the changes made through updating.

Comments: projections for design → perhaps better data than values just collected under normal circumstances??

Annual traffic history → current 18 kip values.

Appendix D. (cont.) DATABASE SUMMARY

Visual Distress Data **Interstate - every year** **All others - every 2 years**	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Actual Data of Measurement Rater Code						√ JCP, CRCP	√
1. Flexible Pavement (ACP)							
Shallow Rutting-visual	Percent						Rutting (# S, #M, #SV)
- measurement	Percent						
Calibrating equipment to take over visual → automated value takes precedence if present.							
Deep Rutting-visual	Percent						
- measurement	Percent						
Calibrating equipment to take over visual → automated value takes precedence if present.							
Patching	Percent						(# G, #F, #P)
Crack Seal Code							√
Failures	Total number (quantity)						Failures per mile (#)
Alligator Cracking	Percent						(# S, #M, #SV)
Block Cracking	Percent						(# S, #M, #SV)
Longitudinal Cracking	Length (ft) per station (0 to 999)						(# S, #M, #SV)
Transverse Cracking	Number per station (quantity)						(# S, #M, #SV)
Raveling (code)	(optional) 0,1,2,3 ≅ 50% populated districts do this & flushing at the same time.						
Flushing (code)	(optional) 0,1,2,3 ≅ 50% populated districts do this & raveling at the same time.						
2. Continuously Reinforced Concrete Pavement (CRCP)							
Overlaid - Y or N						√ CRCP	
Date surveyed						√ CRCP	
Survey section start						√ CRCP	
Survey section end						√ CRCP	
Rater code						√ CRCP	
Number of failures						√ CRCP	

Appendix D. (cont.) DATABASE SUMMARY

Visual Distress Data (cont.)	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Bonding failures						√ CRCP	
Spalled Cracks	Total number						
Number of cracks in section						√ CRCP	
Punchouts	Total number					----	
Minor						√ CRCP	
Severe						√ CRCP	
Asphalt (ACP) Patches	Total number					Number √ CRCP	
Concrete (PCC) Patches	Total number					√ CRCP	
Average Crack Spacing	Feet					----	
Individual Crack Spacing	----					√ CRCP, JCP	
3. Jointed Concrete Pavement (JCP)							
Overlaid - Y or N						√ JCP	
Failed Joints and Cracks	Total number					------	
Faulted transverse joints & cracks						Number of = √ O JCP & N-O JCP	
Spalled longitudinal & transverse joints and cracks						Number of = √ N-O JCP	
Failures	Total number						
Shattered Slabs	Total number of slabs						
Number of Corner Breaks						√ O JCP, N-O JCP	
Slabs with Longitudinal Cracks	Total number of slabs					Number of slabs = O JCP & N-O JCP	
Number of Transverse Cracks for first 200 ft.						√ O JCP & N-O JCP	
Number of Durability "D" Cracking						√ N-O JCP	
Alligator Cracking						(% of rated lanes total surface area) = √ O JCP	
Block Cracking						(% of rated lanes total surface area) = √ O JCP	
Concrete (PCC) Patches	Total number					Number of → 3 Classes = √ N-O JCP	
Asphalt Patches						Number of → 3 classes = √ O JCP & N-O JCP	
Punchouts							
Minor						√ O JCP, N-O JCP	
Severe						√ O JCP, N-O JCP	

Appendix D. (cont.) DATABASE SUMMARY

Visual Distress Data (cont.)	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Rutting Shallow (% of total wheel path area) Deep (% of total wheel path area)						√ O JCP √ O JCP	
Apparent Joint Spacing	Feet						

N-O JCP = non-overlaid JCP
0 JCP = overlaid JCP

Other Data	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Ride Quality Data - (pavement roughness)	Interstate - every year All others - every 2 years Unitless. 0.1 - 5.0 serviceability index						
Skid Resistance Data	(optional)						
Skid Data - Date performed							√
Skid Number - Mean							√
Skid Number - High							√
Skid Number - Low							√
Rutting Data	Automated –same as measurements under visual survey. RMS vertical acceleration profile in some districts → lead to IRI??						

Notes: For PMIS Ride, Rutting and Visual Surveys are done the same year on the roads that have surveys done every other year.
For Automated Rutting Collection phasing in profilers: 4 machines in 1997; 4 additional machines in 1998; and the final 3 in 1999.

Appendix D. (cont.) DATABASE SUMMARY

Various Condition Scores	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Ride Score - (pavement roughness)	5 categories 0.1 - 5.0						
Distress Score (amount of distress on pavement surface)	5 categories 1 - 100						
SSI Score (pavement structural adequacy) Date Average SSI Temperature 5 Readings at each geophone (1-7)	5 categories 1 - 100						Falling Weight Structural Strength Index (SSI) √ √ √ √
Condition Score (average person's opinion of pavement condition - distress & roughness)	5 categories 1 - 100						
Skid Score (pavement skid resistance)	√ 2 digits						
Pavement Rating Score (PRS)							√
PES Pavement Rating Score							√ (old - replaced by PMIS)
Unweighted Visual (UVU) Rating Score							√
Serviceability Index Date Count of observation Mean Standard Deviation Low Value High Value							 √ √ √ √ √ √

Comment: For PMIS actual # stored and category also stored.
For forensics, may want to deal with the number and may want to define different categories.

Maintenance Data	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Date work performed			√ (month)				
Treatment Cost (Project Cost)					√		
Amount Spent Total pavement maintenance Expenditures/cost	Calculated to be a total per year. Last 10 fiscal years ^^^		√				
Function Code for Type of Work			29 types				

Appendix D. (cont.)   DATABASE SUMMARY

Maintenance Data (cont.)	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**
Month-to-Date (MTD) Amounts			Amounts per function code/ month (2 years)				
MTD Material Area			Amounts by function code				
Type/Kind of Work			2 types		4 work codes		
Miscellaneous = description & date of activities						Seal coats, shoulder improvement, slurry seals & widening of existing concrete = √ JCP	
Comments						√ JCP	
Vendor ID							

LEGEND: ^^^ = item used in PMIS is updated and maintained in MMIS

Test Results	**PMIS**	**TRM**	**MMIS**	**CMS**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**	**OTHER RESEARCH**
Material Samples				√P				
Test Results								
Samples from Test Site								
GROUND PENETRATING RADAR (GPR)								√
X-RAY DEFRACTION								√
CATION EXCHANGE CAPACITY								√
ATTERBERG LIMITS								√
ELECTRON MICROSCOPY								√
FALLING WEIGHT DEFLECTOMETER (FWD)								
Geophone configuration						√ CRCP		
Subsection						√ CRCP		
Temperature device						√ CRCP		
Station within subsection						√ CRCP		
Surface temp (°F)						√ CRCP		
FWD drop height						√ CRCP		
Load intensity (lbs)						√ CRCP		
Deflection at each geophone(1-7)						√ CRCP		
DYNAFLECT								
Data performed							√	
Station							√	
Reading at each sensor (1-5)							√	
SIEVE ANALYSIS OF AGGREGATES				√P				
SPECIFIC GRAVITY OF COARSE AND FINE AGGREGATES				√ P				

Appendix D. (cont.) DATABASE SUMMARY

Test Results (cont.)	**PMIS**	**TRM**	**MMIS**	**CM S**	**ROAD LIFE**	**RIGID PVMT D.B.**	**FLEXIBLE PVMT D.B.**	**OTHER RESEARCH**
AASHTO SOIL CLASSIFICATION				√ P				
PORTLAND CEMENT CONCRETE TESTS				√ P				
HBP (HOT BITUMINOUS PAVEMENT) MIX TESTING				√ P				
PARTICLE SIZE ANALYSIS OF SOILS				√ P				
SPECIFIC GRAVITY OF SOILS				√ P				
LOS ANGELES ABRASION				√ P				
MOISTURE-DENSITY RELATIONS OF SOILS				√ P				
SODIUM OR MAGNESIUM SULFATE SOUNDNESS				√ P				
AASHTO M226 BINDER SPECIFICATION				√ P				
SAND EQUIVALENT				√ P				
TOTAL MOISTURE CONTENT OF AGGREGATE BY DRYING				√ P				
MOISTURE CONTENT				√ P				
UNIT WEIGHT AND VOIDS				√ P				
TESTING EMULSIFIED ASPHALTS				√ P				
UNCONFINED COMPRESSIVE STRENGTH				√ P				
ASTM SOIL CLASSIFICATION				√ P				
PORTLAND CEMENT PHYSICAL TESTS				√ P				
MOISTURE DAMAGE TO BITUMINOUS MIXES				√ P				
CLAY LUMPS AND FRIABLE PARTICLES IN AGGREGATE				√ P				
WATER RETENTION BY CONCRETE CURING MATERIALS				√ P				
DUCTILITY OF BITUMINOUS MATERIALS				√ P				
NUCLEAR DENSITY TEST				√ P				
ORGANIC CONTENT IN SOILS				√ P				
DISTILLATION OF CUTBACK ASPHALT PRODUCTS				√ P				
REINFORCING STEEL				√ P				
PCC FREEZE-THAW CYCLING				√ P				
R-VALUE AND EXPANSION PRESSURE OF COMPACTED SOILS				√ P				
HYDRAULIC CEMENT TEST				√ P				
FREE-FORM TEST				√ P				
Samples from Local Pits								
DIELECTRIC VALUE TEST								√
STRENGTH TESTS								√
Mix Design				√ P				
Specification Values				√ P				

Legend : P = Proposed

APPENDIX E: PAVEMENT FAILURE INVESTIGATIONS

Appendix E – 1. Compilation of Distress Types and Method of Evaluation for Asphalt Pavement
(compiled from Finn [2])

Type of Fatigue/ Distress:	Possible Causes:	Additional Details on Cause:	Method of Evaluation
Alligator Cracking	Structural Deficiency	Load distribution properties of the combined thicknesses of the pavement layers above the subgrade plane are inadequate to prevent distress.	Obtain information necessary for a pavement structural design, in accordance w/the latest procedures.
Description = Fatigue Cracking of HMAC	Excessive Air Voids in HMAC	High air voids can significantly reduce the fatigue life of the asphalt bound layers. 3-5 yr old pvmt should have ≈ 3-7% voids.	ASTM Test Method D3203
	Change in Properties of Asphalt with Time/Aging of Asphalt Cement	Changes in asphalt consistency (penetration, viscosity and ductility) with time. As asphalts harden they become brittle and more susceptible to cracking.	
	Stripping in HMAC	Loss of adhesion between the asphalt and aggregate in the HMAC. Reduction of tensile strength or cohesion & reduced structural capacity	
	Properties of Aggregate Used in HMAC	1. Gradation 2. Shape (rounded, angular, flat) 3. Texture (rough, smooth, crushed, uncrushed) 4. Cleanliness (sand equivalent) 5. Durability 6. Amount of deleterious material 7. Plasticity of portion passing the No. 40 sieve 8. Affinity to asphalt 9. Absorption	
	Construction Considerations	1. Asphalt content 2. Construction variability	
	Drainage	1. Surface drainage conditions 2. Subsurface drainage conditions	

Type of Fatigue/Distress:	Possible Causes:	Additional Details on Cause:	Method of Evaluation
Longitudinal Cracking	Alligator cracking: when cracking is in general vicinity of vehicular wheel path, longitudinal cracking is first indication of fatigue cracking of HMAC.		
	Poor Construction Joint		
	Segregation		
	Foundation settlements - usually in fill zones		
	Volume change of subgrade soils		
	Shrinkage		

Type of Fatigue/Distress:	Possible Causes:	Additional Details on Cause:	Method of Evaluation
Rutting	Structural deficiency		
Description - the channeling or grooving of the pavement surface in longitudinal depressions which develop in the wheel path area. Traffic-related form of distress that initially appears in the wheel path area.	Mix Design (HMAC)		
	Asphalt cement properties		
	Stability of pavement layers		
	Compaction (density): all layers		

Type of Fatigue/Distress:	Possible Causes:	Additional Details on Cause:	Method of Evaluation
Raveling	Low asphalt content		
Description - the progressive loss of surface material from HMAC by weathering and/or traffic abrasion.	Excessive air void content in HMAC		
	Accelerated hardening of asphalt		
	Water susceptibility (stripping)		
	Aggregate characteristics		
	Hardness and durability of aggregate		

Type of Fatigue/Distress:	Possible Causes:	Additional Details on Cause:	Method of Evaluation
Transverse Cracking	Properties of asphalt		
	Unusual soil properties		

Type of Fatigue/Distress:	Possible Causes:	Additional Details on Cause:	Method of Evaluation
Flushing	Excessive amount of asphalt		
	Excessive densification		
	Temperature susceptibility of asphalt		
	Loss of aggregate from seal coat		

Type of Fatigue/Distress:	Possible Causes:	Additional Details on Cause:	Method of Evaluation
Roughness	Nonuniform construction		
	Combination of effects of physical distress; i.e., rutting, cracking, etc.		
	Soil properties		

Type of Fatigue/Distress:	Possible Causes:	Additional Details on Cause:	Method of Evaluation
Corrugations	Structural deficiency	Inadequate shear strength in the base, subbase, or foundation layers (shear strength requirements influenced by the thickness of pavement layers, which is a function of the thickness design or actual construction thickness); second most frequent cause.	Structural deficiencies Excessive deflections
Description - transverse depressions and ridges in the pavement surface. Usually associated with areas of deceleration, acceleration, or turning movements. Traffic-related form of distress that initially appears in the wheel path area.	Mix Design (HMAC)	Lack of stability in the HMAC; most frequent cause.	
	Asphalt cement properties	Stripping of the asphalt from the aggregate can effectively reduce the tensile strength (cohesion) within the HMAC	
	Stability of pavement layers		Material properties - stability.
	Compaction (density): all layers		In-place condition - density.

Appendix E – 2. Flexible Pavement Failure Investigations
(Compiled as part of TxDOT #1731 from Finn [1], Finn [2], and Epps.

	TYPE OF DISTRESS								
REQUIRED INFORMATION	Rutting	Corrugations	Raveling	Flushing	Alligator Cracking	Longitudinal Cracking	Transverse Cracking	Roughness	Seal Coat & Surface Treatment
Traffic (per lane)									
Accumulated ESALs to date	√	√			√	LA	√	√	
ADT			√	√		NLA		√	√
Percent trucks			√	√		NLA			√
Design ATHWLD (avg. ten heaviest wheel loads daily)	√	√			√	LA			
Construction Records									
Mix Design - HMAC			√	√			√		
Mix Design - all stabilized materials	√	√			√	LA			
Seal Coat Design - adjustment factors for type of existing surface									√
Seal Coat Design - adjustment factors for condition of existing surface									√
Material properties - base, subbase, subgrade	√	√			√	LA; properties of fill and subgrade mtls (ex. PI) = NLA	√		
Aggregate characteristics			√						
Aggregate source									√
Aggregate type									√
Aggregate gradation									√
Aggregate moisture content									√
Seal coat aggregate spread rate									√

REQUIRED INFORMATION (cont.)	TYPE OF DISTRESS Rutting	Corrugations	Raveling	Flushing	Alligator Cracking	Longitudinal Cracking	Transverse Cracking	Roughness	Seal Coat & Surface Treatment
Asphalt content			√	√					
Asphalt source			√						√
Asphalt type			√						√
Asphalt grade			√						√
Seal coat asphalt spread rate									√
Pavement layer thicknesses	√	√			√	LA	√	√	
Amount of prime coat mtl				√					
Type of prime coat mtl				√					
Amount of tack coat mtl				√					
Type of tack coat mtl				√					
Laydown details						NLA			
Joint Construction details						NLA			
Condition of underlying pavement - type						NLA	√		
Condition of underlying pavement - number of cracks						NLA	Amount √		
Density - all layers								√	
Density - subgrade soil								√	
Site conditions - natural drainage locations								√	
Site conditions - amount of cut and fill								√	
Traffic-control procedures									√
Date of construction									√
Maintenance activities									
Type	√	√	√	√	√	LA, NLA	√	√	√
Amount	√	√	√	√	√	LA, NLA	√	√	√
Effectiveness	√	√	√	√	√	LA, NLA	√	√	√

	TYPE OF DISTRESS								
REQUIRED INFORMATION (cont.)	Rutting	Corrugations	Raveling	Flushing	Alligator Cracking	Longitudinal Cracking	Transverse Cracking	Roughness	Seal Coat & Surface Treatment
Laboratory evaluation -HMAC Properties									
Stability	√	√							
Asphalt content	√	√	√	√	√	LA	√		
Asphalt properties- penetration	√	√	√	√	√	LA	√		√
Asphalt properties- viscosity	√	√	√	√	√	LA	√		√
Asphalt properties- temperature susceptibility				√			√		
Asphalt properties- stiffness at low temperatures							√		
Mixture properties - tensile strength							√		
Mixture properties - stiffness at low temperatures							√		
Aggregate properties - gradation	√	√	√		√	LA	√		√
Aggregate properties - absorption	√	√	√		√	LA	√		√
Aggregate properties - shape	√	√	√		√	LA			√
Aggregate properties - surface texture	√	√	√		√	LA			√
Aggregate properties - mineralogy			√						
Water susceptibility	√	√	√	of asphalt stabilized base √	√	LA			of aggregate properties
Air Void Content	√	√	√	√	√	LA			
Volume change properties of fill soil						NLA			
Volume change properties of subgrade soils						NLA			

REQUIRED INFORMATION (cont.)	TYPE OF DISTRESS								
	Rutting	Corrugations	Raveling	Flushing	Alligator Cracking	Longitudinal Cracking	Transverse Cracking	Roughness	Seal Coat & Surface Treatment
Density profile of fill						NLA			
Consolidation properties of in-place materials						NLA			
Shear strength of fill material						NLA			
Segregation of HMAC near crack						NLA			
Laboratory evaluation - Base, Subbase, Subgrade Properties									
Gradation	√	√			√	LA	Untreated aggregate base √		
Stiffness coefficients	√	√			√	LA			
Triaxial classification	√	√			√	LA			
Mineralogy of clay fraction							Untreated aggregate base √		
Volume Change Potential of subgrade material								√	
Laboratory evaluation -Stabilized Base Properties									
Asphalt treated	√	√			√	LA			
Asphalt treated - tensile strength							Treated base and subbase √		
Asphalt treated - volume change potential							Treated base and subbase √		
Cement or lime treated - compressive strength	√	√			√	LA			
Cement or lime treated - tensile strength	√	√			√	LA	Treated base and subbase √		
Cement or lime treated - volume change potential							Treated base and subbase √		

	TYPE OF DISTRESS								
REQUIRED INFORMATION (cont.)	Rutting	Corrugations	Raveling	Flushing	Alligator Cracking	Longitudinal Cracking	Transverse Cracking	Roughness	Seal Coat & Surface Treatment
Field Evaluation									
Condition survey	√	√	√	√	√	LA, NLA	√	√	√
Drainage	√	√			√	LA, NLA			
HMAC cores (for lab evaluation)			√	√					
Cores of stabilized pavement layers	√	√		Asphalt stabilized base cores for lab evaluation √	√	LA	√		
Undisturbed samples of fill foundation soil						NLA			
Undisturbed samples of subgrade foundation soil						NLA			
Depth of aggregate embedment									√
Deflection (dynaflect)	√	√			√	LA			
Roughness (Mays Ride Meter)	√	√			√	LA, NLA	√	√	
In-place density								√	
Accident records				√					
Skid number				√					
Geometric factors - width of lane						NLA			
Geometric factors - paved or unpaved shoulder						NLA			
Climatological Information									
Climate during construction									√
Minimum temperatures							√	√	
Minimum temperature during construction									√
Minimum temperature immediately after construction									√

	TYPE OF DISTRESS								
REQUIRED INFORMATION (cont.)	Rutting	Corrugations	Raveling	Flushing	Alligator Cracking	Longitudinal Cracking	Transverse Cracking	Roughness	Seal Coat & Surface Treatment
Maximum temperature during construction									√
Maximum temperature immediately after construction									√
Rate of temperature drop							√		
Daily temperature change							√		
Freezing Index								√	
Precipitation								√	
Precipitation during construction									√
Precipitation immediately after construction									√

Key: LA = Load associated; NLA = Non-load associated.

APPENDIX F: DATA REQUIRED FOR FORENSIC ANALYSIS

	Data Required for Forensic Analysis	
	1. Physical/Section Description [**]	**2. Geometric Information**
	Data Category Used	
	Identification Information	***Geometry Related Information***
	Project History & Background [⊗]	
R E Q U I R E D	Location of the project / Texas Reference Marker Highway System [**] TxDOT Project # District Identification Date of Construction - date of initial construction [⊗] - date of overlay [⊗] - date of widening [⊗]	Ditches (design and current) -- Drainage, Dr/Drainage Condition, Cd (ex. Use of Edge Subdrains) [**, SGR #11]
H. D E S I R E	Type of Project	Grade Width of lane [⊄] Curvature Cross Slope Type of Shoulder - paved or unpaved [⊄] Type of Curb Number of Travel Lanes Number of Shoulders
D E S I R E D	Roadbed ID Beginning Reference Marker & Displacement Ending Reference Marker & Displacement	Roadbed type: transition, cut, fill, grade [ψ] Site conditions - amount of cut & fill [⊄] Maximum Cut Heights Average Cut Heights Maximum Fill Heights Average Fill Heights Vertical Alignment Horizontal Alignment
H O P E F U L	GPS Location Visual Evidence	Abutting Land Usage Vertical Clearances at Structures Extent of Shoulder Extent of Curb Site conditions - natural drainage locations [⊄]

	Data Required for Forensic Analysis			
	3. Design Information			
	Data Category Used			
	Design Method Used			
	RIGID			**FLEXIBLE**
REQUIRED	**JPCP**	**JRCP**	**CRCP**	
H. DESIRE	Strength Mix Design [**]	Strength Mix Design [**]	Strength Mix Design [**]	Strength Mix Design [**, ⊄]
DESIRED	Concrete properties: Air content W/C ratio Amount of cement Amount of fine aggregate Amount of coarse aggregate Amount of admixtures Type of joint sealant Load transfer across joint (%) Joint spacing	Concrete properties: Air content W/C ratio Amount of cement Amount of fine aggregate Amount of coarse aggregate Amount of admixtures Dowel bar size Modulus of dowel support Type of joint sealant Load transfer across joint (%) Joint spacing	Concrete properties: Air content W/C ratio Amount of cement Amount of fine aggregate Amount of coarse aggregate Amount of admixtures Dowel bar size Modulus of dowel support Type of joint sealant Load transfer across joint (%) Joint spacing	TxDOT Design Method Marshall Mix Design HVEEM Mix Design Superpave Mix Design Maximum specific gravity of Bulk specific gravity of mix Air voids of mix (%) Asphalt cement in mix (%)
HOPEFUL	Thickness of joint sealant			HVEEM Stability Lottman Tsr

	Data Required for Forensic Analysis				
	3. Design Information (cont.)				
	Data Category Used				
	Design Values - Material Properties				
	Original Surface				**Shoulder**
	RIGID			**FLEXIBLE**	
REQUIRED	**JCPC**	**JRCP**	**CRCP**		
H. DESIRE	Materials Selected [**] Thickness [**] Width Layer ID	Materials Selected [**] Thickness [**] Width Layer ID	Materials Selected [**] Thickness [**] Width Layer ID	Materials Selected [**] Thickness [**] Width Layer ID	Materials Selected Thickness [**] Width Layer ID
DESIRED	Cement type Strength of concrete (Flexural/Tensile) Coefficient of thermal contraction Concrete elastic modulus Concrete drying shrinkage Coarse aggregate gradation Type of aggregate - reactive? Type of cementitious admixture Amount of cementitious admixture Type of chemical admixture Amount of chemical admixture Type of chemical admixture Amount of chemical admixture	Cement type Strength of concrete (Flexural/Tensile) Coefficient of thermal contraction Concrete elastic modulus Concrete drying shrinkage Coarse aggregate gradation Fine aggregate gradation Type of aggregate - reactive? Type of cementitious admixture Amount of cementitious admixture Type of chemical admixture Amount of chemical admixture Grade of reinforcement Area of steel (%) Depth of reinforcement	Cement type Strength of concrete (Flexural/Tensile) Coefficient of thermal contraction Concrete elastic modulus Concrete drying shrinkage Coarse aggregate gradation Fine aggregate gradation Type of aggregate - reactive? Type of cementitious admixture Amount of cementitious admixture Type of chemical admixture Amount of chemical admixture Grade of reinforcement Area of steel (%) Depth of reinforcement	Binder type Viscosity (and temp. test) Creep stiffness Direct tension failure strain Coarse aggregate gradation Fine aggregate gradation Aggregate clay content Type of aggregate reactive? Air voids, VA	

HOPEFUL	Poisson’s ratio	Poisson’s ratio	Mortar (paste) strength	Coarse aggregate angularity	
	Mortar (paste) strength	Mortar (paste) strength	Coarse aggregate angularity	Fine aggregate angularity	
	Coarse aggregate angularity	Coarse aggregate angularity	Fine aggregate angularity	Voids in mineral aggregate VMA	
	Fine aggregate angularity			Voids filled with asphalt, VFA	
	Cement manufacturer	Cement manufacturer	Cement manufacturer	Source of coarse aggregate	
	Source of coarse aggregate	Source of coarse aggregate	Source of coarse aggregate	Source of fine aggregate	
	Source of fine aggregate	Source of fine aggregate	Source of fine aggregate	Source of asphalt	
	Yield stress of steel reinforcement	Yield stress of steel reinforcement	Yield stress of steel reinforcement		
	Steel coefficient: therm. contraction	Steel coefficient: therm. contraction	Steel coefficient: therm. contraction		
	Source of cementitious admixture	Source of cementitious admixture	Source of cementitious admixture		
	Source of chemical admixture	Source of chemical admixture	Source of chemical admixture		

Data Required for Forensic Analysis

3. Design Information (cont.)

Data Category Used

Design Values - Material Properties

	<u>Subgrade</u>	**<u>Subbase</u>**	**<u>Base</u>**	**<u>Overlay</u>**	**<u>Sealcoat</u>**
REQUIRED					
H. DESIRE	Materials Selected [**] Layer ID Width	Materials Selected [**] Thickness [**] Layer ID Width	Materials Selected [**] Thickness [**] Layer ID Width	Materials Selected [**] Thickness [**] Layer ID Width	Materials Selected [**] Thickness [**] Layer ID Width
DESIRED	Type (A1 to A3 or A4 to A7) Modulus of subgrade support Subgrade swelling, S Stabilization type Stabilization depth Texas Triaxial Classification Mix design - all stabilized mtls [¢]	Type: Stabilized or unstabilized Thickness Maximum slab-subgrade friction, F Stabilization type Drainable base Mix design - all stabilized mtls [¢]	Stabilization type Drainable base Mix design - all stabilized mtls [¢]	-More than one layer -Milled layer	
HOPEFUL	Location of layer information - center, right, left Edge support, ES Maximum dry density				Seal coat design - Adjustment factors for <u>type</u> of existing surface [¢] Seal coat design - Adjustment factors for <u>condition</u> of existing surface [¢] Aggregate spread rate [DF] Asphalt distribution rate [DF] Aggregate type [DF] Aggregate properties: [DF] Polish value, PV [DF] Magnesium soundness, MSS

	Data Required for Forensic Analysis			
	4. Construction Information / Construction History [**] **/ Construction Records** [⊄]			
	Data Category Used			
	Construction Methods		***Construction Standards &***	***Change***
R E Q U I R E D	**RIGID** Weather [**, ⊄ , ⊗] Curing / curing techniques [ψ,SGR #13, R2] Placement time [SGR #7, ψ] Timing of joint sawing/ Age of concrete at saw cutting [R1, R2, DF] Depth of saw cutting/ joint sawing [R1, R2, DF]	**FLEXIBLE** weather [**, ⊄ , ⊗]	Construction specifications used (version/year) [**]	Why it happened What actually
H. D E S I R E	Construction diary [**, WRH] Time of first traffic application/ time of opening to traffic/ traffic control procedures [⊄ , TQI] Method of compaction Type of curing compound Amount of curing compound - # of applications [DF] Spacing of joint sawing [R2] Dowel bar alignment [R1, R2] Tie bar alignment [R1] Joint sealant - type [R2] Joint sealant - installation [R1] / design [R2] Contractor performing work Special construction features ex., recycled material, preloading, geotextiles	Construction diary [**] Time of first traffic application/ time of opening to traffic/ traffic control procedures [⊄, TQI] Method of compaction Contractor performing work Special construction features ex., recycled material, preloading, geotextiles	QC/QA requirements Quality control during construction [ψ] How much actually was tested (versus reqd) [SS]	

DESIRED	Age of curing removal Type of machine used Texturing method/surface texture[TQI]/finishing techniques[R2] Macrotexture [SGR #27] Permeability [SGR #28]	Age of curing removal Type of paver Laydown details [⊄] Joint construction details [⊄]		Test does not Dispositioning = decided to do
HOPEFUL	Environmental conditions affecting Evaporation rate: Air temperature Wind velocity Humidity	Condition of underlying pavement- Type [⊄] Condition of underlying pavement- Number of cracks [⊄]		

Data Required for Forensic Analysis

4. Construction Information/ Construction History (cont.)

Data Category Used

Pavement Structure and Materials Information (Actual Field Value During Construction)

	Original Surface				Shoulder
	RIGID			**FLEXIBLE**	
REQUIRE	**JCPC** Materials Selected [**,⊗] Actual Thickness [**, SGR #2, R1] Layer ID Width Date of construction of layer [**] Mix design [**] Strength/Actual strength of concrete (flexural = beam tests/tensile) [SGR#1, R1, CW]	**JRCP** Materials Selected [**,⊗] Actual Thickness [**, SGR #2, R1] Layer ID Width Date of construction of layer[**] Mix design [**] Strength/Actual strength of concrete (flexural = beam tests/tensile) [SGR#1, R1, CW]	**CRCP** Materials Selected [**,⊗] Actual Thickness [**, SGR #2, R1] Layer ID Width Date of construction of layer [**] Mix design [**] Strength/Actual strength of concrete (flexural = beam tests/tensile) [SGR#1, R1, CW]	Materials Selected [**,⊗] asphalt/binder type [⊄] asphalt/performance grade [⊄] Actual Thickness [**] Layer ID Width Date of construction of layer [**,⊄] Mix design [**,⊄] Strength Asphalt content [⊄]	Materials Selected [**,⊗] Actual Thickness [**] Layer ID Width Date of construction of layer [**]
H. DESIRED	Concrete properties Overall Variance Thickness Variability Cement Type [TQI] air content/ % air voids [SGR #23, R1] Actual coeff. thermal contraction Thermal coeff. of coarse agg [ψ] Concrete elastic modulus [SGR #5] Coarse aggregate type [SGR #9] Actual concrete drying shrinkage Coarse aggregate gradation Fine aggregate gradation Fine aggregate durability [SGR #25] Type of aggregate reactive? Type of cementitious admixture Amount of cementitious admixture Type of chemical admixture Amount of chemical admixture Concrete temp. at setting, Tset	Concrete properties Overall Variance Thickness Variability Cement Type [TQI] Air content/ % air voids [SGR #23, R1] Actual coeff. thermal contraction Thermal coeff. of coarse agg [ψ] Concrete elastic modulus [SGR #5] Coarse aggregate type [SGR #9] Actual concrete drying shrinkage Coarse aggregate gradation Fine aggregate gradation Fine aggregate durability [SGR #25] Type of aggregate reactive? Grade of reinforcement Area of steel (%) [SGR#22, R2] Depth of reinforcement [R1, R2, TQI] Depth of tie bars [R1] Type of cementitious admixture Amount of cementitious admixture Type of chemical admixture Amount of chemical admixture Concrete temp. at setting, Tset	Concrete properties Overall Variance Thickness Variability Cement type [TQI] air content/ % air voids [SGR #23, R1] Actual coeff. of thermal contraction Thermal coeff. of coarse agg [ψ] Concrete elastic modulus [SGR #5] Coarse aggregate type [SGR #9,ψ] Actual concrete drying shrinkage Coarse aggregate gradation Fine aggregate gradation Fine aggregate durability [SGR#25] Type of aggregate reactive? Grade of reinforcement Area of steel (%) [SGR#22, R2] Depth of reinforcement [R1, R2, TQI] Depth of tie bars [R1] Type of cementitious admixture Amount of cementitious admixture Type of chemical admixture Amount of chemical admixture Concrete temp. at setting, Tset	Properties: Overall Variance Thickness Variability Performance grade Viscosity (and test temperature) Actual Dynamic shear, G* Creep stiffness Direct tension failure strain Aggregate characteristics: [⊄] Coarse aggregate gradation Fine aggregate gradation Aggregate clay content Type of aggregate-reactive? Air voids, Va Temperature of asphalt as being applied, Tset Source of aggregate coarse[⊄] Source of aggregate-fine [⊄] Source of asphalt [⊄] Aggregate moisture content[⊄] Density - of all layers [⊄]	Properties: Actual Moisture Content Overall Variance Thickness variability

DESIRED	Poisson's ratio Mortar (paste) strength Mortar (paste) density [TQI] Concrete density [TQI] Coarse aggregate angularity Fine aggregate angularity Load transfer [SGR #10] Strength variance [SGR #14] Overall variance [SGR #15] Seal type [SGR #16]	Poisson's ratio Mortar (paste) strength Mortar (paste) density [TQI] Concrete density [TQI] Coarse aggregate angularity Fine aggregate angularity Load transfer [SGR #10] Strength variance [SGR #14] Overall variance [SGR #15] Seal type [SGR #16]	Poisson's ratio Mortar (paste) strength Mortar (paste) density [TQI] Concrete density [TQI] Coarse aggregate angularity Fine aggregate angularity Load transfer [SGR #10] Strength variance [SGR #14] Overall variance [SGR #15] Seal type [SGR #16]	Coarse aggregate angularity Fine aggregate angularity Voids in mineral aggregate, VMA Voids filled with asphalt, VFA	
HOPEFUL	Cement Manufacturer Source of coarse aggregate Source of fine aggregate Yield stress of steel reinforcement Steel coefficient: therm. contraction Source of cementitious admixture Source of chemical admixture Ion levels [SGR #26] Sulfate resistance [TQI] alkali-silica reactivity W/C ratio [SGR #29] Unit weight of concrete [TQI] Foreign materials in aggregate [TQI]	Cement Manufacturer Source of coarse aggregate Source of fine aggregate Yield stress of steel reinforcement Steel coefficient: therm. contraction Source of cementitious admixture Source of chemical admixture Dowel support modulus [SGR #20] Ion levels [SGR #26] sulfate resistance [TQI] alkali-silica reactivity W/C ratio [SGR #29] Unit weight of concrete [TQI] Foreign materials in aggregate [TQI]	Cement Manufacturer Source of coarse aggregate Source of fine aggregate Yield stress of steel reinforcement Steel coefficient: therm. contraction Source of cementitious admixture Source of chemical admixture Dowel support modulus [SGR #20] Ion levels [SGR #26] Sulfate resistance [TQI] alkali-silica reactivity W/C ratio [SGR #29] Unit weight of concrete [TQI] Foreign materials in aggregate [TQI]	Amount of prime coat mtl. [⊄] Type of prime coat mtl. [⊄] Amount of tack coat mtl. [⊄] Type of tack coat mtl. [⊄]	

Data Required for Forensic Analysis

4. Construction Information / Construction History (cont.)

Data Category Used

Pavement Structure and Materials Information (Actual Field Value During Construction)

	Subgrade	Subbase	Base	Overlay	Sealcoat
REQUIRED	Materials Selected [**] Layer ID Width Date of construction of layer [**]	Materials Selected [**] Type: stabilized or unstabilized Actual Thickness [**] Layer ID Width Date of construction of layer [**]	Materials Selected [**] Actual Thickness [**] Layer ID Width Date of construction of layer [**]	Materials Selected [**] Actual Thickness [**] Layer ID Width Date of construction of layer [**] Traffic control procedures	Materials Selected [**] Actual Thickness [**] Layer ID Width Date of construction of layer[**] Traffic control procedures ??
H. DESIRE	Type(A1toA3 or A4 to A7) [SGR #6] Material properties [⊄] Actual Liquid Limit, LL Actual Plasticity Index, PI Actual Moisture Content [TQI] Overall Variance Modulus of subgrade support [SGR #3] Subgrade swelling [SGR #19, ψ] Stabilization type Stabilization depth Texas Triaxial Classification Mix design of stabilized materials [⊄]	Thickness Variability Material properties: [⊄] Actual Liquid Limit, LL Actual Plasticity Index, PI Actual Moisture Content Overall Variance Maximum slab-Subbase Friction, F Stabilization type Drainable base Mix design of stabilized materials [⊄]	Thickness Variability Material properties: [⊄] Actual Liquid Limit, LL Actual Plasticity Index, PI Actual Moisture Content Overall Variance Stabilization type Drainable base Mix design of stabilized materials [⊄]	Thickness variability Material properties [⊄] Overall Variance Mix design [**]	Aggregate spread rate [DF, ⊄] Asphalt distribution/spread rate [DF, ⊄] Aggregate type [DF, ⊄] Aggregate properties: [DF] Polish value, PV [DF] Magnesium soundness, MSS [DF] Thickness variability Material properties: [⊄] Actual Liquid Limit, LL Actual Plasticity Index, PI Actual Moisture Content Overall Variance Mix design [**] ??
DESI ED	Location of layer information Center, right, left Edge support, ES Actual density (max dry, other??) [⊄] CBR-California Bearing Ratio Soaked CBR Actual grading limits-maximum Particle size - % of fines	Density [⊄]	Density [⊄]		Seal coat design - Adjustment factors for <u>type</u> of existing surface [⊄] Seal coat design- Adjustment factors for <u>condition</u> of existing surface [⊄]
HOPEFUL					Aggregate moisture content [⊄] Aggregate source [⊄] Aggregate gradation [⊄] Asphalt grade [⊄] Asphalt source [⊄] Asphalt type [⊄]

Data Required for Forensic Analysis

5. Traffic Data / Traffic History [**] **/ Traffic Information** [⊗] **/ Traffic Per Lane** [⊄]

Data Category Used

***** Traffic History***

	DESIGN (PROJECTED) / PROJECTIONS [⊗]	**ACTUAL / HISTORY** [⊗]
REQUIRED	** ADT [**] Average Daily Traffic Value - Original Average Daily Traffic Value - Projected ** ESALs [**] Load Repetitions (ESALs), W18 - Projected for ____ Years Design ATHWLD [⊄]	Average Daily Traffic Value, ADT - Actual [⊄] Load Repetitions (ESALs), W18 - accumulated ESALs since construction ESALs to date [⊄] Percent Trucks [⊄]
H. DESIRE	Directional Distribution Split, % K Factor Percent Trucks (of ADT) - Original Slab Thickness Values Based Upon Number of Years Projected For	Percent Trucks (of ADT) - Actual Number of Years After Original Design
DESIRED	Percent Trucks (of DHV) - Original % Tandem Axles in ATHWALD SN	Percent Trucks (of DHV) - Actual
HOPEFUL	Load Information Applied Wheel Load, P	

Data Required for Forensic Analysis

6. Environment Related Data

Data Category Used

Environmental Conditions

	DESIGN	DURING CONSTRUCTION [⊄]	ACTUAL/ AFTER CONSTRUCTION
R	Geologic information [⊗]	Min temperature during construction [⊄]	Annual/Yearly Temperature Range (°F) [ψ]
E	Soil information [⊗]	Max temperature during construction [⊄]	Average Annual Precipitation/Rainfall [ψ, ⊄]
Q	Soil - Y for swelling, N for not [ψ]	Temperature differential [R2]	Soil - Y for swelling, N for not [ψ]
U	(Subgrade Swelling)	Precipitation during construction [⊄]	(Subgrade Swelling)
I	Swelling [SGR #19]	Evaporation rate: [DF] (concrete)	Min temperature immediately after construction [⊄]
R		concrete temperature, T_{conc} [DF] (concrete)	Max temperature immediately after construction [⊄]
E		air temperature, T_{air} [DF] (concrete)	Precipitation immediately after construction [⊄]
D		Relative humidity, RH [DF] (concrete)	
		velocity of wind, V_{air} [DF] (concrete)	
H.	Freezing Index	Temperature During Construction - asphalt?	Freezing Index [⊄]
D	Depth of Frost Penetration	Time of Day Construction Took Place?	Depth of Frost Penetration
E	Drainage of Soils	(Here or in construction records?)	Drainage of Soils
S	Annual/Yearly Temperature Range (°F) [ψ]		Rate of temperature drop [⊄]
I	Average Annual Precipitation/Rainfall [ψ]		Daily temperature change/ temperature differential [⊄, R2]
R			Minimum temperatures [⊄]
E			
D			

DESIRED			Link to GIS database of National Weather Service Information
HOPEFUL	Typical Humidity	Actual Humidity During Construction -- asphalt?	Typical Humidity

<table>
<tr><td rowspan="5"></td><td colspan="5">Data Required for Forensic Analysis</td></tr>
<tr><td colspan="5">7. Maintenance and Rehabilitation Information</td></tr>
<tr><td colspan="5">Data Category Used</td></tr>
<tr><td colspan="5">Maintenance and Rehabilitation History</td></tr>
<tr><td colspan="2">Maintenance History</td><td colspan="3">Rehabilitation History</td></tr>
<tr><td>R E Q U I R E D</td><td colspan="2">Type of Work (Record all performed on each section/each maintenance action)
crack sealing, patching etc.
Date of Work</td><td colspan="3">Type of Work (Record all performed on each section/each rehab. Action)
Effect on structure [WRH]
Date of Work</td></tr>
<tr><td rowspan="4">H. D E S I R E D</td><td colspan="2">What Initiated Such Action</td><td colspan="3">What Initiated Such Action</td></tr>
<tr><td>RIGID</td><td>FLEXIBLE</td><td colspan="2">RIGID</td><td>FLEXIBLE</td></tr>
<tr><td></td><td></td><td>Jointed - JCP [DF]</td><td>CRCP [DF}</td><td></td></tr>
<tr><td>Materials Used
Repair of Cracks
Joint Spalling</td><td>Materials Used
Joint Sealing
Type of Seal</td><td colspan="2">Materials Used
Overlay Type
Type of Bond for Overlay
Overlay Thickness
Overlay Reinforcement
Retexturing
Repair of Popouts - * critical for jointed
Repair of Punchouts</td><td>Materials Used
Overlay Type
Type of Bond for Overlay
Overlay Thickness
Overlay Reinforcement</td></tr>
</table>

D E S I R E D	Effectiveness	Surface Preparation for Overlay Effectiveness
H O P E F U L		

<table>
<tr><td></td><td colspan="5">Data Required for Forensic Analysis</td></tr>
<tr><td></td><td colspan="5">8. Performance and Condition Information / Performance History</td></tr>
<tr><td></td><td colspan="5">Data Category Used</td></tr>
<tr><td></td><td>Initial Pavement Condition Survey</td><td colspan="3">Pavement Condition Survey- Detailed Condition Survey</td><td>Observations</td></tr>
<tr><td></td><td></td><td colspan="3">Bi- Annual Pavement Evaluation Information</td><td></td></tr>
<tr><td rowspan="3">R
E
Q
U
I
R
E
D</td><td rowspan="3">Date of Survey
Initial pavement condition survey - early distress
manifestations [TQI]
Early age crack spacing [ψ#3]
Existence and Extent of Cracking
Initial Surface Profile - Surface Roughness [R1,R2]
Surface Texture [TQI, R1, R2]
Initial Surface Friction / Macro Texture [SGR #27]
Initial Serviceability, Po (ride quality) [SGR #18, WRH]</td><td colspan="3">Date of Survey
Distress Modes - Important Distress Evidence [**]</td><td rowspan="3"></td></tr>
<tr><td>RIGID - CRC
<u>Type of Visual Distress</u>
Spalled Cracks,
Punchouts
Asphalt Patches, Concrete
Patches,
Average Crack Spacing,
Spalling, Corner Breaks</td><td>RIGID - JCP
<u>Type of Visual Distress</u>
Failed Joints/Cracks,
Failed Slabs, Slabs with
Longitudinal Cracks
Concrete Patches
Spalling
Apparent Joint Spacing
Corner Breaks</td><td>FLEXIBLE
<u>Type of Visual Distress</u>
ACP - Rutting,
Patching,
Failures,
Alligator Cracking,
Longitudinal Cracking,
Transverse Cracking,
Structural Strength Data</td></tr>
<tr><td colspan="3">Other types of Distress
Value of Distress
Extent of Cracking
Value of Deflection = Falling Weight Deflectometer (FWD) [**][⊗]
Value of Surface Roughness - Automatic Road Analyzer [⊗]</td></tr>
<tr><td>H.
D
E
S
I
R
E</td><td>Drying Shrinkage [SGR #12, R2]
Existence and Extent of Cracking
Rigid After 1 Year or 1 Cycle</td><td colspan="3">Crack Width [SGR #24]
Existence of D-Cracking [SGR #21]
Evidence of Pumping [SGR #17, R2]</td><td></td></tr>
</table>

D E S I R E D		Value of Surface Friction - Skid Resistance Swelling [SGR #19] soil-Y for swelling, N for not [ψ] Settlement / differential settlement [R2] Working Efficiency of Drainable Bases	
H O P E F U L		Use of Non-Destructive Testing Methods ex. Spectral Analysis of Surface Waves [⊗] Impulse Response Method Ground Penetrating Radar (GPR) [⊗] Dynamic Cone Penetrometer (DCP) Results of coring [**] / core rig [⊗]	Observations materials Opinion of Personnel

Data Required for Forensic Analysis

9. Autopsy Data

Data Category Used

Autopsy Data

	Field Evaluation [⊄]	***Materials Sampling & Testing*** [⊗] / ***Laboratory Evaluation*** [⊄]
REQUIRED	Detailed Condition Survey [⊗] / Visual Evaluation [⊗] Date of Survey Falling Weight Deflectometer (FWD) (deflection) [⊗,⊄,**] Distress Modes - Important Distress Evidence [**] Extent of Cracking Other types of Distress Value of Distress Serviceability (last 3 years) [**] Observations of current materials [**]	Results of coring /Core rig [⊄, ⊗, **] 3 or more cores taken from the failed pavement [WRH] 1 or 2 test pits in the failed areas [WRH]

RIGID	**FLEXIBLE**
<u>Type of Visual Distress</u>	<u>Type of Visual Distress</u>
CRC - Spalled Cracks, Punchouts, Asphalt Patches, Concrete Patches, Average Crack Spacing, Spalling, Corner Breaks JCP - Failed Joints/Cracks, Failed Slabs, Slab with Longitudinal Cracks, Concrete Patches Apparent Joint Spacing, Spalling, Corner Breaks	ACP - Rutting, Patching, Failures, Alligator Cracking, Longitudinal Cracking, Transverse Cracking, Structural Strength Data

H. DESIRE **H. DESIRED**	Value of Surface Roughness(Ride Quality) = Automatic Road Analyzer (ARAN) [⊗] Ground Penetrating Radar (GPR) [⊗] Spectral Analysis of Surface Waves [⊗] Core rig/ cores Drainage [SGR #11, ⊄] Working Efficiency of Drainable Bases Evidence of Pumping [SGR #17, R2] Swelling [SGR #19] Settlement / differential settlement [R2] Existence of D-Cracking [SGR #21] Crack Width [SGR #24] Use of Non-Destructive Testing Methods: ex. Impulse Response Method ex. Dynamic Cone Penetrometer (DCP)	(Layer Material Properties - Other Tests?) **HMAC Properties [⊄]** Stability [⊄] Asphalt content [⊄] Asphalt properties - viscosity [⊄] Asphalt properties - temperature susceptibility [⊄] Asphalt properties - stiffness at low temps [⊄] Mixture properties - tensile strength [⊄] Mixture properties - stiffness at low temps [⊄] Aggregate properties - gradation ? [⊄] Aggregate properties - absorption ? [⊄] Aggregate properties - shape ? [⊄] Aggregate properties - surface texture ? [⊄] Water susceptibility [⊄] Air void content [⊄] **Stabilized Base Properties [⊄]** Asphalt treated - tensile strength [⊄] Asphalt treated - volume change potential [⊄] Cement or lime treated - compressive strength [⊄] Cement or lime treated - tensile strength [⊄] Cement or lime treated - volume change potential [⊄]	 **Base, Subbase, Subgrade Properties [⊄]** Gradation ? [⊄] Stiffness coefficients [⊄] (strength) Triaxial classification ??? [⊄] (strength) Mineralogy of clay fraction Volume change potential of subgrade mtl ??
DESIRED	In place density [⊄] Depth of aggregate embedment [⊄] Value of Surface Friction - Skid Resistance/ Skid Number [⊄]	**HMAC Properties [⊄]** Aggregate properties - mineralogy [⊄] Undisturbed samples of fill foundation soil [⊄] Volume change properties of fill soil [⊄] Density profile of fill [⊄] Shear strength of fill material [⊄] Undisturbed samples of subgrade foundation soil [⊄] Volume change properties of subgrade soil [⊄] Consolidation properties of in-place materials [⊄] Segregation of HMAC near crack [⊄]	
HOPEFUL			

	Data Required for Forensic Analysis	
	9. Autopsy Data (cont.)	
	Data Category Used	
	Autopsy Data	
	Observations [**]	***Results of Forensic Investigation/ Hypotheses /Reasoning Behind Conclusions***
REQUIRED	Inspector Interview [**] Opinion of Maintenance Personnel [**]	
H. DESIRE		Settlement / differential settlement - Y or N [R2] Incompressibles in joints - Y or N [R2] Air voids - adequate air void system (freeze thaw behavior) - Y or N [R2] Reactive aggregates - Y or N [R2] Water intrusion to subbase - Y or N [R2]
DESIRED		
HOPEFUL		

LEGEND :

[**] = critical data item as identified by ETG meeting #1

[⊗] = data item identified by TxDOT Administrative Circular on Forensic Investigations

[ψ] = data item identified by CTR Rigid Pavement Database Report

[⊄] = data item identified by TTI Flexible Pavement Database Reports

[SGR #] = data item identified in Stefan Gräter's report - ranking

[TQI] = Total Quality Initiative

[SS] = data item identified by Steve Smith at AASHTO's CMS meeting

[CW] = conventional wisdom

[R1] = Rigid Pavement Failures Table R1

[R2] = Rigid Pavement Failures Table R2

[DF] = Professor David Fowler

[WRH] = Professor W. Ronald Hudson