GIS IMPLEMENTATION PLAN FOR PMIS

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Recommend a Geographic Information System (GIS) for
the Pavement Management Information System (PMIS)

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16. Abstract

This report presents a comprehensive and practical implementation plan of using GIS to enhance the pavement management practice in TxDOT. As the basis of the implementation plan, a "three-stage implementation" concept was used to assess the current practice, define the visionary system, and identify the intermediate solutions. The report covers recommendations not only in the information technologies themselves but also in personnel training. The organizational/institutional issues related to GIS implementation are also discussed. Included in the report is a detailed summary of the completed tasks, major findings and key recommendations from the research project.

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Chapter 1. Introduction

1.1 The Need for a GIS Implementation Plan for TxDOT PMIS

Pavements represent a critical component of the U.S. highway transportation infrastructure. Billions of dollars are spent annually on maintaining and rehabilitating pavements. However, deteriorating pavement conditions, increasing traffic loads, and limited funds present a complex challenge for pavement maintenance and rehabilitation activities. Pavement management systems (PMS) have been developed to cope with these challenges in almost every state during the last two decades. A PMS is developed to identify maintenance needs, help allocate funds, support decision-making, and maintain good pavement conditions under the constraint of limited funds. The Pavement Management Information System (PMIS) is the PMS used in the Texas Department of Transportation (TxDOT).

PMIS is an automated system for storing, retrieving, analyzing, and reporting information needed to support pavement-related decision-making within TxDOT (Ref 1). Although it has worked well in serving its original objectives, the TxDOT PMIS is faced with new challenges arising from diverse data, technologies, and systems and from the resulting inefficient information exchange within the department. The adoption of geographic information systems (GIS) can help overcome these challenges if it is carefully planned and implemented.

Because of their diverse applications, geographic information systems have been variously defined. The Environmental Systems Research Institute (ESRI) (Ref 2) defines a GIS as “a computer-based tool for mapping and analyzing things that exist and events that happen on Earth.” GIS technology integrates such common database operations as query and statistical analysis with the unique visualization and geographic analysis benefits offered by maps. These abilities distinguish GIS from other information systems and make it valuable to a wide range of public and private enterprises for explaining events, predicting outcomes, and planning strategies. The Pennsylvania Department of Transportation (PennDOT) (Ref 3) defines GIS as “an automated system designed to allow users to more easily filter, manage, analyze, display and share location-oriented data and associated explanatory information.”

Dueker and Kjerne (Ref 4) assign another definition to GIS, calling it “a system of hardware, software, data, people, organizations, and institutional arrangements for collecting, storing, analyzing, and disseminating information about areas of the earth.” It employs the element of geography to integrate, organize, and analyze information effectively. The most important benefits for applying GIS to any project generally stem from the following two major groups of GIS functions:

1) To provide a user-friendly database so that a wide variety of data can be accessed easily, manipulated visually, analyzed spatially, and presented graphically.
2) To serve as a logical, coherent, and consistent platform so that diverse databases can be integrated and shared among various divisions of an agency.

Integrating a GIS with an existing TxDOT PMIS is not as simple as merely installing a new piece of software into the existing PMIS and then operating it. A successful GIS implementation involves not only the information technologies themselves but also other elements such as personnel and their GIS skills, the organizational structure within which they work, and the institutional relationships that govern the management of information flow. All of these elements need to be managed in an interactive manner. GIS can serve as a platform for integrating various types of data, systems, and technologies. Because of the nature of rapid changes in GIS and related information technology, a well-developed GIS implementation plan is essential for the following reasons:

1) To reduce the chance of making mistakes.
2) To provide for an integrated management of the various aspects of data issues, computing environment, organizational structure, staff behavior, and information technology application.
3) To provide a reliable platform for dealing with unexpected issues.

The specific benefits of the GIS implementation plan for TxDOT PMIS are outlined as follows:

1) It can provide early warnings of potential problems and serve as the basis for understanding the implications and identifying the solutions.
2) It can help define goals and future directions for the GIS program.
3) It permits the project manager and related staff to proceed with confidence, which improves productivity and efficiency.
4) It provides guidelines for an organized, systematic, and efficient implementation of this new technology so that all the components of a complex system work well together.
5) It can serve as a background for developing budget requests and staff requirements to ensure that the present and future needs of all users will be met through the proposed GIS.
6) It can help justify the program and provide top-level managers with the level of understanding and confidence needed to approve the program.

1.2 Objectives and Scope of Implementation Plan for TxDOT PMIS

The objective of this plan is to provide guidance to TxDOT as it implements GIS to enhance PMIS. This guidance includes step-by-step procedures, standards, and guidelines. The focus of the implementation plan is the identification and selection of GIS activities and resources that are essential for improvement of existing PMIS activities.

The Information Systems Division (ISD) in TxDOT has developed a Core Technology Architecture and a GIS Architecture to define the information technology directions, standards, policies, and procedures for adopting GIS and other computer applications in TxDOT. The GIS implementation plan should be compatible with the Core Technology Architecture.

During the last five years, the Center for Transportation Research (CTR), The University of Texas at Austin, has been conducting research on the use of GIS for the management of roadways, airports, and urban infrastructure. The findings from these research efforts suggest that certain issues must be considered in recommending a GIS. These issues include:

1) The recommendations must be consistent with the established computation environment and long-term development plan of TxDOT.

2) The recommended GIS must have the capabilities to satisfy the defined user requirements and minimize conflict with the legacy systems that will be retained by TxDOT.
3) The interface between the recommended GIS and PMIS should be easy to establish, and the recommended GIS should be able to utilize the existing database(s) either directly or through inexpensive data conversions.
4) The recommended GIS should allow operations to be carried out at several levels of sophistication.
5) The recommended GIS should be easy to learn and have excellent customer support from the vendor(s).

1.3 Organization of GIS Implementation Plan for TxDOT PMIS

The implementation plan consists of ten chapters. Chapter 1 provides an introduction to the background, purposes, objectives, benefits, and organization of this implementation plan. Chapter 2 describes the overall process for implementing a GIS and discusses other important issues. Chapter 3 outlines the present status of TxDOT PMIS and related systems and the future GIS application needs for PMIS. Chapter 4 identifies needed spatial and attribute data. The quality of spatial data is critical for practical use of a GIS. Chapter 5 describes the computing environment for operating GIS for PMIS, which includes the evaluation and selection of GIS software and hardware, database management software, CADD, etc. Chapter 6 discusses the personnel and skills needed to create, use, and maintain the GIS-based PMIS. The type and the number of staff and the necessary training program are also covered. Chapter 7 discusses the necessary organizational structure and the locus of GIS expertise that best suit the needs of GIS-PMIS. Some important institutional issues are also explained. Chapter 8 discusses several ways to integrate GIS with PMIS. Several technologies that are important for successful implementation of GIS for PMIS are also covered. Chapter 9 documents the pilot implementation project conducted with the Odessa district. Major issues related to pilot implementation are explained. Finally, Chapter 10 summarizes the important research findings of the project. Future research areas are recommended based on the research results from this project.

Chapter 2. The Overall Process for Implementing GIS for PMIS

2.1 The Process for Implementing a GIS for PMIS

As shown in Figure 2.1, a GIS is composed of four elements that are indispensable for a successful GIS implementation:

1) Useful and accurate **data** must be available for analysis.
2) An efficient **computing environment** must be configured to manage data and perform analysis effectively.
3) **People** are needed to develop, use, and maintain the GIS applications.
4) Finally, **organizations and institutional arrangements** must be prepared to adopt the technology.

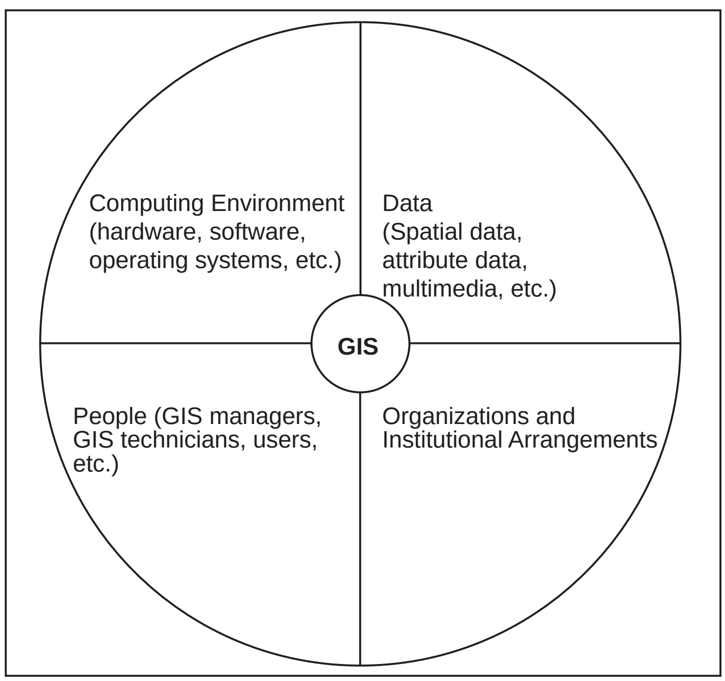

Figure 2.1 The components of a geographic information system (GIS)

Figure 2.1 shows that GIS technology cannot be implemented properly if key elements are isolated from one another. Insufficient attention to any of these four components can lead to implementation failures. For best results, the four components must be considered systematically, with particular attention paid to their interaction.

Figure 2.2 shows the two interacting paths for implementing a GIS for any agency (Ref 5). The first path is the planning and design of a GIS implementation, in which existing resources (computing environment, data, staff and skills, organizational structures, and institutional arrangements) and limitations are analyzed and some potential GIS activities are identified and selected.

The order in which these four components are addressed is important. The first step is to study existing PMIS resources and assess the different levels of user needs. The second step is to identify the expected products or outputs that can satisfy the agency needs. The third step is to identify the data (attributes, accuracy, scale, detail, etc.) required to produce the desired output. Data requirements influence the type of software and hardware required for data processing and management. The complexity of hardware, software, and data inputs, as well as required future applications, will determine the personnel skills needed to develop, use, and maintain the GIS application. Finally, organizational policies are required to ensure that the whole system is developed and works in a coherent, consistent manner. These various components can be addressed concurrently, but it is important that they not be handled in reverse order.

The second implementation path is based on the results of the first path, but the order of components is reversed. First, organizational policies are established to provide a suitable environment for the implementation of GIS. Second, personnel must be trained or hired to develop, use, and manage the system. Third, hardware must be acquired, and software must be installed in the hardware. Fourth, data are developed and loaded into the system. Finally, applications can be developed to serve the needs of the agency.

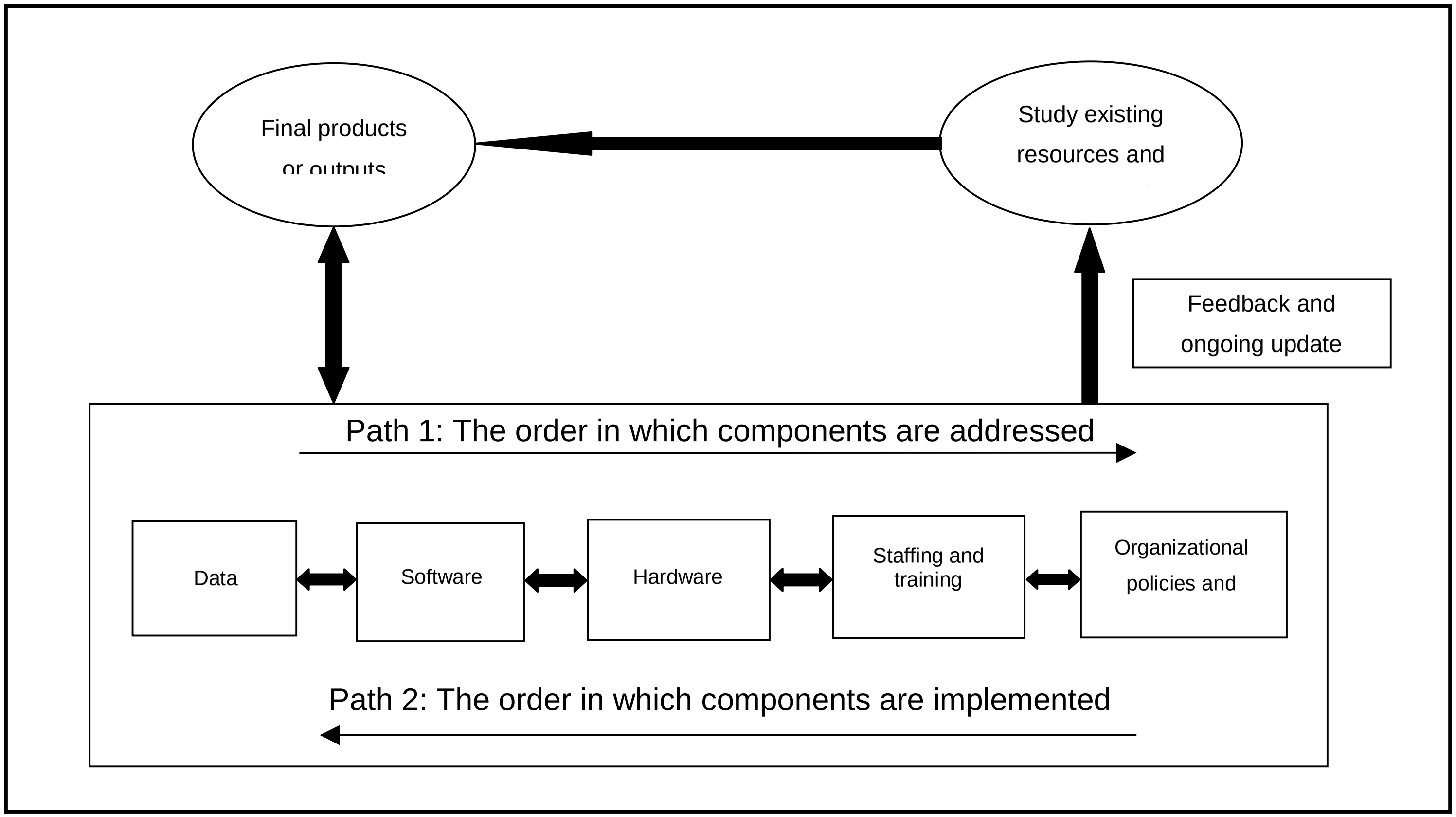

Figure 2.2 The whole process of implementing GIS for PMIS for TxDOT

There will be a time delay between the end of implementation processes and the actual operation of the system. The focus of the work during this period will change from planning, design, and implementation to budgeting, managing projects, managing people, and delivering products to the users (Ref 6).

Because information technologies advance quickly, it is important to monitor the implementation process frequently and adjust the GIS implementation plan according to changes in the four GIS components.

2.2 Critical Issues Related to Implementing GIS for PMIS

Several issues are critical throughout the whole implementation process. The first is the involvement of both management personnel and technical personnel (Ref 7). The management personnel have overall responsibility for deciding future GIS directions. The technical personnel are responsible for designing and implementing GIS. Both managerial and technical personnel should be involved in order for the technology to fit the needs of the agency well. Past experience with successful GIS implementations has revealed the presence of two key individuals called the "sponsor" and the "champion" (Ref 8). The sponsor is a manager at the department or division chief level. The person has budget authority and is a member of the management implementation team. The sponsor must create the conditions for potential champions to emerge, must be able to recognize them when they do, and must be able to support them. A champion is a technical manager, often in a user division. He or she is a technical leader who has vision, devotion, and enthusiasm and works well with people. This person leads the technical implementation team and is probably also a top candidate for the director of the core staff. The champion seeks the approval of the sponsor for initiatives and procurements.

The second key issue concerns multiple technologies. GIS is not the only technology that should be incorporated in an information technology plan. There are other information technologies that must be coherently integrated with GIS efficiency and effectiveness (Ref 7).

The third key issue concerns ever-evolving technology changes. Information technologies related to GIS are changing rapidly, making them difficult to plan and predict. The GIS implementation plan should be a "live" document. When any changes in the four components of a GIS take place, the plan must be updated to reflect the changes (Ref 7).

The last key issue involves data and systems integration. The data integration problem is especially important for GIS technology adoption. Because the costs of geographic data acquisition and maintenance are high, there is a legitimate need for the data to be shared across applications. As an integration platform, GIS has the potential to integrate different systems across the department, making information flow more efficiently.

Attention should be given to several specific procedures as outlined in the following sections.

1) **Assess current status of PMIS:** It will be very important to make a careful assessment of the current status of PMIS before GIS implementation takes place because most of the existing data, staff, and system will have to be used during the transition process. Meanwhile, PMIS activities that have the potential to be improved by GIS operations need to be identified at both the network level and the project level. Correspondingly, potential GIS activities that can be used to improve existing PMIS must also be identified and prioritized.
2) **Identify the products or outputs:** In this step, goals and objectives must be developed. The goals provide a broad policy framework, within which GIS will be planned and implemented for PMIS. For example, the GIS should:
   (a) maximize the level of integration with the corporate information systems strategy;
   (b) minimize the staff requirements;
   (c) facilitate education and training;
   (d) provide the widest range of functionality; and
   (e) provide the highest degree of flexibility in the data architecture. The objectives are more specific statements of how each goal is to be achieved.
3) **Identify the type of data:** The data needed include spatial data (base map) and attribute data. First, the suitability of the current TxDOT digital base maps for PMIS, especially for the accuracy level of the digital base map, has to be evaluated. During this process, those responsible for the GIS implementation should consider future applications of GIS and the availability of data. Furthermore, strategies for maintaining the quality of the database need to be established early.

4) **Evaluate and select software**: GIS software provides the functions necessary to assist an organization addressing its objectives. The criteria used to evaluate given GIS software will depend on its ability to serve GIS functions. A GIS software package may be very strong in certain areas but provide only satisfactory functions in other areas. It is impossible for any GIS software package to provide the strongest functions in every area. However, it is recommended that only one GIS software package be used for all GIS applications for the following reasons:
   (a) There will be no compatibility problems if only one GIS software package is employed.
   (b) The GIS staff will become experts by using one package; therefore, they can provide adequate support for both maintenance and development of GIS applications within TxDOT.
   (c) This single software application will reduce training costs and time. If more than one software package must be used, care should be taken to ensure that data and information can be readily transferred from one package to another.
5) **Evaluate and select hardware:** The types of software and the amount of data will help determine the hardware needs such as CPU, hard drive, and memory requirements. With the advancement of computer technology, the costs of hardware have declined dramatically and will continue to do so.
6) **Evaluate personnel skills and training needs:** It is important to realize the special nature of staffing. In an organization-wide implementation, there are likely to be three levels of GIS staff and users.
   (a) *Core staff* are responsible for spatial database design and development, establishment of standards, training, low-level programming, and application development. The core staff should normally be within the Information Systems Division (ISD).
   (b) *Master users* participate with the core staff in application design and do high-level (macro language) application development. Master users are attached to user divisions such as the Pavements Section.

(c) *Other users* are trained only in the use of fully developed applications. They are an organization's daily users, from entry-level planners and engineers to top management.

Corresponding to the three levels of staff in an organization is the need for three levels of training:

(a) *Core staff* must be intensely trained until they are adept at database and application design as well as GIS programming.

(b) *Master users* must be trained until they are comfortable with the high-level programming or macro languages of the GIS.

(c) *Other users* must be trained to the degree until they are comfortable with the applications and management so that they can make routine use of the system (Ref 8).

Although some training programs are available from vendors, universities, and other training providers, large transportation agencies like TxDOT should consider developing their own internal training services.

7) **Organizational policies and procedures:** They are needed for a successful implementation of GIS for PMIS depend upon the organizational structure and the locus of GIS expertise that best suit the department's GIS needs. The options available include:

3) *Centralized support for decentralized applications*: Specific applications are operated and maintained in division/district offices but are supported by a centralized office in the areas of software updating, personnel training, and other technical assistance needs.

4) *Centralized support for centralized applications*: All applications are developed and maintained by a centralized office. Division/district offices have access to the applications for usage but have no control over them.

5) *Decentralized support for decentralized applications*: All applications are controlled completely by the division/district offices based on their needs.

2.3 The Three-Stage Implementation Concept

A three-stage implementation concept is useful for implementing a GIS. The three stages include the current, intermediate, and ideal stages. Assessing the resources at the current stage is important because this stage is the point from which everything starts. The ideal system is the visionary system for the future. It represents the ideal system and procedure for the agency without being compromised because of any constraints or limitations. In other words, the ideal system is the optimal one technically, although it may not be the one politically feasible in every aspect. It is the best goal. However, there are always trade-offs between the ideal systems and the actual resources available in making recommendations for each GIS component. Therefore, it is critical that the implementation plan cover not only the current status analysis and the ideal future directions, but also the process of effectively and efficiently conducting the transition from the current state to the ideal system. The intermediate solution is the bridge between the current status and the ideal system, as illustrated in Figure 2.3. The bridge has to be smooth at both ends.

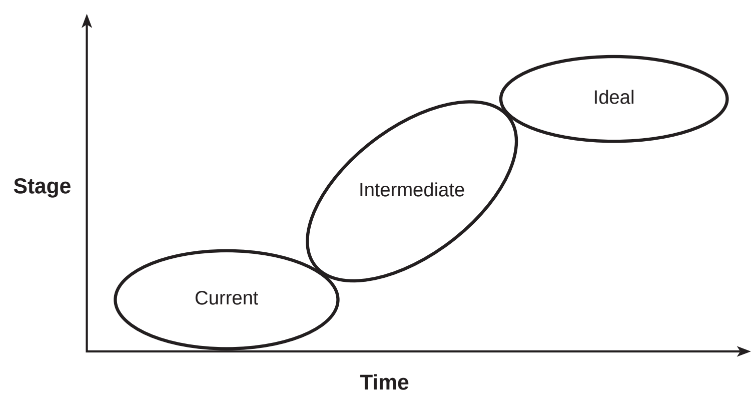

Figure 2.3 Illustration of the intermediate solution concept

The following areas in the GIS implementation plan should be addressed with the intermediate solution concept:

1) GIS-PMIS Functions
2) Data Collections and Management
3) Computing Environment

4) GIS Staff and Training
5) Organizational Structure and Policy
6) Integration of GIS with PMIS

Chapter 3. Determining Potential GIS Operations for PMIS and Identifying the Final Products

3.1 Primary GIS Operations

Table 3.1 summarizes five primary GIS categories of operations or tasks. They are as follows:

1. Data Entry
2. Manage, Transform, and Transfer Data
3. As an Integration Platform and a Common Location Reference System
4. Query and Analysis
5. Display and Report

Table 3.1 Primary GIS operations

CATEGORY	SUBCATEGORY
Data Entry	Digitizing Scanning (automatic or semiautomatic) Global Positioning System Digital Cameras, Remote Sensing Stereo Plotter Photogrammetric Stations COGO Voice Keyboard, etc.
Manage, Transform, and Transfer Data	Storage Data Access, Retrieve, and Edit Data **Handle Raster and Vector Data and Convert Between Them** Search and Sort Data Classify and Reclassify Data Data Import and Export ❖ Traditional media (tape, disk, CD-ROM) ❖ Network transfer Map Projection Spatial Data Exchange Geocoding
As an Integration Platform and a Common Location Reference System	Integrate Different Systems Integrate Different Processes Integrate Different Technologies

Table 3.1 Primary GIS operations (continued)

CATEGORY	SUB-CATEGORY
Query and Analysis	**Point-and-Click Queries** **Logical Query** **Spatial and Attribute Query** **Spatial Analysis** **Buffering** **Network Analysis** • Dynamic segmentation • Network overlay • Other (shortest path analysis, optimum tour routing) **Polygon Overlay**
Display and Report	**Onscreen Display** • Thematic mapping ❖ Attributes classification ❖ Color-coding or patterning attributes, such as pavement condition • Zoom in, zoom out, pan, etc. Layout and Report (maps, tables, charts, and statistics, etc.) • Cartographic output • Thematic mapping ❖ Attributes classification ❖ Color-coding or patterning attributes, such as pavement condition **Static vs. Dynamic** **Multimedia** • Video-logging • Photo-logging **Internet**

3.1.1 Data Entry

Before data can be used in a GIS, they must be in a compatible digital format, which may require system conversions from such existing formats as hard-copy maps, tables of attributes, aerial photos, and satellite imagery. **Digitizing** is a widely used method for converting data from non-digital sources into computer files. Modern computer technology can automate this process using **scanning technology**; small jobs may require manual digitizing. In addition to these two primary methods, existing digital files can be loaded directly into a GIS. The following data entry methods can also be used to support GIS:

- **Global Positioning System (GPS)** receivers and other electrical data collectors providing spatial data information directly in electrical format can be used to support GIS.
- **Digital cameras and remote sensing technology** capture digital images directly in raster form.
- **Photogrammetric stations** and **coordinate geometry (COGO)** from field surveys are also used for data entry for GIS.

3.1.2 Manage, Transform, and Transfer Data

Access and retrieve operations on both spatial and nonspatial data involve selective searches of databases and output of retrieved data in response to various queries. Queries can be made by location or by characteristics.

Editing includes zooming and panning, adding, deleting, copying, moving, and transforming objects by pointing, by encompassing data within an area, or by manipulating data with attribute values.

Spatial and nonspatial data management typically includes a GIS package manages spatial data with customized software that is linked to a database management system (DBMS) for managing attribute data.

Spatial data exchange is important for the integration of disparate data sets from dissimilar computer systems or GIS software. The two basic methods for data exchange between different GIS are 1) direct conversion of data from one system to another using proprietary formats and 2) translation of data via a standardized neutral exchange format.

Data transformation is either between data models or between coordinate systems. Transformations between data models include raster-to-vector conversion and vector-to-raster conversion. Coordinate systems transformation can be 1) arbitrary-to-ground, 2) between geodetic datums, or 3) ground-to-ground (Ref 7).

3.1.3 As an Integration Platform and a Common Location Reference System

The most important benefits for applying GIS for any project emerge from its role as an "integrator" (Ref 8). Transportation management systems have been developed and implemented by state DOTs in many forms. However, most of these systems were developed and operated as stand-alone systems. The data structures and computing environments (software, hardware, etc.) vary tremendously across departments. The incompatibilities among these systems have been serious obstacles for data sharing and the free flow of information. Since most of the data in all organization levels, policies, management, and operations are geographically referenced, GIS makes it possible to link and integrate different systems, processes, and technologies that are difficult to connect through any other means. GIS is the most effective computerized common location reference system (Ref 9).

3.1.4 Query and Analysis

A GIS provides both simple point-and-click query capabilities and sophisticated analysis tools to provide timely information to users (Ref 7). Query is the process of selecting information from a GIS by asking spatial or logical questions of the geographic data. Spatial query is the process of selecting features based on location or spatial relationships. Logical query is the process of selecting features whose attributes meet specific logical criteria. Analysis is the process of extracting or creating new information about a set of geographic features. There are two important types of analysis in GIS: spatial analysis and network analysis.

1) **Spatial analysis** functions distinguish GIS from other information systems and from computer-aided drafting (CAD) systems.
2) **Network analysis** is the most important GIS operation for transportation applications. Dynamic segmentation and network overlay are two critical network analysis operations that make possible spatial analysis and integration of highway inventory databases and any other linearly referenced databases. Dynamic segmentation is the ability to store attribute data in a single storage item for multiple and partial segments of graphic elements. If used effectively, it can reduce the data input and storage requirements.

Polygon overlay operations combine separate spatial databases and at the same time integrate their attributes. There are three variations: 1) polygon-on-polygon; 2) line-in-polygon; and 3) point-in-polygon.

The overlay functions (both network overlay and polygon overlay) best exploit the data integration power of GIS. The purpose of overlay is to combine existing databases in such ways that new information is created (Ref 7).

3.1.5 Display and Report

A GIS allows users to visually display the results of database queries and pavement management analyses on a map. Through color-coding of pavement conditions, users can view network conditions and projected work programs. Integrated with graphs, tables, charts, and multimedia, maps are very efficient in helping PMIS engineers make the right decisions and communicate effectively with colleagues and administrators.

3.2 Current TxDOT PMIS and GIS

The Texas PMIS assists the districts and department in the following (Ref 1):

1) Planning, consisting in:
   - Budgeting.
   - Scheduling.
   - Prioritizing projects.
4) Highway design, including:
   - Project-level pavement type selection.
   - Rehabilitation strategy identification.
   - Maintenance.
3) Maintenance and rehabilitation, incorporating network-level strategy development.
4) Evaluations covering both the network level and the project level.
5) Research, encompassing:
   - In-house pavement-related studies.
   - Contract pavement-related studies.
6) Reporting, entailing:
   - Current condition.
   - Future condition.
   - Needs.
   - Work.

For the senior management level and technical level, the following personnel are directly or indirectly involved in the operation of PMIS:

1) District PMIS Coordinator.
2) District Update Users.
3) Other District Users.
4) Design Division, Pavement Section.
5) Other Division Users.

As seen in Table 3.2, PMIS is a mainframe application. PMIS runs under a combination of two operating environments. They are 1) District Access Environment (CICS) and 2) Batch Operating Environment (ROSCOE) (Ref 11). The PMIS is updated from other automated systems within the department on an annual basis. PMIS receives annual updates from:

1) Texas Reference Marker (TRM) system maintained by the Transportation Planning and Programming Division.
2) Road Life System (RLS) maintained by the Transportation Planning and Programming Division.
3) Maintenance Management Information Systems (MMIS) maintained by the Maintenance Division.

Table 3.2 Mainframe connectivity (Ref 11)

Mainframe Environment	***Capability***
CICS	Access PMIS Generate PMIS Reports Store Data
ROSCOE	View Reports Print Reports Upload and Download Data Store Data Do ad hoc Reporting

TxDOT is not actively using GIS at this time, apart from supporting some aspects of the base map process and some ad hoc application development, such as the El Paso District Corridor Study and Odessa District video-log data integration. Table 3.3 shows the computing environment in TxDOT as a mixture of several types of technology, each representing a specific stage of data processing technology development. The end result is a heterogeneous environment composed of mainframe computers, RISC chip-based workstations, and PC platforms and their accompanying operating systems, communication protocols, and software. Furthermore, the majority of data is held in ADABAS and accessed through interfaces programmed in Natural.

Data transfer from ADABAS to PC or UNIX-based workstations is accomplished through ASCII files.

Most pavement management activities can be grouped into two basic working levels: network level and project level (Ref 10). The primary purpose of the network-level management activities is to develop a priority program and schedule of rehabilitation, maintenance, or new pavement construction work within overall budgets. Project-level work comes in at the appropriate time in the schedule. Table 3.4 shows the PMIS activities for both network level and project level aggregated and sorted in the order of sequence.

3.3 Improving PMIS Functions through Implementing GIS

A GIS used as a common location reference system and an integration platform makes it possible to link and integrate different systems, processes, and technologies that are difficult to associate through any other means. Some improved PMIS functions that can be achieved through implementing GIS are as follows:

1) Information sharing and communication among different divisions.
2) Reduction in data redundancy.
3) Improvement of organizational integrity by eliminating multiple map set problems.
4) Integration of different software, hardware, systems, and technologies.
5) Cost reduction of data, systems development, and maintenance.
6) Enhanced productivity and improvement of efficiency and effectiveness by doing more with the same or fewer resources; deriving greater benefits from staff activities; and making better decisions with knowledge from the review of more alternatives.
7) Effective computerized common location reference system.
8) User friendly interface.

Table 3.3 As-is GIS in TxDOT (Ref 11)

	Hardware	Operating System	Network	DBMS	GIS Software	Base Map	Referencing System
Present	Dumb Terminals CLIX Workstations PC Workstations	CLIX (UNIX)	Stand-alone GIS access FTP access for design files	ADABAS	MGE, Microstation	Urban .dgn file 1:24000 scale	TRMIS, CSM DFO Statewide routes <150 ft accuracy
Future	PC Workstation	Windows NT	LAN in District-GIS file server WAN connection to central data server	Sybase Products MS Access Data Warehousing	Microstation ARC/INFO ArcView MapObjects SDE	Urban .dgn file 1:24000 scale DOQQs– 1-30 meters resolution GPS-differentially corrected	LRS based on GIS route system 30´–40´ accuracy Anchor points or GPS to calibrate TRM to LRS

Table 3.4 Current PMIS activities

Network-level PMIS activities	Project-level PMIS activities
• Segmentation • Data acquisition and processing • Identification of available resources • Summarization of current status • Identification of present and future needs • Identification of candidate projects for improvement • Generation of Maintenance and Rehabilitation (M&R) alternatives • Analysis of technical and economic data • Prioritization of M&R alternatives • Budget planning and distribution • Development of M&R programs • Summarization of future status • Justification of budget requests: Legislators are faced with a variety of competing requests • Study of effects of less capital • Study of effects of deferring work or lowering standards • Study of effects of increased load limits • Study of effects of the implementation of M&R • Updating of data • Utilization of feedback information to improve model • Updating of M&R program	• Subsectioning • Data acquisition and processing • Summarization of current status • Generation of alternatives • Technical and economic analysis • Selection of best alternatives • Summarization of future status • Implementation • Effects of implementation • Updating of data • Rescheduling measures • Utilization of feedback to improve models

For each GIS operation, there are specific improvements for PMIS users from the implementation of GIS:

1) **Data entry:**
   - Collect data more efficiently and accurately as various data collection methods compatible with GIS become available.
   - Identify omitted or erroneous pavement attributes through visual data verification.
   - Verify spatial accuracy through visual spatial data inspection.
2) **Query and analysis:**
   - Obtain the expected new information more efficiently and effectively.
   - Reduce data input requirements and data storage requirements.
3) **Display and report:**
   - Make information easier to obtain and more meaningful by investigating data visually.
   - Encourage better decision-making by obtaining more meaningful information.
   - Communicate with public and legislature more efficiently and effectively.

There are three levels of PMIS users who can benefit from applying GIS technology (Ref 10):

1) **Legislative-level users:** The issues and questions at the legislative or elected official level are fairly broad in scope but have to be recognized by the administrative and technical levels.
2) **Administrative-level users:** The administrative and planning people responsible for developing capital spending and maintenance programs need to recognize and respond to legislative-level issues and require certain answers from the technical level, in addition to facing questions at their own level.

3) **Technical-level users:** The technical-level people are responsible for providing answers for both administrative-level users and legislative-level users**.**

Appendix A (Ref 10) summarizes the improvements from implementing PMIS for pavement management activities in general, as well as some specific improvements for three different pavement management level users: elected representatives, senior managers, and technicians. The improvements from the adoption of GIS for PMIS users are also summarized in Appendix A.

3.4 Ideal GIS-PMIS Activities and Corresponding Benefits

Appendix B and Appendix C summarize the GIS operations that have the potential to improve the existing PMIS activities at both the network level and the project level. For each PMIS activity, the resulting improvements from the adoption of GIS are summarized in Appendix A.

3.5 Intermediate Solution and Expected Final Products

The transition from the current TxDOT PMIS to the ideal GIS-PMIS should be as smooth as possible. It is not feasible to implement all the potential GIS-PMIS activities at once. The ideal GIS-PMIS activities need to be prioritized. One Expert Task Group (ETG) meeting was held for this purpose at the CTR. During that meeting, practicing engineers from selected districts were asked to list several issues that were most important for GIS-PMIS based on their daily business activities. More detailed information from the ETG will be discussed in Chapter 9.

The final product should meet the following minimum requirements:

1) It should not conflict with state GIS inter-agency standards, GIS Architecture, or Core Technology Architecture established by TxDOT.
2) It should be as consistent as possible with the existing computing environment and the long-term development plan of TxDOT.
3) It should maximize the level of integration with TxDOT information systems strategy.
4) It should minimize staff requirements.
5) It should be able to facilitate education and training.
6) It should provide the widest range of functionality.
7) It should provide a high degree of flexibility in the data architecture.

8) The interface between the recommended GIS and the PMIS should be easy to establish.
9) It should be able to use the existing databases either directly or through inexpensive data conversion.
10) It should allow operations to be carried out at several levels of sophistication.

It should be easy to learn and have excellent customer support from the software vendor(s).

Chapter 4. Data Issues and Related Technologies

4.1 The Base Map Accuracy Required for PMIS

A base map contains geographic features used for location referencing. The accuracy level of a base map is a critical issue that has to be addressed during the GIS planning stage. Although the accuracy and precision of base maps are very important issues, until recently few people involved in developing and using GIS paid attention to base map accuracy from the perspective of engineering applications.

Because base maps provide a reference system to correlate other data, the quality of the base map to a large extent determines the success of a GIS project. With the introduction of new data collecting technologies, such as GPS, the location accuracy of events and objects related to PMIS has been significantly improved. The accuracy level of the base map should be consistent with this change. However, more accurate and precise data require more resources to produce and maintain the data.

There are always trade-offs between accuracy and the costs needed to achieve such accuracy. Furthermore, different applications require different base map accuracy levels. For example, the base map accuracy level required for statewide transportation planning is apparently different from that required for project engineering, which requires a more detailed and accurate base map.

This chapter describes an approach to investigating the base map accuracy level required for TxDOT PMIS from the perspective of engineering applications. TxDOT PMIS attribute data are examined first because the base map must be capable of representing the smallest possible roadway segments based on these data. From the PMIS attribute data, distress data are selected for analysis of base map accuracy required for PMIS because distress data change most frequently along the roadway. Both the absolute accuracy and relative accuracy level of the base map required for TxDOT PMIS are discussed. Finally, the accuracy of the existing TxDOT base map is examined last to see if it satisfies the PMIS requirements.

4.1.1 Some Definitions

Base map accuracy can be defined as the object's location on a map compared to its true location on the ground. There are two kinds of accuracy that are important for the base map: absolute accuracy and relative accuracy.

1) *Absolute Accuracy* is the degree to which any well-defined position on a map conforms to the actual location of that point on the ground with respect to a fixed reference correction. If the x-y coordinate of a particular point on the earth is determined by a land survey and is also determined by scaling from a map, the difference in the x-y coordinates is the absolute accuracy. This means that when we see a point on a map we have its "probable" location within a certain area. The same applies to lines and objects (Ref 12).
2) *Relative Accuracy* is the accuracy associated with the distance between two particular points relative to each other. If the distance between two points, as measured by a land survey on the surface, is compared to the distance measured between these same two points on a map, the difference in the two distances is the relative accuracy. Relative accuracy of the base map is an important concept for GIS-PMIS because the distance of a specified roadway segment is frequently measured in PMIS. More details regarding relative accuracy will be discussed in the following sections.

It is also important to distinguish accuracy from precision and resolution.

1) *Precision* refers to the degree of refinement with which a measurement is taken or a calculation is made, with higher refinement being expressed as the greater number of significant figures. It is useless to talk about precision without considering accuracy.
2) *Resolution* refers to the smallest level of detail visible in an image. For example, the resolution of a USGS DOQQ is one meter.

4.1.2 TxDOT PMIS Data

For researchers to investigate the base map accuracy level required for PMIS from the perspective of applications, they must carefully examine TxDOT PMIS attribute data for an important reason: the base map must be capable of representing the smallest possible roadway segments based on available PMIS attribute data.

The following pavement-related data are collected and maintained by TxDOT PMIS. All of these data are important for pavement management and will be referenced on the base map (Ref 1).

1) *Visual Distress Data* — Pavement distress data examine individual surface distresses and rate them according to the severity level. Trained pavement raters collect pavement distress data each year on entire highways within each county. The sample size is about 50 percent per year. Distress data are collected for the following broad pavement types:
   - Flexible pavement or asphalt concrete pavement (ACP).
   - Continuously reinforced concrete pavement (CRCP).
   - Jointed concrete pavement (JCP).
2) *Ride Quality Data* — Ride quality data describe the pavement's "roughness." Ride quality data are also collected on entire highways within each county. The sample size is about 50 percent per year. Ride quality data are collected on the following pavement types:
   - Flexible pavement (ACP).
   - Continuously reinforced concrete pavement (CRCP).
   - Jointed concrete pavement (JCP).
3) *Deflection Data* — Deflection data describe the pavement's structural adequacy. Deflection data collection is optional. Deflection data are collected only on flexible pavement for PMIS.
4) *Skid Resistance Data* — Skid resistance data measure the relative skid resistance of pavements. Collecting skid resistance data is optional. Skid resistance data are collected for the following pavement types:
   - Flexible pavement (ACP).

- Continuously reinforced concrete pavement (CRCP).
- Jointed concrete pavement (JCP).

5) *Automated Rutting Data* — A rut is a surface depression in a wheel path. Procedures and equipment for collecting automated rutting data are under development. When completed, the automated rutting data will replace the “shallow rutting” and “deep rutting” distress types collected manually. When completed, automated rutting data will be collected for entire highways within each county. The sample size will be near 50 percent per year. Automated rutting data will be collected only for flexible pavements.
6) *Other Pavement Data* — Besides pavement evaluation data, PMIS obtains other pavement data from the following TxDOT automated systems:
   - Texas Reference Marker (TRM) System.
   - Road Life System.
   - Maintenance Management Information System (MMIS).

Other pavement data include:

- Location Data.
- Traffic Data.
- Climatic Data.
- Pavement Type and Characteristics Data.
- Cross-Section Data.
- Date of Last Surface Data.
- Pavement Maintenance Expenditure Data.

Among these types of TxDOT PMIS attribute data, distress data change most frequently along the roadway. For this reason, distress data are used for the analysis of base map accuracy level required for PMIS.

4.1.3 Current TxDOT PMIS Visual Distress Data Collection and Management Method

The annual PMIS survey currently consists of two separate surveys: a visual evaluation survey and a ride quality survey (Ref 14). Other data, such as skid resistance and structural strength may be collected; however, these other data are not included in the current PMIS analysis procedures. Currently, a PMIS section length can vary from 0.1 mile to 0.6 miles, but it is typically 0.5 miles in length. A data collection section is somewhat homogeneous in construction. The section is defined when the following changes occur:

1) Pavement.
2) Geometric.
3) County Line.
4) Reference Marker.

When traveling across a PMIS section, raters rate the lane that shows the most distress on each roadbed. Undivided highways have only one roadbed; divided highways have two or more roadbeds. The lane being rated can change from section to section as raters travel down the road. For flexible pavement sections, raters travel along the side of the road and stop at least once in every PMIS section. The first stop is made at the beginning of the section, and raters observe and log all distress types visible. The purpose of the stop is to calibrate the raters' vision as to which distress types exist within the section. Additional stops are made where major changes occur to "recalibrate" the raters' vision. At the end of the section, raters enter their overall section ratings for all of the flexible pavement distress types. For rigid pavement sections, raters begin counting distress occurrences at one end of the section and travel along the edge of the road. The only stop required is at the end of the section, where raters enter the evaluation data. For safety reasons, the raters are responsible for counting only "easy" distresses, such as concrete patches, punchouts, or failed slabs. The rating consists of a one-, two-, or three-digit number for each of these distress types. The numbers indicate either the area or the amount of each distress that was observed. As shown in Table 4.1, three methods are used to process the raw data for different distress types in the TxDOT PMIS. After the raw pavement distress data are processed, they are distributed along the PMIS sections, thus becoming the attribute data related to the PMIS sections, the linear objects.

1) *Percentage* — After the total distance of the distress (such as shallow rutting) is assessed, the percentage of distress data is determined by using a reference table in the pavement condition evaluation manual. All the distress data with procedures belonging to this category are for flexible pavements. They include:
   - Rutting (Shallow and Deep).
   - Alligator Cracking.
   - Longitudinal Cracking.

   All distress types are rated according to the percentage of the rated lane's total surface area. The area measured throughout the PMIS section should be converted to full lane width first; the reference tables are then used to determine the percentage of the distress area. The two distress types using this procedure are:
   - Patching.
   - Block Cracking.
2) *Total Number* — Raters should count the total number of distress data types observed along the entire section or per station. The following distress types belong to this category:
   a) Flexible Pavement.
      - Failures.
      - Transverse Cracking.

   b) CRCP.
      - Spalled Cracks.
      - Punchouts.
      - Asphalt Patches.
      - Concrete Patches.

   c) JCP.
      - Failed Joints and Cracks.
      - Failures.
      - Shattered Slabs.
      - Slabs with Longitudinal Cracks.
      - Concrete Patches.

3) *Attribute* — The rating code indicates the percentage of the rated lane's observed value, when the rating code rather than the percentage value is used. Table 4.2 gives the rating codes and their corresponding percentage values.

Table 4.1 TxDOT PMIS data type and corresponding rating methods

Data Type			How rated in TxDOT PMIS
Pavement Distress Data	Flexible Pavement	Shallow Rutting	Percent
		Deep Rutting	Percent
		Patching	Percent
		Failures	Total Numbers
		Alligator Cracking	Percent
		Block Cracking	Percent
		Longitudinal Cracking	Length per Station
		Transverse Cracking	Number per Station
		Raveling	None, Low, Medium, or High
		Flushing	None, Low, Medium, or High
	CRCP	Spalled Cracks	Total Number
		Punchouts	Total Number
		Asphalt Patches	Total Number
		Concrete Patches	Total Number
		Average Crack Spacing	Feet
	JCP	Failed Joints and Cracks	Total Number
		Failures	Total Number
		Shattered Slabs	Total Number
		Slabs with Longitudinal Cracks	Total Number
		Concrete Patches	Total Number
		Apparent Joint Spacing	Feet
Ride Quality Data			The Walker Roughness Device (SIO meter)
Deflection Data (only for flexible pavement)			FWD
Skid Resistance Data			A Locked-Wheel Skid Trailer and Tow Vehicle
Automated Rutting Data (only for flexible pavement)			The Walker Roughness Device (SIO meter)

Table 4.2 Rating codes for pavement distress

RATING CODE		AMOUNT (PERCENT AREA)
0	NONE	0
1	LOW	1–10
2	MEDIUM	11–50
3	HIGH	>50

For raveling and flushing on flexible pavements, the rating code is generally used.

For average cracking (CRCP) and Apparent Joint Spacing (JCP), the rating procedure is different. In general, the total number of transverse cracks or apparent joints observed along the highway section is counted and then averaged.

4.1.4 Ideal TxDOT PMIS Data Collection and Management Method

Currently, TxDOT PMIS data are linearly referenced in a one-dimensional model. This means that all PMIS-related attribute data are linearly referenced. Recent advances of GPS technologies, integrated with dynamic segmentation functions of GIS, allow for more efficient and flexible data collection and storage. Using GPS receivers, raters can drive along the highway and define the beginning and ending points of sections when there are changes in pavement distress along the highway. Dynamic segmentation makes it possible to store attribute data in a single storage item for multiple and partial segments of graphic elements and thus facilitates data collection in the most logical manner. Data sets that are linear in nature can be stored using either fixed-length or variable-length segmentation as seen in Figure 4.1 (Ref 15). Fixed-length static segments break the roadway into pre-defined lengths and are insensitive to changes in attributes, which can result in significant data redundancy. Presently, TxDOT PMIS uses fixed-length (normally 0.5 miles) segmentation. For example, with the current fixed-length segmentation of 0.5 miles, if 10 miles of highway section are reconstructed, the attribute database will have 20 entries in it. Variable-length segments through the dynamic segmentation approach, on the other hand, can be of any length and can be broken for any reason, such as pavement distress change.

For example, if there are only two distress type records and three ride quality data along a reconstructed 10-mile highway section, the attribute database will have just two entries and three entries, respectively.

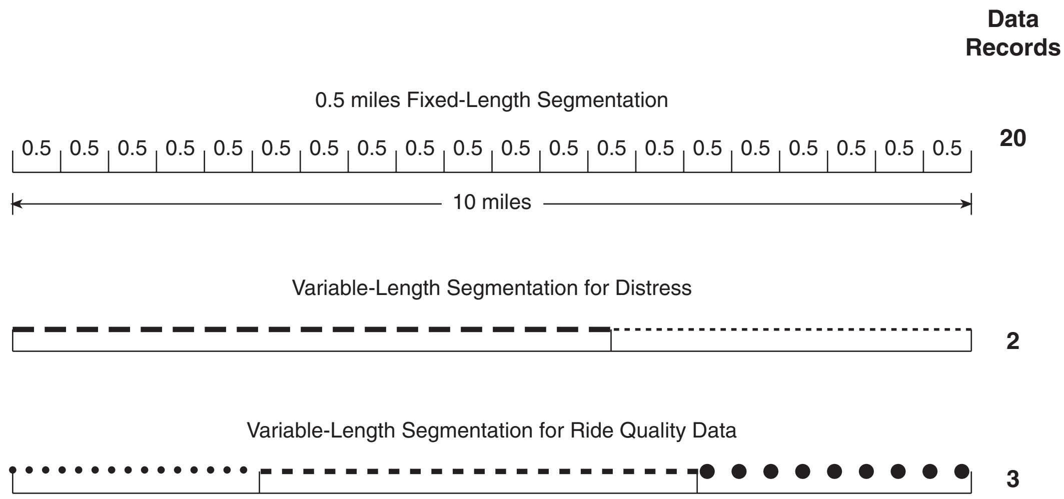

Figure 4.1 Existing PMIS fixed-length segmentation method

4.1.5 Intermediate Solution

A highly segmented road network is inefficient when used with dynamic segmentation because more records have to be processed when data are placed on the road network with GIS. This impedes the storage efficiency, GIS analysis, and query efficiency. Although location accuracy is not affected by a highly segmented road network, the likelihood that other types of topological or connectivity errors occurring will increase (Ref 6). Thus, the highway section length should be at least 0.5 mile long (the current highway survey section length) for the following reasons:

1) Highway sections less than 0.5 mile long are generally not practical for the actual work of pavement maintenance or rehabilitation.
2) The 0.5-mile highway sections, which were the basic segments used in the original TxDOT PMIS database, can still be used.
3) A highly segmented highway network is inefficient when used with dynamic segmentation and will impede storage, GIS analysis, and query efficiency.

This means that raters should still use the 0.5-mile highway section length calculations if the highway section length is less than 0.5 mile. However, for varied-length segmentation, all of the raw pavement distress data will also need to be combined and distributed along the PMIS section, thus becoming the attribute data related to the PMIS section, which is a linear object.

The primary limitation when one uses GPS for pavement data collection is the data accuracy as it relates to the base map accuracy. The GPS positional accuracy recommended in GIS Architecture is +/- 5 meters; however, the existing TxDOT base map accuracy is +/- 15 meters. Positional relationship conflicts often occur if the data to be entered are far more accurate than the map shows (Ref 11). Consideration should be given to the level of GPS collection accuracy.

4.1.6 Base Map Accuracy Required for PMIS from the Perspective of Engineering Applications

Highways are linear features, and the spatial database must represent the smallest possible highway segments based on the associated attribute database. Thus, attention should be given to the absolute accuracy for the beginning and ending points of the PMIS sections along the route and the relative accuracy for the length of the PMIS sections.

4.1.7 Required Absolute Accuracy Level of the Base Map for PMIS

With the use of GPS receivers, the beginning and ending points of the PMIS sections can be accurately located. The base map should be accurate enough to let the survey, construction, and maintenance staff find the location of the beginning and ending points of the PMIS section easily on site. There are two standards that can be used to check the absolute accuracy level of the base map for PMIS.

1) The USGS Mapping Standards

   Traditionally, the base map is often digitized by using map or aerial photographs. For this kind of base map, both accuracy and precision are functions of the scale at which a map (paper or digital) was originally created. The mapping standards employed by the United States Geological Survey (Ref 13) specify that:

> Requirements for meeting horizontal accuracy as 90 percent of all measurable points must be within 1/30th of an inch for maps at a scale of 1:20,000 or larger, and 1/50th of an inch for maps at scales smaller than 1:20,000.

Table 4.3 lists the USGS National Map Accuracy Standards for scales often used. The main drawback for the USGS Mapping Standards is that the standards were developed for the publication of paper maps, not digital map layers.

Table 4.3 USGS National Map Accuracy Standards (NMAS)

Scale	Positional Accuracy (+/-)	
	Foot	Meter
1:1,200	3.33	1.01
1:2,400	6.67	2.03
1:4,800	13.33	4.07
1:10,000	27.78	8.47
1:12,000	33.33	10.17
1:24,000	40.00	12.2
1:36,000	60.00	18.3
1:100,000	166.67	50.83
1:500,000	833.33	254.17

2) American Society for Photogrammetry and Remote Sensing Standards

   The American Society for Photogrammetry and Remote Sensing (ASPRS) Specifications and Standards Committee proposed a method to calculate accuracy at ground scale so that digital spatial data of known ground scale accuracy can be related to the appropriate map scale for graphic presentation (Ref 11). Horizontal accuracy is the RMS (Root Mean Square) error, includes the discrepancies between checked ground points and the planimetric survey coordinates of the digital data set. RMS is calculated by:

$$RMS = \sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + ... + d_n^2}{n}}$$

Where d_n is the distance between digital map coordinates for a point and the ground reference coordinates for that point, n is the number of points tested, and RMS is the cumulative result of all errors introduced by ground survey, map compilation, and extraction of coordinates from the maps. The ASPRS standards define a Class 1 category of coordinate accuracy as shown in Table 4.4.

Table 4.4 ASPRS Horizontal Accuracy Standards for Class 1 maps (Ref 6)

Typical Map Scale	Limiting RMS Error in Feet
1:60	0.05
1:240	0.20
1:600	0.50
1:2400	2.00
1:4800	4.00
1:9600	8.00
1:10000	10.00
1:12000	16.70

The standard can also be extended to the lower accuracy maps; for example, a Class 2 map would have twice the RMS as a Class 1. ASPRS standards also provide guidelines for testing compliance. A minimum of twenty checkpoints derived from a horizontal check survey of higher accuracy (GPS or Orthoimagery) is required for compliance. The guidelines suggest that checkpoints be spaced at intervals of 10 percent of the distance of the map sheet diagonal and that each quadrant of a rectangular map contain 20 percent of the points.

4.1.8 Required Relative Accuracy Level of the Base Map for PMIS

Relative accuracy refers to the accuracy associated with the distance between two particular points relative to one another. For one-dimensional PMIS segments, the relative accuracy refers to the difference between the length of PMIS sections measured on the map and the length actually measured by a land survey.

In TxDOT's PMIS, only linear distress types of a certain length, such as rutting, alligator cracking, patching, block cracking, and longitudinal cracking, are germane to the relative accuracy for PMIS. According to the reference tables (as illustrated in Table 4.5) from TxDOT PMIS Rater's Manual (Ref 14), the PMIS area percentage is precise to 1 percent at most, so the actual possible range of the percentage should be 0.5 percent.

$$S / (L \pm X) = P \pm 0.5\% \qquad \text{(Equation 4.1)}$$

Where

S is the actual pavement distress length measured by a land survey,

L is the mean PMIS section length measured on the map, varied length or fixed length,

X is the deviation for PMIS section length measured on the map, and

P is the percentage of the pavement distress length. P = S/L from 1 percent to 100 percent.

Thus, the deviation for PMIS section length measured on the map can be calculated using

X = 0.05L / (P-0.005) or X = 0.05L / (P + 0.005) (Equation 4.2)

When P is 100 percent and the X value is the least, meaning S equals L.

For example, when L is 0.5 miles which is least, TxDOT PMIS segment length and P is 100 percent, the deviation X is:

X = (0.005)(0.5)(5280)/0.995 = 13.27 (ft) or

X = (0.005)(0.5)(5280)/1.005 = 13.13 (ft)

Thus, the deviation of a highway section with 0.5 miles is around 13 ft from the perspective of PMIS's applications.

The relative accuracy (RA) for the base map is the difference between the length of PMIS sections measured on the map and the length actually measured by a land survey. The RA value of the PMIS section on the base map should be less than the magnitude of X that is calculated using Equation 2. For TxDOT PMIS, the RA for 0.5 miles highway sections on the base map should be less than 13 feet.

Table 4.5 An example reference table (for patching and block cracking) (Ref 2)

Area Percentage	**SECTION LENGTH (Miles)**					
	0.1	0.3	0.5	0.7	0.8	0.9
	TOTAL FEET OF PATCHING OR BLOCK CRACKING					
1%	5	16	26	37	42	48
2%	11	32	53	74	84	95
3%	16	48	79	111	127	143
4%	21	63	106	148	169	190
5%	26	79	132	185	211	238
6%	32	95	158	222	253	285
7%	37	111	185	259	296	333
8%	42	127	211	296	338	380
9%	48	143	238	333	380	428
10%	53	158	264	370	422	475
15%	79	238	396	554	634	713

20%	106	317	528	739	845	950
25%	132	396	680	924	1056	1188
:	:	:	:	:	:	:
60%	317	950	1584	2218	2534	2851
65%	343	1030	1716	2402	2746	3089
70%	370	1109	1848	2587	2957	3326
75%	396	1188	1980	2772	3168	3564
80%	422	1267	2112	2957	3379	3802
85%	449	1346	2244	3142	3590	4039
90%	475	1426	2376	3326	3802	4277
95%	502	1505	2508	3511	4013	4514
100%	528	1584	2640	3696	4224	4752

There are currently no standards available for the relative accuracy level of the base map, so many samples should be examined. However, this approach can help GIS staff to investigate whether the relative accuracy level of the base map can satisfy the requirements of the PMIS.

4.1.9 Current TxDOT Digital Base Map

TxDOT has created a 1:24,000 scale on-system base map in digital format for all twenty-five districts in Texas.

These files were originally digitized from USGS 7.5-minute quads. Updates to these files were made periodically (every six months) using TxDOT highway construction plans, aerial photographs, official city maps, and field inventory by the Transportation Planning and Programming Division. These files contain most of the features found on 7.5-minute quads, except for items such as contour lines, fence lines, jeep trails, electrical transmission lines, oil pipelines, and control data monuments. The Transportation Planning and Programming Division (TPP) of TxDOT has added some necessary attribute data to the urban-county maps to make them true GIS maps. Although these maps were not originally intended for use as GIS base maps, by extracting portions of the existing ".dgn" files along with the MGE attribute data and converting them to ARC/INFO format, one can obtain base layers of sufficient quality. As summarized in Table 4.6, these digital maps have also been converted from North American Datum of 1927 (NAD 27) to North American Datum of 1983 (NAD 83).

The initial TxDOT base layers to be made available will be (Ref 11):

- On-system, state-maintained highway centerlines.
- Off-system county road centerlines.
- City street centerlines (where available).
- Railroads.
- Political boundaries.

Table 4.6 A review of the existing TxDOT base map

Map Projections	**TEXAS STATEWIDE MAPPING SYSTEM (NAD 27)**	**TEXAS STATEWIDE MAPPING SYSTEM (NAD 83)**
Available Formats	DGN, DWG, and DXF	Arc/Info Export (e00)
Projection	Lambert Conformal Conic	Lambert Conformal Conic
Spheroid	Clarke 1866	Clarke GRS80
Datum	North American 1927	North American 1983
Longitude of Origin	100 degrees west (-100)	100 degrees west (-100)
Latitude of Origin	31 degrees 10 minutes north	31 degrees 10 minutes north
Standard Parallel # 1	27 degrees 25 minutes north lat.	27 degrees 25 minutes north lat.
Standard Parallel # 2	34 degrees 55 minutes north lat.	34 degrees 55 minutes north lat.
False Easting	3,000,000 feet (914,400 meters)	1,000,000 meters
False Northing	3,000,000 feet (914,400 meters)	1,000,000 meters
Unit of Measure	feet (international)	meters

The exact positional accuracy of these base maps is not known. Given the USGS stated positional accuracy (for major items) of plus or minus 12 meters (40 feet) for its 7.5-minute quads, and given that 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 map files will be approximately plus or minus 15 meters (50 feet). This accuracy level is satisfactory for TxDOT's main purpose of pavement management. The relative accuracy level of the digital base map still needs to be checked. If necessary, the accuracy of the base map can be tested by comparing the positions of points whose locations or elevations are shown on maps with corresponding positions as determined by surveys or an independent source of higher accuracy map when necessary. In the field, a GPS can be used to determine the exact locations. Aerial photographs can also serve as sources of higher accuracy. Of course, it should be noted that higher accuracy also means higher costs in obtaining and maintaining the data.

4.1.10 Other Recommendations for Base Map

In addition to the issues discussed in the previous sections about base map, some additional recommendations are important to base map and are presented as follows.

1) *Projections* — Base maps should either be based on the Texas Statewide Mapping System (TSMS) or left unprojected. TSMS has been optimized to permit the entire state to be displayed on a single plane without introducing unnecessary distortion. This is not possible with other popular projections such as State Plane and Universal Transverse Mercator (UTM), both of which define more than one zone for the state of Texas. If data are left unprojected, users can easily project data into any projection appropriate to their application.
2) *Datum* — All GIS base layers should be projected based on the North American Datum of 1983 (NAD 83) defined in meters. All urban-county maps based on NAD-27 should be converted from NAD-27 to NAD 83.
3) *Scales* — Different applications require spatial data at different scales. No one single scale can support all necessary and feasible TxDOT applications, although the map scale can be changed on the screen at will. It is reasonable to suggest that several scale themes be used. The most commonly used scales are listed below and are shown in Table 4.8 (Ref 7):
   - *1:1,000,00 – 1:500,000 for statewide planning.* This relatively high level of abstraction supports statewide budget planning and analysis, program development and evaluation, and policy-making at the upper-management level. These applications require summary statistics, aggregations of more detailed, larger-scale data, and wide-area, overview perspectives. Executive information systems are supported at this level. On this map scale, the widths of highways are exaggerated by their line weights. No detail is present at major interchanges. Streets and local roads do not appear.
   - *1:500,000 – 1:100,000 for district-level planning and facilities management*. This intermediate level of abstraction supports budget development, strategies for program delivery, and management of resources and facilities. These applications use data acquired at the operational level but presented on a more general or

regional basis. On hard-copy, divided highways appear as solid lines. Ramps at major interchanges are generalized. Streets and local roads appear as medium-weight lines.

- *1:12,000 – 1:24,000 for facilities management and corridor management.* These relatively large scales support preliminary engineering for projects and other aspects of program delivery that require detailed information over considerable geographic extents. This scale range is most likely to be compatible with those of spatial databases developed at the local government level. On hard-copy maps, the medians of divided highways appear. Ramps at interchanges are detailed. Widths and cul-de-sacs are plotted for streets and local roads.
- *1:120 – 1:12,000 for project engineering*. This scale range has exceeded the original scale from which the current TxDOT digital base map was digitized.

Table 4.7 Map scale and related PMIS activities (Ref 11)

Geographic Extent	Activity	Scale of Data
State	Statewide planning and management	1:500,000
Multi-District District	Corridor Selection District Planning	1:100,000
Metro Area	Facilities Management Corridor Analysis	1:12,000-1:24,000
Project	Engineering Design Construction	1:120-1:12,000

4.1.11 Precautions for Base Map

1) A paper based map's scale is fixed when it is printed and cannot be changed. However, a base map in a GIS digitized from a paper map can be zoomed in and out at will on the screen. This means that geographic data in a GIS do not really have a map scale. However, the accuracy, precision, and resolution of the spatial data are determined by the scale of the original map (digitized or photographed) and do not change with the change of the digital base map scale (Ref 12). Zoom-in and zoom-out functions can mislead users into believing that the accuracy has been improved. For a base map developed directly in digital format, such as a base map developed by using GPS, there are no more fixed scale problems. The characteristics of the GPS receivers and mapping methods used determine the accuracy, precision, and absolution of the base map. The accuracy, precision, and resolution level of the base map also do not change with the change of the base map scale.
2) In addition to the ability to change map scales, map overlay is another GIS capability that always excites the potential GIS users. Both capabilities are indeed very useful,

yet both capabilities may also mislead decision-makers. Map overlay involves superimposition of two or more data layers. If the layers coming from several sources have different accuracy levels, it is critical to check the reliability of the final results.

4.2 Data Quality Assurance (QA) and Quality Control (QC) of Data

GIS data are composed of spatial data that are used to define the geographic features and associated attribute data. The associated attribute data provide further descriptive information about the features. Any data that can be tied to a location on the earth have the potential of being used in a GIS. Certainly, all data suffer from inaccuracy, imprecision, and error to some extent; it is inevitable. If the errors, inaccuracy, and imprecision are left unchecked, they will make a GIS project analysis result almost worthless (Ref 12). More importantly, because spatial data will be transferred and shared by many users, they must be as accurate as possible.

GIS data quality refers to the relative accuracy and precision of a particular GIS database. The information for GIS data quality should be documented with data quality reports. Generally, data quality reports should include data sources, data input techniques, positional accuracy, attribute classifications and definitions, and quality control procedures used to validate the spatial data. It is dangerous to use undocumented data in a GIS. The quality of data depends on all of the processes involved with collecting, storing, and managing spatial and nonspatial databases. Any type of data manipulation and editing can affect the data quality, so caution should be taken when manipulating and editing data. Rules and guidelines for manipulating and editing data should be established (Ref 6). It is recommended that one verify positional accuracy, attribute accuracy, completeness, correctness, and integrity before using any data. Positional accuracy is defined by how well the true position of an object on the earth's surface matches the same object stored as a series of digital coordinates in a GIS data layer. Attribute accuracy describes the error associated with the values of attribute data elements. Completeness measures the number of features included in the digital data set as a result of data input and conversion. Correctness describes how well the digital features match the objects on the ground. Integrity is another measurement of data quality specifically concerned with the completeness of relationships among data elements.

Most verification procedures require manual validation that verifies accuracy and completeness of a spatial database. However, there is software designed to automatically verify the integrity of the GIS database. Manual verification procedures include creating check plots, field checks, and measurements. Automated data quality measurements search for logical inconsistencies and missing or strange attribute values. Data quality assurance and quality control (QA/QC) ensure the delivery of high-quality data. The scope of QA/QC review should include the following considerations (Ref 11):

1) Verification of data set accuracy and completeness against reference or source material.
2) Verification of the internal integrity of the data set and its conformance to the specified structure.
3) Testing of data on target platforms.
4) Assurance of compatibility with the software.
5) Documentation of data quality.

4.3 Data Management Strategy

The real world is dynamic, and changes in the real world need to be reflected on time. A means of updating the data and keeping them current with real-world events is required. A data management strategy should be provided to set up guidelines for structuring the collection, management, and storage of data. The data management strategy affects the allocation of staff and funds and therefore affects the organization's management structure (Ref 6). The data management strategy will also affect the type and distribution of technology and therefore affects the operation of the organization.

GIS data should be maintained by units most responsible for the collection and dissemination of the data. This policy adheres to the recommendations of TxDOT's Data Management Architecture that outline the data steward concept.

The following recommendations are made for data management strategy:

1) GIS data will be developed and maintained by units most responsible for collection and dissemination of the data. Maintenance of base map layers should be assumed by the appropriate data steward. Data steward, a concept outlined by TxDOT Data Management Process, makes the creator or principal user of a particular data set responsible for the maintenance and distribution of that data. ISD, the GIS data producer, and the user should work together to identify the data steward for a specific

GIS data set. In the case of GIS data, the steward for some data layers will be a Texas agency other than TxDOT.

2) GIS data can come from sources internal and external to TxDOT.
3) Base maps will be developed to meet the majority of TxDOT's GIS needs.
4) GIS data will be developed and cataloged for sharing throughout TxDOT and outside of TxDOT through the Texas Natural Resource Information System (TNRIS).
5) GIS data will be standardized as much as possible with regard to features, projection, scale, and accuracy.

4.4 Spatial Data Exchange and Database Transformation

Spatial data exchange is important in GIS for the integration of disparate data sets from dissimilar computer systems. The two basic methods for data exchange between different GIS are 1) direct conversion of data from one system to another using proprietary formats and 2) translation of data via a standardized neutral exchange file format (Ref 7). The use of neutral exchange file formats offers more advantages because only two software routines are required. The following are some of the most widely used neutral exchange formats developed by either major data producers or national standards institutions:

- GBF/DIME.
- TIGER.
- DLG.
- IGES.
- SDTS.

At certain times it is necessary to perform data transformations on entire spatial databases. The transformations take two general forms:

1) Between data models. These transformations include raster-to-vector conversion and vector-to-raster conversion. These automated procedures often lead to interactive editing of the data after transformation.
2) Between coordinate systems. Coordinate system transformations take three specific forms:
   - Arbitrary-to-ground.
   - Between geodetic datum.
   - Ground-to-ground.

4.5 Data Sources and Sharing with Internal Offices and External Agencies

GIS data can be from both internal and external sources. Internal sources can include any department, district, division, or specific office, while external sources may include federal and state agencies, universities, and private entities. The principal external partners with which TxDOT may coordinate include: 1) other state agencies; 2) private corporations; 3) federal agencies (FHWA, NGS, DOD, EPA, USGS, BLM, and USDA); and 4) regional, county, and municipal government agencies (Ref 6). Appendix D contains a listing of TNRIS agencies, data stewards, available data, and contact information. Unlike many other information systems at TxDOT that rarely share data outside the department, GIS data are often shared with outside agencies and universities. This nature of data sharing encourages successful and cost-effective GIS implementation since costs can be shared among divisions, departments, agencies, and universities. GIS data sets are often very large and can be very cumbersome even when compressed. Data sharing over the Internet is becoming increasingly efficient and is the preferred method of sharing data.

A statewide effort to coordinate GIS efforts in state government and promote data sharing between state entities is being directed by the Texas GIS Planning Council. TxDOT is a founding member of the Planning Council. According to the GIS Business Plan, maintenance and updating of individual GIS data layers would be done by the agency with the most knowledge and expertise in that field, and the resulting information would be available for all agencies.

The programs directed by the Texas GIS Planning Council include:

1) *Partnership Initiative* –
   Calls for the development of standards for the support and creation of geospatial data.
2) *Data Sharing Initiative* –
   Calls for the use of the Internet and standards in storage and documentation to assist agencies in sharing data more quickly and easily.
3) *Base Map Initiative* consists of two parts –
   (a) *The Texas Orthoimagery Program* (TOP) –
       Utilizes existing USGS funding to assist in the creation of data layers. TOP's ultimate goal is to create rectified aerial imagery of the state of Texas.

(b) *The StratMap Program –*
Like TOP, StratMap is a cost-sharing program. StratMap will share the cost of developing significant data layers between state entities and the federal government if data can be used by USGS to develop Digital Line Graphs (DLG).

4) *Field Data Collection Initiative –*
Recommends the standardization of data collection processes through the use of GIS.

4.6 Some Related Technologies

Populating a GIS is an expensive task. Initially, data were captured from maps and aerial photographs. This was accomplished by digitizing or scanning. Some alternatives for data collection are now available as Global Positioning System (GPS), Digital Orthophoto Quadrangle Quarters (DOQQs), and remote sensing.

4.6.1 Global Positioning Systems (GPS)

A global positioning system is a three-dimensional measurement system based on received radio signals from the U.S. Department of Defense (DOD) NAVSTAR satellite system. The NAVSTAR satellite system consists of twenty-four satellites: twenty-one navigational Space Vehicles (SVs) and three active spares circling the earth twice daily. Each satellite continuously transmits precise timing radio signals. The GPS receivers convert radio signals into position, velocity, and time estimates. This technology has been used extensively for navigation, positioning, time dissemination, and other research.

When one uses GPS technology, several factors can cause the positional errors. The major sources of error affecting the positional accuracy of GPS receivers are satellite orbit estimation, satellite clock estimation, ionosphere and troposphere interference, and receiver noise (Ref 16). Intentional error, called selective availability, for national security reasons, can also be introduced to the GPS satellite range signals.

Differential processing is a technique for correcting these errors. It may be used in post-processing or real-time techniques. Differential processing uses a minimum of two GPS receivers taking in radio signals from the same satellites at the same time. Through differential post-processing, three-dimensional baseline vectors between observing stations can be obtained. One receiver is positioned over a known location called a base station. The base station data is then used to adjust other GPS receivers' positions at unknown locations. Through the use of differential post-processing, the accuracy down to a few centimeters can be achieved (Ref 17). GPS navigation data can also be processed in "real time" using an on-board computer interfacing with the GPS receiver. The base station receiver transmits the corrections to the remote receiver(s) via a radio link so that the remote receivers can compute the positions in real time. Real-time differential GPS significantly reduces the post-processing time and expands the applications of GPS technologies.

The value of integrating GPS with GIS is potentially enormous. There are several types of real-world applications of GPS for GIS in the Pavement Management System.

1) GPS is used as a more powerful, cost-effective tool for assessing spatial accuracy of a landscape map and identifying omitted or misaligned road segments.
2) GPS is used as a more efficient method for collecting and updating inventory data of roadway than the conventional instruments. For example, GPS can be used to define pavement sections (through defining beginning and ending points) with certain kinds of distress and then add the result to the inventory data. When GPS is used for field data collection, multiple receivers can be used at the same time, thereby increasing the productivity.
3) GPS is used as a video-logging tool. When a vehicle is equipped with both GPS and video cameras, it is possible to record the positions of physical features on or near the roadway by geo-referencing individual video frames. Centerline roadway or lane location data may be collected simultaneously.
4) GPS is used as a more accurate method for base map development. Whereas traditional data collection techniques determine positions from a map or photo, GPS references accurate positions to a map. GPS coordinates used in combination with GIS and map data allow the users to know their locations with respect to other objects in the area base.

There are also some problems with applying GPS technology (Ref 18):

1) The availability of base station data for post-differential correction has been a main issue.
2) Bad GPS signal reception could result in missing data. Visibility of and from the sky is important for using GPS receivers. The radio signals from satellites are susceptible to being blocked by tall buildings, bridges, and even trees.
3) Unfavorable satellite configurations at particular times and particular locations of GPS receivers are another concern.

There are several methods of achieving real-time differential GPS in the field. Each method has its advantages and disadvantages relative to accuracy, cost, and potential application. As a promising technology, subscription services are available from John Chance and Associates in Houston to provide real D-GPS correction broadcasts by satellite (Ref 11). The subscription to this service with a mobile satellite communications receiver costs about $3,000 per year. TxDOT is currently a subscriber. Using a Trimble Geoexplorer handheld receiver and an ACCQPOINT differential correction FM receiver, raters are able to collect position and attribute information on a notebook computer. The FM station receiver takes in the same differential correction from the twenty base stations used by John Chance and Associates and are broadcast as part of the FM carrier signal. The FM receiver for differential correction is less expensive and lighter than satellite receivers, but the measurements must be within the range of the FM broadcast station. Currently, the vendor acknowledges that only 90 percent of Texas is covered. Post-processed differential correction is possible for the base mapping function.

GPS equipment falls into three basic categories: survey grade, mapping grade, and recreational grade. Survey-grade receivers are dual-frequency, carrier-phase units that are expensive but offer accuracy to the centimeter level. Mapping-grade receivers are single-frequency, code-based units that offer sub-meter to meter accuracy. Mapping-grade receivers will be the equipment used by TxDOT. The primary statewide coverage solution at this time is OMNISTAR.

The Transportation Planning and Programming (TPP) Division of TxDOT has initiated a project to use the Global Positioning System (GPS) to accurately map all the county roads in the state. It will be finished in 1998 and will produce a very accurate county road base layer for GIS. Integration of data with existing maps will be somewhat difficult because of the difference in accuracy. Collecting data for the remaining highways and streets using GPS would greatly improve the integration. The recommended GPS mapping and accuracy standard is NAD 83 (93) HARN for the horizontal datum. Any vertical data recorded will be referenced to the NAVD 88 vertical datum with an accuracy level of at least twice that of the respective data's horizontal value.

4.6.2 Digital Orthophoto Quadrangle Quarters (DOQQs)

DOQQ is a geographically accurate digital image of the earth produced from aerial photography using photogrammetric techniques. An orthophoto is a photograph with images of ground features in their true map positions. Thus, unlike conventional images, orthophoto maps can be used to make direct measurements of distances, angles, positions, and areas (Ref 19). Unlike photo enlargement, which has varying scales due primarily to the aircraft tilt, terrain relief, and camera lens distortion, the effects of tilt, relief, and lens distortion on the orthophoto have been removed through a photogrammetric process. The significant advantage of DOQQ is based on this fact: orthophoto can provide a true representation of all of the surface objects found in the area represented by the image. As such, surface objects shown in the orthophoto can be directly correlated with the actual objects as observed at the site. Vectors can be superimposed over orthophotos to clarify information in the image or to add to the information conveyed by the map.

Digital orthophotos are accurate backdrops for many GIS applications. In addition to enhancing the visual display of information, for the first time digital orthophotos can be used as a base map for adding or correcting the locations of features from the computer screen. Like any other GIS base mapping alternatives, digital orthophotos may be a cost-effective base mapping option for GIS managers like county appraisers and public works managers, who need a detailed, accurate base map. Besides functioning as an accurate backdrop, digital orthophotos also have three other functions within GIS (Ref 20):

1) *Updating other attributes*: This function requires that GIS have a screen digitizing function.
2) *Quality control*: Digital orthophotos are an accurate guide that can correct the errors of other attributes.
3) *New mapping*: Digital orthophotos identify locations not present on any existing map.

Digital orthophotos contain only raster data. While attributes (information) can easily be associated with vector data, attributes cannot be linked to raster data at the present time, so users cannot perform data queries or produce maps that have only selected features. The other problem is related to the device and equipment. Most importantly, because every pixel in digital orthophotos contains data, digital orthophotos can create large files that require huge amounts of disk space. Furthermore, viewing digital orthophotos covering large areas at one time may be a significant problem because of file sizes and additional set time. Second, in order to access and use digital orthophotos, additional equipment, such as image-processing software and a high-resolution graphic monitor, is needed. It is also necessary to have a high-quality output device such as an electrostatic plotter or inkjet plotter to produce plots of the raster image.

Digital orthophotos offer a complete, accurate base map for many GIS applications. New technologies will further advance the production and quality of digital orthophotos. A GIS will have the ability to analyze the raster image so that orthophotos can be more easily integrated with other databases in the near future. As new technologies further enhance the production and quality of digital photos, greater attention will be given to them.

For TxDOT to take advantage of existing United States Geographic Survey (USGS) programs that provide funds for developing significant data layers, it must use several base map initiatives for developing a base map in Texas. Currently, one program, the Texas Orthoimagery Program (TOP), has the ultimate goal of developing rectified aerial imagery (DOQQs) for the state of Texas. TxDOT is collecting the ground control for the rectification process and will in return receive a copy of the final product. DOQQ can provide current and accurate data that can serve as the basis for updating and refining other base map layers. Data layers produced from DOQQ should be of sufficient cartographic quality to meet the needs of most state agencies.

4.6.3 Remote Sensing

Remote sensing is the art and science of obtaining information about phenomena without being in contact with them. Remote sensing deals with the detection and measurement of phenomena with devices sensitive to electromagnetic energy such as light (cameras and scanners), heat (thermal scanners), and radio waves (radar). Remote sensing satellites gather much of their information in wavelength bands from the near and mid-infrared parts of the spectrum to microwaves, which are not visible to the human eye. Satellite images consist of many rectangular pixels or dots; each has a homogeneous electronic or digital value representing the average of irradiant intensity measured over the corresponding area of the earth's surface. Unlike this type of data collection, some Russian remote sensing satellites have used high-quality photographic film that is then digitized. With this system, resolution down to 2 m has been achieved. Radar imagery has recently become available; this technique scans the earth from space with a beam of radio waves and records the waves reflected back to the satellite. ERS-1 and JERS-1 are common radio wave (radar) systems used in geological and hydrological applications. The results from radar can be difficult to interpret, but they have the advantage of being able to operate through cloud cover and in the dark, in contrast to the optical sensors.

Over the past 20 years, advancements in technology have improved satellite image resolution greatly, first to 80 m, and then down to 30, 20, and even 10 m on commercial satellites. At 30 m resolution, crops and land use are visible, but roads and houses are not clearly visible. The 10 m resolution monochrome, or panchromatic, image allows many features to be identified, but it does not give as much information about land use (Ref 21).

One particular problem with using satellite imagery is cost constraint. With the improvement of computer technology, hardware and software costs no longer pose a serious problem for applying satellite remote sensing techniques. However, imagery itself can still be relatively expensive, depending on the area covered and the resolutions needed. The higher the resolution, the higher the basic cost per square kilometer of higher-resolution imagery. The highest possible resolution may not always be the most appropriate. Temporal coverage of the image is another limitation for satellite remote sensing. For higher-resolution images from satellites, it would normally take two to three weeks to finish the temporal repeat coverage. Remote sensing data has other limitations, such as atmospheric scattering, image distortion, and cloud cover interference, which may be related to the wavelength being sensed (Ref 22). Another problem with using satellite remote sensing is the need to take out the curvature of the earth. Before data interpretation and subsequent data incorporation can occur, the image must be geometrically corrected to take out the curvature of the earth by applying map projection. Some clearly visible control points, such as crossroads or bridges, must be identified and then matched to the coordinates of the same points on the image map. Sometimes GPS receivers are necessary if the conventional maps available are not clear or accurate enough (Ref 23).

The major obstacles to making practical use of satellite imagery are the special skills needed to interpret the imagery. Particular wavelengths should be chosen to show the appropriate color, and then the intensity of each color should be adjusted to achieve the maximum detail. The next level of interpretation is identifying areas with similar characteristics. After the analysis is completed, a number of the areas automatically identified by the computer should then be checked against the ground; the proportion of areas correctly identified gives a confidence level for the remainder. Normally, an 85 percent correct classification would be considered good for such an analysis.

Remote sensing imagery has been successfully used in land-use interpretation. One major benefit to using remote sensing imagery for GIS is that it can be extracted directly in digital form. New satellites will make higher-quality data available that will be more useful for many applications. Satellite remote sensing imagery with a resolution at meter level will be available soon, while radar images can ensure that data are actually collected when they are needed.

4.6.4 Video-Logging

Traditional information management systems were developed to handle tabular data. The advancement of information technology makes it possible to handle multimedia data, such as videos, sounds, images, and texts. The integration of multimedia with GIS not only enhances the capability of PMIS, but also makes possible a wide spectrum of other engineering applications in transportation infrastructure management. When a vehicle is equipped with both GPS and video cameras, it can record the positions of physical features on or near the roadway by geo-referencing individual video frames. Centerline roadway or lane location data may be collected simultaneously. The Odessa District is currently piloting a video-logging project. It incorporates digital video cameras with GPS and an inertial guidance system to record centerline data, roadway inventory, and data for base maps.

Chapter 5. GIS Computing Environment and Related Technologies

The establishment of a GIS computing environment for PMIS includes the evaluation and selection of software and hardware, the selection and setup of the operating systems and network architecture, etc. The software recommendations include GIS software, database management software, CADD software, etc. Because the costs of hardware tend to decline continuously, it is better to purchase the hardware after both software and data have been selected. All of the recommendations for software, hardware, operating systems, and network architecture must comply with the regularly updated Core Technology Architecture and GIS Architecture developed by TxDOT. It should also be noted that GIS has not proposed to replace business processes that are working well. For example, the Microstation CAD environment for engineering design would continue to be enhanced by some software such as GeoGraphics and GeoPak (Ref 11).

5.1 GIS Software

GIS software provides the functions and tools needed to store, analyze, and display geographic information. Key components of GIS software always include (Ref 2):

1) Tools for the input and manipulation of geographic information.
2) A database management system (DBMS).
3) Tools that support geographic query, analysis, and visualization.
4) A graphical user interface (GUI) for easy access to the tools.

Today, there is a wide range of GIS software packages on the market. As seen from Figure 5.1, the GIS software packages from the ESRI family (ARC/INFO, ArcView, and PC ARC/INFO) and Intergraph family (MGE and GeoMedia) are the most extensively used GIS software packages (Ref 32).

Although it is impossible for any single GIS software package to provide the strongest functions in every area, one primary GIS software package is still recommended for all GIS applications because this strategy not only can minimize the incompatibility problems but also can reduce training costs and time. Taking into account several factors, including the software's ability to serve GIS functions, the researchers compared several GIS software packages; as a result, the GIS software package from ESRI is recommended.

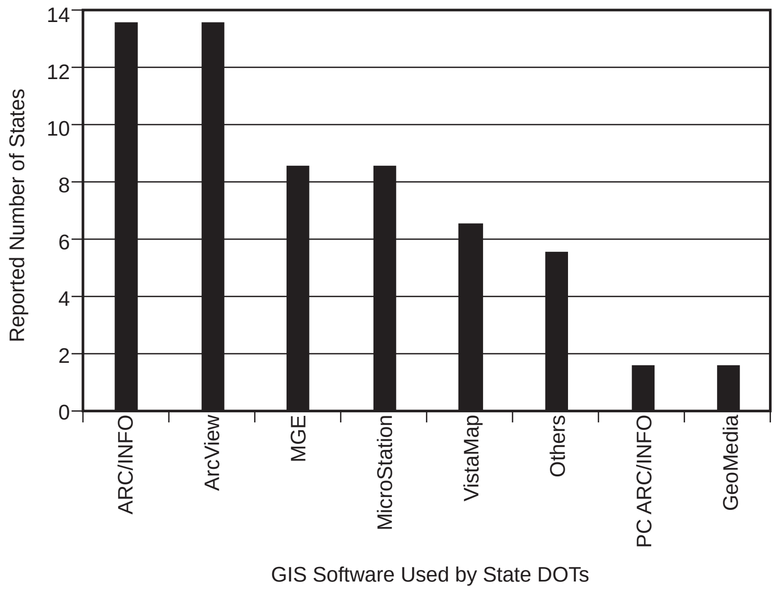

Figure 5.1 The GIS software packages used for PMS in state DOTs

5.1.1 Introduction to GIS Software Packages

Presently, there is a wide range of GIS software packages on the market for developing GIS applications. Basically, there are two main categories of GIS software: 1) the high-end GIS software (such as ARC/INFO) and 2) the desktop GIS software (such as ArcView). The high-end GIS software is more sophisticated and usually requires powerful UNIX-based workstations. This kind of GIS software provides almost all the functions one would need for most applications. The high-end GIS software is also capable of managing very large databases with many users working individually. With the advancement of computer technology, a major development in the GIS software market over the past few years is the so-called "desktop GIS software." As the name suggests, desktop packages are designed to run on desktop personal computers, usually using a Windows- and mouse-based interface. These packages have fewer functions and are primarily designed for simple analysis and query and the production of maps and graphs. However, some additional functions have been added, and the analysis and query ability has been improved to include such functions as network analysis and spatial analysis. It is the trend that more and more functions will be added into the desktop mapping GIS software. In addition to these two main categories of GIS software, there are also other kinds of GIS software developed for specific purposes.

GIS Data Management Software provides integration with other applications and a centralized data storage system. This capability enables persistent long transactions, support of spatial data types and multimedia integration, multi-user access, and distributed data delivery. Large data volumes are handled by such applications as the Spatial Database Engine (SDE) from ESRI, FRAMME from Intergraph, and ModelServer Continuum from Bentley.

Developer Tools create specialized solutions for mapping and GIS needs, with tools that provide mapping and GIS functionality, such as MapObjects from ESRI.

Internet GIS Software is used to publish live maps or provide map and data access via the Web; these products include ArcView Internet Map Server, GeoMedia Web Map from Intergraph, and ModelServer Publisher.

5.1.2 Recommended GIS Software Package

GIS software provides the functions necessary to assist an organization in addressing its objectives. A GIS software package may be strong in certain areas and provide only satisfactory functions in other areas. It is impossible for any GIS software package to provide the strongest functions in every area. However, it is recommended that only one GIS software package be used for all GIS applications. There are several reasons for doing so. First, there are no compatibility problems within one organization if only one GIS software package is employed. Second, this will allow the GIS staff to become experts in one package; therefore, they can provide adequate support for both maintenance and development of GIS software within TxDOT. Third, this strategy will reduce training costs and time. If different software packages have to be recommended, they should be compatible with one another to ensure that information can be readily transferred from one to another.

The criteria used to evaluate a given GIS software package will depend on the functions needed. According to Table 3.1, six main GIS operation categories (Data Entry, Manage, Transform and Transfer Data, as an Integration Platform and a Common Location Reference System, Query and Analysis, and Report and Display) are used to evaluate GIS software packages from different vendors. Some other issues also need to be considered, such as user interface, support for client/server architecture, multimedia and Internet ability, costs, training program available, supported DBMSs, etc. With attention to the key features, products from ESRI, Intergraph, and Bentley for both high-end GIS software and desktop mapping GIS software are compared and summarized in Table 5.1 and Table 5.2 (Refs 2, 24, 25).

Table 5.1 Comparing high-end GIS software

Key	Features	ARC/INFO	MGE	MicroStation
Platform Requirements	**UNIX**	**X**	**X**	**X**
	DOS		**X**	**X**
	Windows 3.x			**X**
	Windows 95		**X**	**X**
	Windows NT	**X**	**X**	**X**
	Macintosh			**X**
	IBM OS/2 Warp			**X**
Data Input	**Digitizing**	**X**	**X**	**X**
	Scanning	**X**	**X**	
	Key Entry	**X**	**X**	**X**
	GPS Data	**X**	**X**	
Raster and Vector Data		**Both**	**Both**	**Both**
Map projection		**X**	**X**	
Standard Data Format		**DXF, DLG, IGDS, TIGRE, CGM, EPS, etc.**	**ARC, CGM, DLG, DXF, HPGL, IGPS, TIGER, etc.**	**DWG, DXF, IGES, CGM, VersaCAD, SPEP, etc.**
Graphic File Format		**TIFF, JPEG, BIL, ERDAS**	**HPGL, PS, EPS, etc.**	**EPS, JPEG, TIFF, HPGL**
Import/Export Connectivity		**X**	**X**	**X**

Table 5.1 Comparing high-end GIS software (continued)

Key Features		ARC/INFO	MGE	MicroStation
Interfaced DBMSs	**Oracle**	**X**	**X**	**X**
	INGRES	**X**	**X**	**X**
	SYBASE	**X**	**X**	
	INFORMIX	**X**	**X**	**X**
	SQL Server	**X**	**X**	**X**
	dBase		**X**	
	FoxBASE			**X**
	Microsoft Access	**X**	**X**	**X**
	Editing ability	**X**	**X**	**X**
Analytical and Query Tools		**X**	**X**	
Customizing Ability and Application Development Tools		**AML, Visual Basic, C++, PowerBuilder, etc.**	**Visual Basic, C/C++, MDL, etc.**	**MicroStation BASIC, MDL, Visual Basic, etc.**
Dynamic Segmentation		**X**	**X**	
Integrating Multimedia		**X**	**X**	**X**
Internet Connectivity		**X**	**X**	**X**
Support Client/Server Architecture		**X**	**X**	**X**
CAD Function		**Yes (Supported by ArcCAD)**	**Yes (Based on Microstation)**	**Yes**
User interface		**GUI, Command Language**	**GUI, Command Language**	**GUI, Command Language**

Table 5.2 Comparing different desktop GIS software

Key Features		ArcView	GeoMedia	MicroStation Geographics
Platform Requirements	**UNIX**	**X**		**X**
	DOS			**X**
	Windows 3.x	**X**		**X**
	Windows 95	**X**	**X**	**X**
	Windows NT	**X**	**X**	**X**
	Macintosh	**X**		**X**
	IBM OS/2 Warp			**X**
Data Input	**Digitizing**	**X**		
	Scanning			
	Key Entry	**X**		
	GPS Data			
Raster and Vector Data		**Both**	**Both**	**Both**
Map projection		**X**	**X**	**X**
Standard Data Format		**DXF, DWG, ARC/INFO, DGN**	**DXF, DWG, DGN, MGE, CGM**	**DGN, IGES, DXF, DWG, CGM, MGE, TIF**
Graphic File Format		**TIFF, JPEG, ERDAS, GIF, PICT, SPOT, BMP, etc.**	**TIFF, JPEG, GIF, etc.**	**TIFF, CIT, COT**
Import and Export Connectivity		**X**	**X**	**X**

Table 5.2 Comparing different desktop GIS software (continued)

Key Features		ArcView	GeoMedia	MicroStation Geographics
Interfaced DBMSs	**Oracle**	**X**	**X**	**X**
	INGRES	**X**	**X**	**X**
	SYBASE	**X**	**X**	**X**
	INFORMIX	**X**	**X**	**X**
	SQL Server	**X**	**X**	**X**
	dBase	**X**		
	FoxBase	**X**		
	Microsoft Access	**X**	**X**	**X**
Editing Ability		**X**	**X**	**X**
Mapping and Cartographic Output		**X**	**X**	**X**

Table 5.2 Comparing different desktop GIS software (continued)

Key Features	ArcView	GeoMedia	MicroStation Geographics
Analytical and Query Tools	**X**	**X**	**X**
Customizing Ability and Application Development Tools	**Avenue**	**View/Toolbars, Visual Basic, C++, PowerBuilder, Delphi, etc.**	**MDL, MicroStation Basic, Visual Basic, C/C++, etc.**
Internet Connectivity	**X**	**X**	**X**
Dynamic Segmentation	**X**	**X**	**N/A**
Integrating Multimedia	**X**	**X**	**N/A**
Support Client/Server Architecture	**X**	**X**	**X**
CAD Function	**Yes (Supported by ArcCAD)**	**X**	**X**
User interface	**GUI**	**GUI**	**GUI**
Install Requirements (For PC)	**At least 80486, 18MB RAM (24 MB recommended)**	**At least 80486, 32 MB RAM minimum, 35 MB for typical installation plus data**	**At least 80486, 16 MB RAM minimum, 32 MB recommended, 250 MB disk space minimum**

1) *ESRI GIS Product Family*: One of the leading GIS software manufacturers, ESRI, provides a family of GIS software products designed for use by different levels of users in different computational environments in a very flexible manner. All the software architectures in ESRI's GIS family can be integrated through their common, underlying data structure. It is worth noting that the powerful script languages associated with ESRI's GIS products allow users to customize their applications and develop new applications. The open data structure of ARC/INFO and ArcView makes it possible that data from most of the database management systems can be directly used in the GIS application.

2) *Intergraph GIS Family*: Key products of the Intergraph GIS family are MGE and Geomedia. MGE is a fully functional GIS package based on the Microstation core, but it is not an open architecture system. There are certain advantages to using the MGE product, such as Windows compliance, an integrated suite of software that runs on Windows NT. It also has the ability to import and export in other formats, and the ability to use different relational databases such as Oracle, Informix, Ingres, Sybase, and RDB on different servers. MGE is more difficult to learn than some GIS software because of the multiple capability of the software suite. However, the data files are binary compatible between UNIX, Windows, and Macintosh platforms. Utilities are also included to convert data from other GIS such as ARC/INFO, MapInfo, Altlas*GIS, into MGE format. Geomedia is a package that is similar to ArcView, a kind of desktop software.

3) *Bentley GIS Family*: Bentley, the company that designed Microstation, designs Microstation Geographics, a GIS package fully compatible with Microstation 95. Microstation Geographics operates under DOS, Microsoft Windows and Windows NT, and the UNIX environment. With its SQL Manager, Microstation Geographics allows users to create and manage links between map features and non-geographical attributes from a wide variety of databases, including Microsoft Access, Microsoft SQL server, Oracle, and Informix. It works with MGE files but has a smaller package of spatial analysis tools than MGE.

Both ESRI and Intergraph have provided GIS service for years and control a significant majority of the GIS marketplace. Both GIS packages are excellent products and provide full GIS functions to satisfy the users' requirements for both high-end GIS software and desktop mapping GIS software. Bentley's MicroStation is actually computer-aided drafting and design (CADD) software. MicroStation Geographics is also a CADD-based GIS software. At the same time, ESRI provides ArcCAD, a CADD-based GIS software that can create, edit, and manipulate drawing entities as well as create spatial relationships (topology) among those entities. Since the desktop GIS software and high-end software serve different purposes, they are evaluated separately.

Based on these criteria, the following products from ESRI and Bentley are recommended for use as GIS software for TxDOT PMIS:

1) An ARC/INFO suite license for complex, full GIS functionality.
2) ArcView licenses for simple query, analysis, and display functions provided so each user can have access without delays and without working under the same license.
3) MapObjects for adding GIS functions to non-GIS applications, using ObjectLinking and Embedding (OLE) programming techniques on an as-needed basis.

The following are primary reasons to select GIS software products from ESRI for TxDOT PMIS:

1) ESRI products offer the complete, powerful GIS functions that are necessary for PMIS. They include data entry, transform and transfer data, integrating different platforms and systems, query and analysis, dynamic segmentation, network overlay, and display and report. All of these functions provided by ESRI's GIS software are powerful.
2) ESRI products have sufficient capacity to upgrade GIS when necessary, such as Linear Network Management, cell-based analysis, raster processing, etc. In addition to the high-end and desktop mapping software, there are several other kinds of software available. These include MapObjects, which is a set of mapping and GIS components that allow developers to add mapping and GIS capabilities to applications; and ArcView Internet Map Server, which provides a method for publishing GIS data on the Web.
3) ESRI products have a strong customizing interface function and flexible application development ability. Avenue and AML are used for customizing interface and automating procedures to fit the users' specific needs in ArcView and ARC/INFO, respectively.

4) ESRI's products support enormous graphic file formats, including graphic files and the existing MicroStation ".dgn" file commonly used by TxDOT. Most ESRI products are hardware-independent and can work in most operating systems.
5) ESRI's products provide a powerful spatial data management function. Spatial Database Engine (SDE) is a high-performance, object-based spatial data access engine that has been implemented in several commercial DBMSs using open standards and true client/server architecture.
6) ESRI provides training programs for its products in San Antonio. Many universities and colleges are also offering GIS courses using ESRI's software. Furthermore, when it is necessary to hire new GIS staff, more GIS specialists mastering ESRI's products are available on the job market than are specialists using other GIS software.
7) The Information Systems Division (ISD) in TxDOT recommends ESRI's software as the standard GIS software within TxDOT. At the same time, ESRI's products are most predominantly used in state agencies in Texas and other states.

5.2 CADD Software

MicroStation from Bentley is recommended for the Computer Aided Drafting and Design (CADD) software for the following reasons.

1) The graphic design functionality of MicroStation 95 is far superior than that offered by ARC/INFO.
2) The ".dgn" file generated by MicroStation 95 can be translated into ARC/INFO coverages.
3) TxDOT has used MicroStation as CADD software for years. Users are already familiar with it; thus training fees can be saved.

5.3 Database Management Systems

Most GIS packages have a database management system, either bundled internally (dbase within ArcView, INFO within ARC/INFO) or interfaced with an external, third-party database management system (DBMS). Unlike internal GIS database management systems, third-party DBMSs are specialized in the storage and management of all types of data, including geographic data. DBMSs are optimized to store and retrieve data, and GIS rely on them for this purpose.

Tables 5.3 and 5.4 summarize database selection guidelines by "application type" and "when to use," respectively. Presently, most DBMSs are relational databases. The relational database model is made up of tables with the following characteristics:

1) A table consists of rows and columns.
2) Each column has a name and single data type.
3) Multiple dimensions are represented by multiple tables, which are joined to construct a multi-dimensional object, or by multiple rows in a table.

The focus for recommending a DBMS should be on better integration of the recommended GIS package and the DBMS. At the same time, the recommended database software can easily be accessed by the GIS users. Based on these criteria, the following DBMSs are recommended to support GIS application for PMIS.

1) Sybase SQL Server for enterprise-wide and workgroup applications.
2) Sybase SQL Anywhere for PC workstation applications that have the potential of expanding beyond a single workstation and for small workgroup applications.
3) Microsoft Access for individual workstation database applications

Table 5.3 Database selection guidelines by application type (Ref 11)

Application Type	Database Options for Application Development			
	Sybase SQL Server	**Sybase SQL Anywhere**	**Microsoft Access**	**Software AG ADABAS**
Enterprise	**X**			**X**
Workgroup	**X**			
Workgroup/Small		**X**		
Workstation/Single user		**X**	**X**	
Laptop/Single user		**X**	**X**	

Table 5.4 Database selection guidelines for when to use (Ref 26)

Database Alternatives	When to use
Sybase SQL Server	**Enterprise or workgroup application development** **Decision Support Systems (DSS)** **Online Transaction Processing (OLTP)** **Number of users > 40** **Database size > 2 gigabytes** **SMP environment, up to 30 CPUs**
Sybase SQL Anywhere	**Workgroup applications** **Decision Support Systems (DSS)** **Workstation applications with potential for being shared** **Number of users ≤ 40** **Database size ≤ 2 gigabytes** **Applications with potential expansion above size and use limits**
Microsoft Access	**Workstation applications for a single user with no data sharing**
INFO	**Limited or restricted solely to GIS applications on an as-needed basis**

There are two main reasons for this recommendation:

1) ARC/INFO and ArcView can be easily interfaced with these recommended DBMSs. Future large enterprise data sets with multiple users are to be developed in Sybase System SQL Server. ARC/INFO is able to connect directly to a Sybase database through a standard module called Database Integrator. ArcView uses Microsoft Open Database Connectivity (ODBC) to establish a connection to a Sybase database. Future workgroup-size databases should be developed using Sybase SQL Anywhere. ARC/INFO and ArcView can use ODBC to connect to an SQL Anywhere databases. Stand-alone, local applications can be developed using the integrated relational table structure within ARC/INFO and ArcView, or they can be developed in Microsoft Access and connected using ODBC.
2) In addition, the recommended database software is compatible with the “Core Technology Architecture” (Ref 26) and “GIS/GPS Architecture,” which are developed for ensuring that all new information technologies are consistent, manageable, non-redundant, and easily integrated within TxDOT. All GIS-related projects should be developed using a standardized relational database management system (Core Technology Architecture).

Presently, PMIS populates ADABAS databases on TxDOT’s IBM mainframe. Since GIS is not able to access these databases directly, a process for periodic downloads of this data into a relational database, or access through a database gateway product, is necessary.

5.4 Network Architecture

Because of the current trend toward computer networking and the fact that an integrated transportation management system usually requires the involvement of more than one division within the department, the efficient and economic operation of a transportation management system can be achieved by employing network computing. Major benefits from computer networking include: 1) easy software and file sharing; 2) economic hardware resource sharing; 3) convenient data and database sharing; and 4) cross-division workgroup structure (Ref 26). Client/server architecture can serve as an ideal environment for data sharing and information exchange, which state DOTs are increasingly demanding. TxDOT has finished retooling its computers to accommodate client/server architecture, using Microsoft Windows NT as its operating system. This means that any software recommendations should comply with the Windows NT environment.

As recommended in the Core Technology Architecture (Ref 26), the enterprise network architecture is summarized as follows:

Transmission Control Protocol / Internet Protocol (TCP/IP): In order to address the needs of future client/server and Internet technologies, the present multi-protocol topology of TxDOT wide-area and local area networks (LAN) should be consolidated into a GIS TCP/IP protocol.

Ethernet Topology: Ethernet is recommended as the medium of choice for local area connectivity for all new sites. Present locations such as division offices and district offices will continue to use both Token Ring and Ethernet with eventual conversion to Ethernet when feasible. All new installations at districts, divisions, offices, and area offices are to be based on Ethernet.

Network Extension: TxDOT WAN/LAN TCP/IP network should be extended to all offices. T1 or fractional T1 circuits should connect all divisions and districts.

Redundancy in Network: The existing wide-area network should be reconfigured to provide redundant connectivity where possible. This will provide a more robust fault-tolerant network, which is required for a successful implementation of client/server and Intranet technologies.

3270 Terminal Replacement: All existing 3270 dumb terminals should be eliminated and replaced with PC workstations supporting 3270 emulation. This replacement strategy will provide a platform for client/server and office product support on every PC workstation.

More detailed information will be available in the latest TxDOT Core Technology Architecture.

5.5 Operating Systems

According to the Core Technology Architecture (Ref 26), the future PC workstations and laptop operating systems should provide a consistent graphic user interface (GUI) for the end users, as well as a high-level, 32-bit capability with preemptive multi-tasking and multi-threading application use and development. The operating systems should also be compatible with existing 16-bit applications. The recommended network server operating systems should provide a high level of connectivity throughout the department. The local area network (LAN) operating systems are scaleable across a variety of hardware and software configurations. Furthermore, the network server operating systems should provide consistent software application development platforms.

Table 5.5 summarizes the operating systems recommended for future application development according to "Core Technology Architecture."

Table 5.5 Operating systems selection guidelines (Ref 11)

Operating Systems Selection Guidelines	
LAN-attached PC workstation	**Windows NT workstations**
486 PC Workstation (Dial-in)	**Windows 95/98**
Laptop	**Windows 95/98**
Print/File Server	**Novell NetWare 4.1**
Application Server	**Windows NT Server** **UNIX (High transaction volumes/Intergraph CADD)** **MVS/ESA (Mainframe)**
Database Server	**Windows NT Server** **UNIX (High transaction volumes)** **MVS/ESA (Mainframe)**

5.6 Hardware

GIS is an intensive computer application requiring hardware capable of handling large amounts of data input, output, and manipulation. According to the Core Technology Architecture, TxDOT's hardware strategy for workstations, laptops, and servers is to standardize on single-processor architecture. TxDOT's hardware strategy for printers, scanners, and copiers (connected to a workstation, server, or network) is to standardize on Windows NT compatible devices. Connection to the network will be standard for PC workstations, servers, and shared devices. TxDOT will standardize on a limited number of hardware vendors. At the same time, GIS hardware for PMIS should take advantage of the latest computer technology. Because the price of the computer hardware has dropped very quickly and will continue to drop as capabilities rise, it is important not to purchase the hardware until both the data and software are ready. The mainframe platform should remain in place to support present legacy applications and future applications that may operate more efficiently on the mainframe than in other environments.

Since they are consistent with the TxDOT Core Technology Architecture hardware configuration as summarized in Table 5.6, the following hardware configurations are currently recommended and should be updated continuously:

1) For high-end GIS, a high-end Pentium PC running Windows NT 3.51 or later.
2) For desktop GIS, a mid- to high-end Pentium PC running Windows NT 3.51 or later.
3) A high-resolution (1,600 x 1,200) 21 in. color monitor.
4) Application, file, and database servers, where needed, capable of fast, efficient data input and output.
5) Current CADD printers and plotters where possible. Laser printers are recommended for all TxDOT business applications.
6) Peripherals using 4 mm DDS/DDS-2 magnetic tape for backup and off-system data transfer.
7) Digital VideoDisks (DVD) to transfer larger data sets outside the network.

There are three purchasing guidelines for hardware explained in the TxDOT Core Technology Architecture:

1) Purchase a workstation with one processor installed and install a second processor later. This is the less expensive strategy.
2) Buy at the low point of the price-performance curve, and then upgrade the disk and memory subsystems when the users' needs require it. This strategy results in significantly lower initial capital costs.
3) Migrate machines from more demanding situations to less demanding ones annually.

These recommendations should be considered a guide for assistance in budgeting and providing a general idea of the hardware necessary to run GIS efficiently. PC hardware technology is rapidly changing and improving; therefore, users should contact the Information Systems Division (ISD) for the latest recommendations. It is better not to purchase the hardware until both data and software are ready.

Table 5.6 Hardware configuration

Configuration	PC Workstations		
	Low	Mid	High
Processor	**Intel Pentium 120-166 MHz** **Intel Pentium Pro 166 MHz** **AMD k5 120-166MHz** **Cyrix 6x86 120-166 MHz**	**Intel Pentium 200, 233MHz** **Intel Pentium Pro 188, 200 MHz** **Intel Pentium MMX 166, 200 MHz** **AMD K6 166, 200 MHz** **Cyrix 6x86MX PR166, 200**	**Intel Pentium MMX 233MHz** **Intel Pentium II 233, 266, 300, 333MHz** **AMD K6 233 MHz** **Cyrix 6x86MX PR233**
Monitor	**One 17 in. or one 21 in.**	**One or two 21 in. or two 17 in.**	**One or two 20 – 27 in.**
CD-ROM	**Minimum 8x**	**Minimum 16x**	**Minimum 32x**
Hard Drive	**Minimum 1 GB**	**Minimum 2.1 GB**	**Minimum 3.2 GB**
Memory	**Minimum 32 MB**	**Minimum 64 MB**	**Minimum 128 MB**

5.7 Emerging Techniques For GIS Computing Environment

5.7.1 GIS Software

The next generation of GIS is likely to be object-oriented and should become available in the next year or two. Objects may enhance dynamic segmentation and may ultimately replace some of the dynamic segmentation procedures.

ARC/INFO: Although ARC/INFO is fully integrated into Windows NT, it does not run under a typical Windows interface of buttons and menu bars. It is anticipated that ARC/INFO version 8.0 will include the Windows interface. This release is expected during the fourth quarter of 1999.

ArcView: The ArcView 3D Analyst extension enables users to create, analyze, and display surface data and helps users integrate 3D data into their analyses. In ArcView 3D Analyst, the most commonly used functions are accessible from pulldown menus and tool buttons that are added to the ArcView GIS interface when the extension is installed. Some planned new extensions of ArcView GIS include VPF Viewer, StreetMap, Image Analyst, Dialog Designer, Data Viewers, and ArcPress for ArcView.

SDE: The Spatial Database Engine (SDE) is a high-performance spatial database manager that employs a true client/server architecture combined with a set of software services to perform efficient spatial operations and manage large, shared geographic data.

ArcView Internet Map Server: Until recently, serving dynamic maps over the Internet was a daunting challenge. Now, ESRI has introduced simple-to-use solutions for deploying maps on the World Wide Web. The ArcView Internet Map Server is an out-of-the-box GIS and mapping solution for publishing ArcView GIS maps on the World Wide Web. With the Internet Map Server, TxDOT may add digital maps to its Web sites as a public service. Meanwhile, it is also possible to use GIS mapping and analysis capabilities via TxDOT's Intranet to reach non-GIS specialists. Rather than simply viewing static maps, users may browse, explore, and query active maps. It is therefore recommended that serious evaluation be given to Internet-based PMIS and GIS applications as the next generation of PMIS for TxDOT.

MapObjects Internet Map Server: MapObjects Internet Map Server is used for developing specific mapping applications for the World Wide Web. MapObjects Internet Map

Server extends MapObjects, providing Windows developers with a powerful collection of components to create a variety of custom Web mapping solutions.

Power ++: Like Visual Basic and Visual C++, Power ++ is another development tool. This new development tool reportedly has the Power front end but generates C code that directly accesses Sybase.

5.7.2 Database Management Systems

Database management systems play a key role in implementing a GIS for any organization. Presently, most GIS packages use relational database management systems (RDBMS). One of the drawbacks of the relational database system is its inability to handle Binary Large Objects (BLOBs) such as images, video, audio, animations, and mixed media, the new world of information (Ref 34). Object-oriented database management systems (OODBMS) were developed for this purpose. With an object-oriented data model, the database is viewed as a collection of objects. Each object has a unique identifier called the object-ID. Objects with similar properties are grouped into a class. A class may have subclasses. Compared with a relational database, an object-oriented database can:

1) Access or extract internal components of an object, such as one or two frames of a video.
2) Execute operations or functions against objects without exporting them to the client.
3) Extract enough information about the object to develop an “intelligent” search plan to optimize performance. For example: The user wants multiple frames of a video, plus information on actors, royalties, and rights. The OODBMS gauges the speed of retrieval for each item and optimizes a retrieval plan using server resources, freeing the client to continue work.

However, the principle of the object-oriented database is still new, and the technology lacks experienced, quality programmers. Furthermore, there is currently no consensus on standards or definitions. To overcome these problems, a third kind of system, the object-relational database system, also called the hybrid relational object-oriented database, has been developed. It tries to combine the best of two worlds. Progress Software Corporation (Burlington, MA) has added a front end to its database system, allowing it to handle OO-structured data within relational tables. Newcomer Illustra Information Technologies (Oakland, CA) offers a genuine OO-database in SQL (the standard relational database interface language) framework even though it stores objects directly, rather than as relational tables. Object-relational database systems are still young but are expected to mature over the next few years.

RDBMS Use with Internet and Intranet Technologies: Future versions of DBMSs are expected to include enhanced database and middleware products to provide security, directory services, and interfaces that support safe use of the Internet and Intranet for business applications. These features will allow customer service applications through the Internet and Intranet. It is highly recommended that TxDOT take advantage of the Internet and Intranet technologies for its mission of pavement management.

5.7.3 Network Architecture

ATM (Asynchronous Transfer Mode): ATM is a very high-speed (155 mbps), connection-oriented replacement for Ethernet and Token Ring. It offers the promise of high-speed, predictable communication in multimedia environments.

High-Speed Switching: Another new technology already starting to be used as a replacement for network routers and bridges in some networks is the high-speed switch. This device, if used correctly, can greatly increase the performance of LAN networks, reducing congestion and improving throughput.

5.7.4 Operating Systems

1) *64-bit operating systems*: The current development of 32-bit operating systems is the result of the design of 32-bit processor architecture. The next generation of 64-bit microcomputer processors is in the design and testing stage now. It will not be uncommon by the year 2000 to have a 64-bit PC workstation processor. Operating systems must be developed to handle these newer and larger-capacity processors.
2) *Symmetrical multiprocessing (SMP) for large numbers of processors*: SMP is the combination of several physical processors to make a large logical processor capable of handling multiple operations. The benefit of this technology is the ability to take relatively inexpensive processors, link them together logically with the operating systems, and perform large tasks. Operating systems must be able to take advantage of this technology.

3) *Internet browser interfaces*: The Internet is projected to become the main medium of information transmission in the near future. Operating systems must provide a transmission mechanism to aid in the seamless transmission of information.
4) *Object-Oriented Operating Systems*: Traditional operating systems link lines of written code as applications are developed. Object-oriented operating systems allow the linking of objects. The objects contain coded operations for particular functioning. Such features will aid in the rapid development of information systems.
5) *Multimedia Effects on OS Efficiency*: Multimedia operations such as teleconferencing, computer-based training, and distance learning will require additional bandwidth in current telecommunications networks. Operating systems must be able to manage the incoming data streams in an efficient manner.

5.7.5 Hardware

1) Digital VideoDisks (DVDs) are the heir apparent to the CD-ROM. Current DVDs are the same size and shape of standard CD-ROMs, but they offer seven times the storage capacity. This type of device could prove beneficial for the transfer of ARC/INFO coverages, multimedia data, or other large data sets outside the network.
2) The 440LX is also the first P6 (Pentium Pro or Pentium II) chip set to support SDRAM (synchronous DRAM) memory, for faster data streaming between the CPU and I/O devices, and Ultra ATA, for faster IDE hard disk transfer rates.
3) The cost of Rewritable Optical Storage is dropping rapidly.
4) 120 MB 3 ½ in. floppy drives are beginning to be offered as a replacement for exiting 1.44 MB floppies.
5) Wide format copiers (36 in. wide media) have changed recently such that these devices may also be used as scanners and printers.

5.8 Related Technologies

5.8.1 Client/Server Architecture

Client/server architecture is a new technology that has grown very quickly in the last several years. With the advancement of computer technology, the computing model evolves from the initial, centralized, host-based computing model, to the distributed personal computing model, to the network/file server computing model, to present client/server architecture. Client/server technology is the architecture for network computing, in which users running applications at network-attached computers (clients) interact with applications running at server systems (Ref 27). A client/server system has three distinct components: server, client, and network. Integrated with client/server architecture, GIS's role changes from one of the center to one of the servers, providing spatial services if and when needed. Based on the responses of major client/server vendors, GIS client/server architecture has several significant benefits over traditional GIS configurations (Ref 28):

1) GIS can provide services to other programs, providing broader access to mapping and spatial analysis technology.
2) Multiple users can share a single centralized database in a more timely fashion.
3) Because of the centralized administration and control of the database, client/server technology greatly simplifies the administration of database and software. Server-based data storage also provides improved data integrity and greater security.
4) Client/server technology provides a better capability for incremental growth. Additional data storage capacity can be provided by adding new servers or expanding existing ones; additional users can be handled by adding client workstations as needed. Data can be updated and maintained in one place.
5) Users can take advantage of the processing power of the server.
6) The network loads are reduced.

During the last few years, software vendors have released an intermediary piece of software for the client/server model: middleware, a software layer between the client and the server that helps manage and deliver data (Ref 29). These middlewares provide an advanced tool for supporting high-performance client/server access to spatial data by multiple users in an enterprise environment.

1) ESRI's spatial database engine (SDE) moves GIS data from a separately maintained proprietary database to a centrally maintained database built on open relational database management system (RDBMS) standards. ESRI recently introduced an SDE CAD client, which allows AutoCAD and MicroStation to act as clients to SDE.

2) Bentley Systems has just introduced ModelServer Continuum, which serves as an enterprise-wide engineering information broker connecting engineering client software from Bentley and other suppliers to data stored in Oracle Universal Server using Spatial Data Option (SDO). Supported clients include MicroStation GeoGraphics, MicroStation GeoOutlook, and ESRI's ArcView.

5.8.2 Project Management Software

Project management software provides a useful tool for developing, maintaining, and monitoring plans. The features of these systems generally include various reporting capabilities and tools for personnel and financial management planning, in addition to schedules and compatibility with other various software. Other features provide the ability to define and schedule tasks, to place tasks in sequential order graphically, to allocate resources, and to determine which tasks must be completed before others begin.

5.9 Current Computing Environment and Intermediate Solution

As seen in Table 3.3, TxDOT's computing environment is a mixture of several types of technology, each representative of a specific stage of data processing technology development. The end result is a heterogeneous environment composed of mainframe computers; RISC chip-based workstations; and PC platforms and their accompanying operating systems, communication protocols, and software. The majority of data is held in the non-relational database ADABAS and accessed through interfaces programmed in Natural. Data transfer from ADABAS to PC- or UNIX-based workstations is accomplished through ASCII files. The transition speed from the existing environment to a recommended computing environment involves many uncertainties, such as availability of funds. Meanwhile, information technology advances so rapidly that it renders an optimum static-computing environment impractical. It is recommended that Internet-based databases and management systems be planned in such a way that even though the PMIS database server is located in the office headquarters, district and area engineers can access and update the PMIS database via the TxDOT Intranet.

Chapter 6. GIS Staff and Needed Training Program

6.1 Ideal Staff and GIS Skills Required

GIS Architecture suggests that there are likely to be five classes of GIS staff within TxDOT, each corresponding to an organizational level (Ref 11):

1) Local GIS User
2) Local GIS Specialist
3) GIS Application/Data Steward
4) Central GIS Support Specialists
5) Statewide GIS Coordinator

For PMIS in TxDOT, the local-level users represent all users in specific application areas. Local-level users consist mainly of the districts and divisions. The GIS staff at the local level are the GIS users, the local GIS specialists, and possibly the GIS application/data stewards. A coordinated approach to GIS support at the local level is recommended. For each district, there should be a person or a small group designated by the district that serves as the single contact for applications such as GIS-PMIS. A group composed of representatives from each application area within the district should be responsible for the review of GIS policy and direction for the entity. This larger GIS coordinating group does not need to be staffed by GIS experts, but, more appropriately, by individuals who are able to perceive the needs and requirements of each of the areas from a business perspective and who have the authority to commit resources.

Central support consists of a core group within the ISD that is responsible for researching, evaluating, recommending, and supporting the technologies related to GIS. This group is made up of the statewide GIS coordinator, the central GIS support specialists, and possibly some GIS data/application stewards.

Table 6.1 summarizes the responsibilities for each GIS user who must be capable of fulfilling the responsibilities necessary to support the architecture at each level.

Based on the level of GIS knowledge needed, there are likely to be three levels of GIS staff and users (Ref 7). These include the following:

1) “Core” staff who are responsible for spatial database design, development, and management; GIS activities planning and coordination; administrative support; training and outreach; establishment of standards; software installation and maintenance; low-level programming and application development; maintenance of primary contact with vendors; determining and implementing solutions for technical problems; systems integration and administration; and network and communications administration. The core staff should be within the ISD.
2) “Master” users who participate with the core staff in specific application design and who do high-level (macro language) application development; application operation and maintenance; and PMIS database administration. Master users are attached to user divisions. A particular district may have one GIS staff member assisting all GIS users.
3) “Other” users who are trained only in the use of fully developed applications. This level includes most of an organization’s employees, from entry-level engineers to top-level managers. A customized graphic user interface should be created to assist the GIS users in accomplishing tasks without their having to learn the details of the GIS software.

Table 6.1 GIS staff and related responsibilities

Staff	Responsibilities
Local Users	Use GIS application to answer questions, make business decisions, and create maps or cartographic output to present and display information.
Local GIS Specialists	Coordinate all GIS development and operations; implement policy, standards, and procedures for GIS; coordinate training and education and ensure that the platform complies with the TxDOT GIS architecture; implement and maintain GIS data collection and management process; and communicate with the GIS personnel at the ISD. All of these roles are within the District/Division/Special Office.
GIS Application/ Data Steward	Originate and aid in the development and implementation of GIS applications that directly apply to the steward's discipline; collect, store, and manage all aspects of PMIS data; and provide support for the data and application-specific questions.
Central GIS Support Specialists	Develop technical implementation procedures for GIS components; implement policies, standards, and procedures for GIS; coordinate training and education within TxDOT; participate in the implementation and maintenance of a GIS data management process within TxDOT; and participate in the construction of a technical knowledge base for resolution of GIS hardware and software problems.
Statewide GIS Coordinator	Coordinate overall GIS operations within TxDOT, and coordinate overall GIS directions, standards, and policies with other public agencies to promote data sharing.

Table 6.2 lists the GIS staff needed for GIS-PMIS. From the perspective of required GIS knowledge level, there are likely to be two levels of GIS staff and users associated with PMIS: master users and other users. Based on the organizational level where they are positioned, there is likely to be three levels of GIS staff associated with PMIS: 1) local GIS users; 2) local GIS specialists; and 3) the GIS application/data steward. Table 6.3 lists the knowledge and skills required for GIS-PMIS staff.

Table 6.2 GIS staff needed for GIS-PMIS

Staff	**Core Staff**	**Master Users**	**Other Users**
GIS Application/Data Steward		X	
Local GIS Specialists		X	
Local Users			X

Table 6.3 Knowledge and skills required for GIS-PMIS staff (Ref 11)

Knowledge/Skills		**Local GIS Users**	**Local GIS Specialists**	**GIS Application/Data Steward**
Approved GIS and CADD Software	ArcView	√	√√	√√
	ARC/INFO		√√	√√
	GIS Concepts and Fundamentals			
	Software Installation Procedures			
	ARC/INFO License Management		√√	
	Misc. Vendor GIS Products			
	MicroStation 95		√	√
Approved Database Software	Sybase, Access, SQL Anywhere		√	√
	ODBC Connectivity		√	√
	RDBMS Design			
Mapping Support	Cartography and Digital Mapping			
	Digital Orthophotography			
Internet and Intranet	Internet/Intranet Browser (Netscape)			

√ **Need Basic Knowledge**

√√ **Need Extensive Knowledge**

(Blank cells helpful but not required)

Table 6.3 Knowledge and skills required for GIS-PMIS staff (continued)

Knowledge/Skills		**Local GIS Users**	**Local GIS Specialists**	**GIS Application/Data Steward**
Project Development	Avenue		√	√√
	AML		√	√
	Software Development Methodology and Standards		√	√
	TxDOT Applications			
	TxDOT Network Configuration			
	Project Management Skills		√	√
	Relational Database Concepts and Design		√	√
	PowerBuilder, Visual Basic, Visual C++			
	New and Emerging Technologies for GIS			

√ **Need Basic Knowledge**

√√ **Need Extensive Knowledge**

(Blank cells helpful but not required)

Table 6.3 Knowledge and skills required for GIS-PMIS staff (continued)

Knowledge/ Skills			**Local GIS Users**	**Local GIS Specialists**	**GIS Application/Data Steward**
Network Support	TCP/IP	TCP/IP Protocol		√	√
	Windows NT	Windows NT Workstations and Server		√	√
		GIS Network Configurations		√	√
		Printer/Plotter Connectivity		√	√
		File Management (GIS Directory Structures)			
	Server/ Workstations Backup	Backup/Maintenance		√	√
PC Hardware Support	Hardware Trouble-shooting Skills			√	√

√ **Need Basic Knowledge**

√√ **Need Extensive Knowledge**

(Blank cells helpful but not required)

Table 6.3 Knowledge and skills required for GIS-PMIS staff (continued)

Knowledge/Skills			**Local GIS Users**	**Local GIS Specialists**	**GIS Application/Data Steward**
Mainframe	Attachmate				
	ROSCOE, JCL, Natural/ADABAS, VSAM, Disk File Creation, RDBMS				
	Data Migration Principles				
Data Support	Data Collection	GPS Concepts and Fundamentals		√	√
		Data Collection Techniques (GPS, Digital Imagery, Video-Logging, TRMS)		√	√
	GIS Data Types	Raster, Vector, ASCII, Mainframe Data Types		√	√
Other Software	Microsoft Office Suite			√	√
Other	Written and Oral Communication		√	√	√
	Problem Solving		√	√	√
	Trouble-shooting			√	√
	Training			√	√

√ **Need Basic Knowledge**

√√ **Need Extensive Knowledge**

(Blank cells helpful but not required)

The central GIS group should work closely with the central database management group of ISD regarding RDBMS issues. Furthermore, because GPS data collection activities are inherently linked to the GIS architecture and GIS support, GIS and GPS should be managed and coordinated as a logical entity. The coordination of these groups would allow cross training of personnel, which in turn would promote better understanding of how these technologies can be utilized. These groups could be combined into one large unit, or two units under common direction, dedicated to these geospatial technologies.

Coordinating these support groups has many advantages:

1) Cross training of key personnel to promote better understanding of how these technologies can be best utilized.
2) Providing better beginning-to-end support for projects utilizing both technologies.
3) Avoiding over-specialization of support personnel.
4) Combining limited resources.
5) Avoiding duplication of effort and conflicting support recommendations.

6.2 Current Stage and Intermediate Solution

Currently, TxDOT does not hire GIS staff only for its PMIS. Ideally, one or more staff members could fill each job for GIS-PMIS. Realistically, one individual would probably handle several of these responsibilities. The staff members who know the existing PMIS and also have knowledge about GIS are essential to creating, using, and maintaining GIS-based PMIS. If possible, new staff should be hired. Future GIS staff can be acquired by training existing staff or by hiring new personnel to fill GIS positions. Limited agency resources require that choices be made concerning which staff members should be trained first in the use of GIS. Consequently, those individuals or groups who have the most interest in GIS and who can potentially generate the highest payoff applications would be provided the opportunity for training. As early GIS applications come on line and benefits are documented, additional staff members are likely to request training. For PMIS, the GIS application/data steward should receive priority for training, followed by local GIS specialists and local users.

The specific skills and the number of staff members with such skills will depend on the size of the system (number of applications), contracting decisions (how much of the work is performed by the organization), the technology used (hardware and software architecture), and the scale of the operation (the size and diversity of the database and the number of users). As seen in Figure 6.1, based on the survey conducted by CTR in 1997 (Ref 32), few state DOTs hire more than two GIS staff members for their PMIS. One in three state DOTs had not hired any GIS staff members for PMIS.

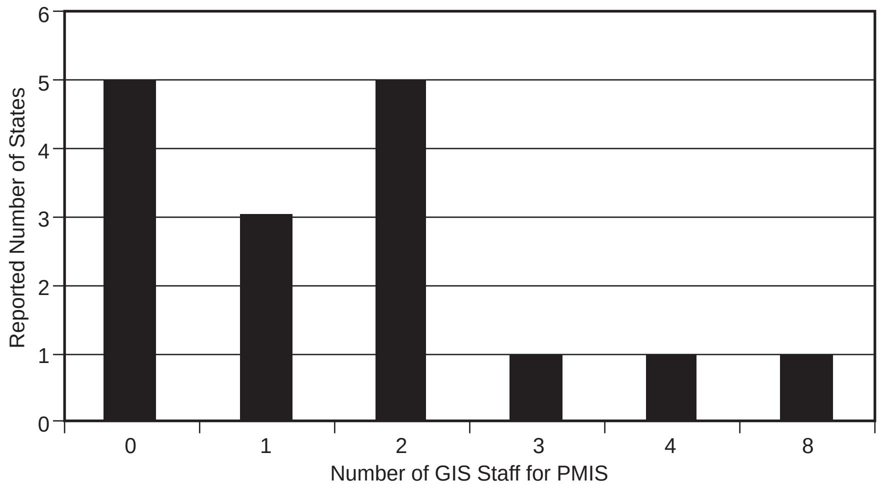

Figure 6.1 Reported number of GIS staff for PMIS

6.3 Recommended Training Programs

It is important to realize the special nature of GIS staffing problems. The required GIS knowledge is not a part of traditional software training and experience. Significant training is required, for example, in the areas of relational database management systems and of cartographic design. In many cases GIS staff are prevented from taking other positions. In any case, it is critical that core staff members be allocated full-time to GIS and not have their responsibilities split, with GIS being limited to “something on the side.”

There are three levels of training, corresponding to the three levels of staff. These include:

1) Core staff must be intensively trained in database and application design and in GIS programming.

2) Master staff must be trained until they are comfortable with the high-level programming or macro languages of the GIS, such as AML for ARC/INFO and Avenue for ArcView.
3) Other users must be trained until they are comfortable with the applications and management so they can make informed decisions about the technology.

Training for the GIS support personnel is extremely important to the success of GIS. The emphasis in earlier phases of work should be on building awareness through workshops and seminars to facilitate the needs analysis and general design activities. Table 6.4 summarizes available training sources for different skills. ESRI provides training in the base software products in its San Antonio office. These courses are specific to the ESRI products and are a very good introduction to GIS using the ARC/INFO and ArcView products. The courses address GIS in a very generic sense and will not address many transportation-related issues; however, they are very beneficial for those learning to use the products and becoming familiar with GIS. Third-party training is available for some of the recommended software products. Other GIS training courses are offered at local colleges and universities and can be very beneficial.

Some universities offer introductory continuing education short courses on GIS. Training services (introductory through advanced) can be obtained from consultants and from software vendors. Such services can be provided either on-site or at a remote central location of the provider's choosing. For organization-wide implementation, there will be some need for training on a continuing basis when there is personnel turnover, when new applications are being introduced, and when new releases of the core GIS software become available. Large transportation agencies should consider establishing their own internal training services, which should include staff whose job is to provide GIS training for other staff. Resources will also be needed to provide GIS training facilities with space and workstations devoted to training on at least a part-time basis.

While the vendor- and college-supplied training is usually very good, most will not focus on the specific needs for transportation. The GIS support group at ISD should develop a TxDOT-specific course to provide some general GIS training but more specifically to provide training in TxDOT GIS architecture and transportation application on a periodic basis. Training provided by

ISD should provide users with the information necessary to implement and support GIS at a district, division, or office in accordance with the TxDOT GIS architecture.

Table 6.4 Training sources for different skills (Ref 11)

Knowledge/Skills/Tools	Training Curriculum	Source/Format (If known)
ARC/INFO	ESRI Certified Training	ESRI Certified Training Centers
ArcView	ESRI Certified Training, ISD GIS Training	ESRI Certified Training Centers, ISD
GIS Concepts and Fundamentals	ESRI Certified Training, ISD GIS Training, College Level Coursework in GIS and Cartography	ISD, ESRI
ARC/INFO License Management	ISD GIS Training, ESRI User Documentation	ISD, ESRI
Misc. GIS Vendor Products	Vendor Training	Vendor
MicroStation 95	CADD Training	ISD
GEOPAK	GEOPAK Training	ISD
Relational Database Concept and Design	SYBASE Certified Training, ISD GIS Training	SYBASE, ISD, CBT
Sybase	SYBASE Certified Training	SYBASE Certified Training Center, CBT
Access	Microsoft Certified Training	DIR, CBT
ODBC Connectivity		OJT
Microsoft Office Suite	TxDOT Training	DIR, CBT, OJT
SQL Anywhere	TxDOT Core Technology Training	CBT
Software Installation Procedures	User Manuals and Documentation	OJT

Table 6.4 Training sources for different skills (continued)

Knowledge/Skills/Tools	Training Curriculum	Source/Format (If known)
Raster, Vector, ASCII	ISD GIS Training, Vendor Training	ISD, Vendor, OJT
Mainframe Data, Attachmate, Natural/ADBAS, ROSCOE, JCL, VSAM, Disk File Creation		OJT
PC Hardware	User Manuals and Documentation	OJT
New/Emerging Technologies for GIS		OJT, Vendor
GPS Concepts and Fundamentals		OJT
GIS Data Collection Techniques		OJT
Cartographic and Digital Mapping	College Coursework	OJT
Digital Orthophotography		OJT
GIS License Management	ESRI Documentation, ISD GIS Training	ESRI, ISD
Data Migration Principles		OJT
TCP/IP		OJT
TCP/IP Applications (FTP, Telnet, NFS)		OJT
Windows NT	TxDOT Core Technology Training	CBT
GIS Network Configuration		OJT
Printer/Plotter Connectivity	User Manuals and Documentation	OJT
TxDOT Network Configurations		OJT
Backup/Maintenance Techniques	User Manuals and Documentation	OJT

Table 6.4 Training sources for different skills (continued)

Knowledge/Skills/Tools	Training Curriculum	Source/Format (If known)
Development Environments (PowerBuilder,Visual Basic, Visual C++, MapObjects)	Vendor Training	CBT, Vendor
Avenue	ESRI Certified Training	ESRI Certified Training Centers
AML	ESRI Certified Training	ESRI Certified Training Centers
Software Development Methodology and Standards		OJT
ISD Software Standards		OJT
File Management (GIS Directory Structures)	ESRI Training, ISD GIS Training	ESRI, ISD
TxDOT Applications		OJT
Project Management Skills		OJT
Written and Oral Communication Skills		OJT
Troubleshooting Skills		OJT
Problem-Solving Skills		OJT
Training Skills		OJT

6.3.1 Top-Level Education for Senior and Middle Management Levels

The top-level education is aimed at senior management and addresses the following:

1) Features and benefits of a GIS and how the project will be implemented.
2) Impact on policies and procedures.
3) Impact on personnel and budgets.
4) Importance of senior management dedication and commitment to the project.
5) Where and when during GIS implementation their specific involvement is needed.

The emphasis is on familiarization, impacts, and management action.

Middle management is provided with much of the same material as senior management, plus more specific knowledge about the following:

1) The underlying concepts and the important success factors.
2) Functional components of the system and how the new system will work.

6.3.2 In-House Staff versus Outside Consultants

The lack of existing personnel who have the skills needed to develop, operate, and maintain the GIS in the organization may lead the GIS managers to recruit outside consultants. In general, in-house staff are considered to be more responsive to the needs of the users, primarily because of their knowledge of the local culture and their dependence on the continued success of the organization. Consultants, on the other hand, are considered to be more knowledgeable about recent technological developments and methodologies that have been successful in other jurisdictions.

Chapter 7. Organizational Structure and Institutional Issues

GIS is not just a software package like word processing, spreadsheet, computer-aided design, and other popular computer products that one buys, installs, and learns how to use. Successful implementation of geographic information systems must take management and institutional arrangement issues into consideration. The introduction of new information technologies like GIS must be accompanied by appropriate adjustment of organizational structures and institutional arrangements.

7.1 Present TxDOT Organizational Structure

It is inevitable that public agencies like TxDOT face a set of challenges when introducing new information technologies like GIS into their traditional organizational structures. Traditional organizational structures are usually based on hierarchies of power and control of information. For TxDOT, the districts and the Design Division are the PMIS users that will benefit most from the implementation of GIS. The Information Systems Division (ISD) serves as the chief information resource center that established the TxDOT GIS Architecture and Core Technologies Architecture. The Transportation Planning and Programming Division (TPP) is responsible for maintaining and updating the statewide digital base map. Information among the divisions must flow up and down through the hierarchy of the organization.

7.2 Ideal Organizational Structure

For an organization to be most effective, information should reside in all parts of the system, in much the same way as the brain stores and processes information throughout the neural network (Ref 30). In order to realize fully the benefits of new information technologies like GIS, TxDOT must adjust its organizational structure to allow a horizontal as well as vertical flow of information. On the other hand, new information technologies potentially have the power to redistribute information, decision-making processes, responsibility, and power in an organization. The introduction of the new information technologies will at last force the public agencies to change their management structure. Presently, the implementation of new information technologies provides an opportunity for evaluating the existing organizational procedures and structures.

As seen in Figure 7.1, a specific organizational structure model will provides the conceptual framework needed for successful GIS implementation. The organizational structure model uses a non-hierarchical design to foster the cooperation and coordination needed to share data, applications, and personnel across TxDOT to the greatest extent possible. It also adds external agencies into this organizational structure model so that TxDOT can coordinate with other agencies and share the information as much as possible. In addition, it incorporates feedback among various levels and prevents excessive control by any one entity in the structure.

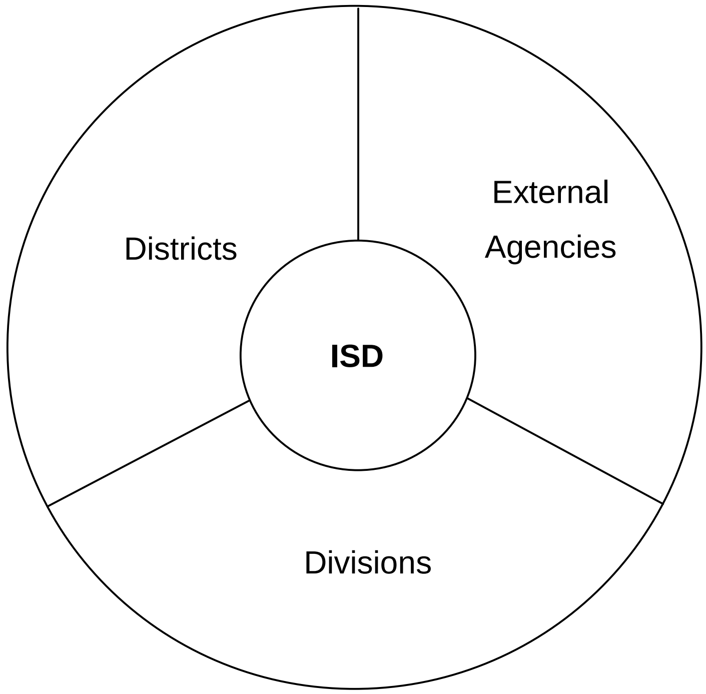

Figure 7.1 Recommended TxDOT organizational structure model for GIS

With such an organizational structure, GIS technology can be used to optimize limited resources in a wide variety of areas such as:

- The need to collect data only once for all to use.
- The elimination of redundant needs for highly qualified personnel.
- Better information for better decisions made by personnel with limited experience.
- The ability to respond in a timely manner to management's need for specific information while minimizing the impact on already limited resources, particularly when the legislature is in session.

7.3 Intermediate Solution

As discussed above, traditional organizational structure sometimes can be a main obstacle for implementing new information technologies. Therefore, it is important to examine the existing organizational structure for potential reorganization. There are four procedures for reorganization:

1. *Evaluation (Unfreezing):* Performance measurement is required to convince management that the change is necessary.
2. *Initiation:* Development of an idea and a plan to change the organization to improve the performance.
3. *Implementation:* Resources must be available and the tasks must be undertaken.
4. *Routinization (Refreezing):* Behavior, attitudes, and values must be refrozen.

Depending on the resistance to the change, the following methods may be used to make sure that the implementation is successful.

1) Education and communication.
2) Participation and involvement.
3) Facilitation and support.
4) Negotiations and agreement.
5) Manipulation and cooperation.
6) Explicit or implicit coercion.

7.4 GIS Management Strategy

For a successful implementation of GIS for PMIS, it is necessary to determine the management strategies that best suit the PMIS users' needs. The following options are available: a) centralized support for decentralized applications; b) centralized support for centralized applications; or c) decentralized support for decentralized applications (Ref 31).

Decentralization is a trend for information management; this tendency is actually beneficial to the introduction of new information technologies into an organization. People within the organization are most familiar with the real problems. However, this management strategy can result in data redundancy and system incompatibility across the organization because different application areas may have their own methods of collecting and maintaining their resources.

Another strategy in contrast to decentralization is to turn over the entire responsibility of the management to a centralized group (e.g., the ISD), but such a centralized approach may bring about concerns regarding successful introduction of new information technologies into an organization. The centralized group may not fully understand the specific problem, and sometimes there is resistance from the people in the application areas within the organization.

The best strategy for an effective GIS implementation is to combine the primary benefits of both decentralized and centralized strategies. A top-down, then bottom-up strategy should be adopted for GIS planning and implementation (Ref 6).

At first, some degree of centralization and some degree of top-down planning are preferred because of the need for the following: 1) sharing data across applications and departments and considering data as a corporate resource (especially spatial data), like the data steward concept; 2) setting and maintaining data-processing standards across the entire organization; and 3) establishing and maintaining a modern networking infrastructure. If done correctly with strategies that avoid costly redundancy and enable sharing across applications, this strategy would be an organization-wide, top-down activity. Once all of these issues are addressed, GIS technologies can be exploited to bring up particular applications on the basis of decentralized, bottom-up user initiative.

7.5 Some Institutional Issues

Besides the organizational structures, other obstacles arise in the process of implementing any new information technologies:

1) Tight fiscal budgets.
2) Rigid purchasing guidelines.
3) Restricted payroll scales.
4) Legacy management styles.
5) Concerns about job elimination that characterize the traditional government office.

Salary structure and budget cycles in the public sector are fixed over periods of time by the legislature. Agencies are reluctant to purchase and incorporate rapidly changing information technologies. Because of the low salary offered in the public sector, many of the best technicians have the tendency to move to the private sector. Thus, public agencies always find it difficult to have enough excellent technicians to implement new information technologies. Specific attention should be given to these issues for a successful GIS implementation to occur.

Chapter 8. Integrate GIS with PMIS and Related Technologies

8.1 Integrate GIS with PMIS

To a large extent, the success of GIS implementation is determined by the integration of various databases. The intended GIS should be able to utilize the existing PMIS databases either directly or through inexpensive data conversion. According to the methods of database integration, there are three approaches for integrating PMIS and GIS:

1) *Seamless integration*: The PMIS is implemented within the GIS through their sharing of a common database.
2) *Database linkage*: The PMIS data are exported and then imported into the GIS for display or querying through database linkage methods such as SQL (Structural Query Language).
3) *Other approaches such as map export*: The map is exported from the GIS and then imported into the PMIS for use in a map display.

Table 8.1 compares the three approaches for implementing GIS with TxDOT's PMIS.

8.1.1 Seamless Integration

By sharing a common database, GIS can be integrated with the existing PMIS seamlessly. This approach is best suited to an agency with the following conditions:

- It has established a PMIS database consistent with the database required for GIS (a relational database) that has dynamic segmentation ability.
- PMIS users are already familiar and comfortable with using GIS software and want the seamless integration approach.
- GIS and PMIS have a common platform.

8.1.2 Database Linkage

Through inexpensive database conversion methods such as SQL or ODBC, the PMIS data are exported and then imported into the GIS for display and querying. This approach is best suited for an agency where the databases for GIS and PMIS are maintained as separate databases. The disadvantage of this approach is that users have to perform data conversion each time the

PMIS data are updated. However, this approach allows the mixing of platforms for GIS and PMIS.

Table 8.1 Comparison of three GIS-PMIS integration approaches

	Seamless Integration	Database Linkage	Map Export
Approach	PMIS and GIS share common database	PMIS data are exported to GIS	Maps are exported from GIS to PMIS
Data Export/Import	No	Yes	Yes
Hardware platform	GIS and PMIS restricted to common platform	PMIS and GIS can exist on different platforms	PMIS and GIS have different user interface
Consistency of User Interface	Consistent interface between PMIS and GIS portions of system	PMIS and GIS have different user interface	Consistent interface between PMIS and GIS (PMIS map display) portions of system
Ease of use for PMIS Engineer	GIS knowledge needed	GIS and data transfer knowledge needed	Ease for PMIS engineers
Ability to access PMIS data	All GIS users can access PMIS data	All GIS users could access PMIS data	GIS users cannot access PMS data

8.1.3 Other Approach (Map Export)

The map is exported from the GIS and then imported into the PMIS for map display. Although this approach demands little GIS knowledge on the part of PMIS users, it does not make full use of the power of GIS, such as the ability to integrate various data, systems, and technologies. In addition, this approach can only be used in a PC environment.

Figure 8.1, based on the results of a survey conducted by CTR in 1997 (Ref 32), illustrates that the majority of state DOTs use database linkage as the approach for integrating their GIS with PMS.

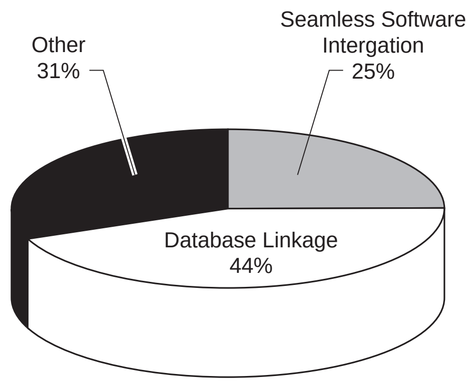

Figure 8.1 Reported GIS-PMIS integration approaches in state DOTs

8.2 Costs for Integrating GIS with PMIS

There are several major cost categories that must be recognized in developing and managing the budget for GIS services (Ref 6). They are as follows:

1) Data collection and maintenance.
2) Equipment acquisition.
3) Software acquisition.
4) Maintenance of equipment and software.
5) Labor.
6) Other expenditures (materials and supplies, internal services).

8.2.1 Data Collection and Maintenance

The costs for the base map development account for most of the expenditures during the initial stage, while data maintenance costs dominate over the long term. All of the costs for developing and maintaining the base map and attribute data should be distributed to all of the potential users, including external agencies and divisions within the organization.

8.2.2 Equipment

All equipment purchase or lease costs, including those for computer hardware, printers, and plotters, as well as those for furniture, copiers, fax machines, and so on, fall into this cost category. Equipment obtained specifically for a project should be charged to the responsible department's account. Indirect equipment costs (the costs of new or replacement equipment for the centralized GIS installation) should be distributed fairly among all users.

8.2.3 Software

The costs of purchased or leased software packages should be treated in the same manner as the costs of equipment. The cost of a software package for a specific project should be assigned to that project and then charged to the account of the respective department. Indirect costs of software for the central system that benefits all users should be distributed fairly among all users. The software packages include GIS software, DBMS software, operating system software, CADD software, and other third-party software.

8.2.4 Maintenance of Equipment and Software

The annual costs of maintaining GIS software and hardware can be as much as 8 to 12 percent of the purchase price. Such costs should be allocated to users in the same manner as the costs of the equipment and software. In other words, they should be allocated directly to the department that uses the product or among all users for centralized products.

8.2.5 Labor

Labor costs include all of those costs associated with the use of human resources to perform work. Direct labor costs are those associated with the time spent by contractors or in-house staff on a particular project. Indirect labor costs are those associated with time spent by the GIS staff on work that is not directly related to an approved project. This work includes problem resolution, administration, training, and general system support such as preventive maintenance and daily backups.

8.2.6 Other Expenditures

Other expenditures include the purchase of materials and supplies, as well as internal services. Materials and supplies expenses include the costs of office supplies, periodicals, books, maps, and so on to support the office of the GIS staff. Internal services costs include spending on office occupancy, photocopying services, printing, telephone, postage, and other similar services.

There are a few other costs included in the GIS operation and maintenance, such as travel and car allowance.

As discussed above, there are various costs that need to be funded during implementation of GIS. Some of them, such as data collection and maintenance costs, can be shared with other external agencies or internal divisions. It is difficult to compute these fees just for PMIS. Table 8.2 presents typical cost ranges for GIS hardware and software purchase, maintenance costs, and training costs.

Table 8.2 Cost estimation for implementing a GIS (Ref 34)

	First Seat*	**Added Seats****
Personal Computer	$8,000–20,000	$3,000–10,000
Engineering Workstation	$13,000–25,000	$5,000–15,000
Mini- or Mainframe Workstation	$50,000–100,000	$20,000–50,000
Annual Maintenance Costs	$8,500–16,000	$4,000–9,000
Annual Salary Charges	Each $35,000	
Annual Training Charges	Each $2,000	
Annual Utility Charges	Each $500	

* Includes software license, plotter, and large disk drive

** Includes software license

8.3 Current Status of TxDOT PMIS with Regard to the Integration with GIS

8.3.1 Database and Data Structure

TxDOT's PMIS is a mainframe application at this time and cannot be used in GIS directly. PMIS is currently operating in a combination of two environments: an on-line environment (using CICS) and a batch environment (using ROSCOE). Mainframe PMIS data is stored in a non-relational database (ADABAS) and is summarized, analyzed, and reported using programs written in the NATURAL computer language. PMIS data can be downloaded to TxDOT workstations as Microsoft Access database files using file transfer protocol (FTP).

8.3.2 Location Reference System

Linear referencing of transportation data is a core feature of GIS-Transportation and a critical activity for the successful implementation of GIS for PMIS. Linear referencing is considered a special case of location referencing that is designed specifically for transportation network data management. It involves developing a standard method of referencing activities or events that occur along a section of highway. Most Linear Referencing Systems (LRSs) were developed before the emergence of GIS, in which relative rather than absolute geographic referencing criteria are employed. Relative geographic referencing includes measurements from a known point, such as an intersection, or the beginning of a designated route, such as the state boundary line. In most cases, local control points or mile point markers are used as the known points. Most problems that arise with a linear LRS occur because of a poorly designed (or overly complex) referencing system or because one fails to accommodate changes in the road system. Additional problems arise if several different linear LRSs are in use by an agency. TxDOT uses many methods of locating highway sections or projects in the field (for example, control-section, control-section-job, construction stations, and even layman's descriptions of from and to points). To minimize disruption to users, a GIS-based location referencing system for TxDOT must accommodate all of the location referencing methods that TxDOT uses.

8.4 Ideal Solution for Integrating TxDOT PMIS with GIS

8.4.1 Ideal Method of Integrating PMIS with GIS

The ideal method for integrating PMIS with GIS should employ a seamless integration. The integration of PMIS and GIS does not require data import and export because PMIS and GIS share a common database and hardware platform. Thus, integration can reduce the complexity of data integration and reduce the required knowledge and skills of users. It can also minimize the error caused by data import and export and reduce the time necessary for GIS users to obtain the updated PMIS data. Of course, such a seamless integration would require that TxDOT convert the entire PMIS database from the current mainframe ADABAS format to a relational database format. After the conversion, the PMIS database should be operated and maintained in a relational database such as Sybase or Oracle.

8.4.2 Ideal Location Reference Method

GIS provides capabilities to help manage the data, including cross referencing between different LRSs. Using GIS as a location referencing tool would require GIS to adopt a standard Linear Reference System (LRS). Once accomplished, updating of TRM can be managed via GIS in the district offices and divisions, and the need for a separate CSM will disappear. Linear data management in GIS and Sybase would replace the existing processes for data entry and maintenance in the Microstation environment and in databases residing on ADABAS.

At minimum, a standardized LRS should:

1) Establish a well-defined hierarchy of route numbers (e.g., interstate, U.S. primary, state route, county route, etc.) such that a single route number could be associated with each network segment; this concept has been used in the TRM at TxDOT.
2) Eliminate the practice of using equations to tie reconstructed routes back to original reference points. All routes would be newly referenced after major realignment.
3) Change from a county-based to a state-based road inventory system. State sign routes that cross county lines would be sequentially referenced from their beginning to end instead of being reset at county boundaries.

8.4.3 Cost Estimate

Using the principles discussed in the earlier sections regarding the costs for GIS implementation, the researchers made the following assumptions for the Odessa District (with twelve counties) for the purpose of cost estimate:

1) A GIS system has a server with high-speed CPU and thirteen personal computers (twelve personal computers for daily use and one personal computer for training).
2) The total cost for the personal computers, including software, plotters, and peripheral devices, equals $5,000 per computer.
3) The purchase costs are amortized over five years using straight-line depreciation.
4) The annual maintenance costs amount to 10 percent of the purchase costs, including hardware maintenance and software upgrades.
5) Annual salary charges are $35,000 per employee. There is one full-time GIS specialist.
6) Annual training charges are $2,000 per employee. Twelve people will receive training.
7) Annual utility charges are $500 per machine.

The total annual cost can be calculated as follows:

1) Total purchase cost:
   $10,000 + 12 x $5,000 = $70,000
2) PMIS data conversion from mainframe to a relational database and corresponding data update:
   $50,000
3) Annual depreciation charges:
   $70,000/5 = $14,000
4) Annual maintenance charges:
   $14,000 x 0.1 = $1,400
5) Annual salary charges:
   $40,000 x 1 = $40,000
6) Annual training charges:

$2,000 x 12 = $24,000

7) Annual utility charges:

   $500 x 12 = $6,000

With a total purchase of $70,000, a data conversion cost of $50,000, and a total annual charge of $85,400, the grand total cost for the first year would be $205,400.

As seen above, most of the annual costs come from the salary charges and training charges; however, the salary charges can be reduced by utilization of existing staff through training programs, and by assigning one individual to handle several responsibilities.

8.5 Intermediate Solution for Integrating TxDOT PMIS with GIS

8.5.1 Linkage between TxDOT PMIS and GIS

Based on the comparisons of these approaches and existing TxDOT PMIS and GIS resources, the database linkage approach is recommended for integrating GIS with PMIS as an intermediate solution for the following reasons:

1) The existing TxDOT PMIS database is not a relational database and cannot be integrated into GIS directly.
2) PMIS users are not familiar with using GIS software.
3) GIS and PMIS use different computing platforms.

If GIS and PMIS are to be integrated seamlessly, TxDOT PMIS data should be transferred to a relational database such as Sybase or Microsoft Access.

The GIS-integrated PMIS would produce a user-friendly and very flexible tool that would truly make pavement management more viable. The integrated system would allow the analyzed results from PMIS to be used directly in GIS for displaying, mapping, and manipulation in the state-of-the-art Multiple Document Interface (MDI) environment. The GIS-integrated PMIS would handle a wide variety of data and information visually, analyze it spatially, and present the results graphically.

A GIS-based and multimedia-integrated Infrastructure Management System (IMS) was developed by Zhang, at CTR, in 1996 (Ref 9). This IMS can serve as an example of how to integrate recommended GIS with TxDOT's PMIS.

8.5.2 Intermediate Options for Location Reference System

A number of migration options are available for TxDOT to implement LRS within the GIS architecture (Ref 11). The options are as follows:

1) No change.
2) TRMDB data migration to Sybase.
3) Enhance the base map.
4) On-system/off-system roads: Improve TRM based on anchor points and sections and county highway signed route instances.
5) On-system roads: Redesign TRM as "monuments" based on anchor points and sections and statewide highway signed route instances.

GIS Architecture recommends that the options be implemented incrementally. Options 1 and 2 are short-term options and can be used in pilot projects. Option 3 is designed to improve the accuracy level of the base map. However, Option 5 should be the ultimate LRS implementation option, because it would result in a highly accurate linear referencing method based on the fixed reference markers. If county-based routes are needed, Option 4 could be integrated at a later date (Ref 11).

8.5.3 Cost Estimate

The basic assumptions for cost estimates under the intermediate solution are basically the same as those made for the ideal solution scenario, except that the server with high-speed CPU and the PMIS data conversion are not required. Accordingly, the costs are estimated as follows:

1) Total purchase cost:
   12 x $5,000 = $60,000
2) Annual depreciation charges:
   $60,000/5 = $12,000
3) Annual maintenance charges:
   $12,000 x 0.1 = $1,200
4) Annual salary charges:
   $40,000 x 1 = $40,000
5) Annual training charges:
   $2,000 x 12 = $24,000

6) Annual utility charges:

   $500 x 12 = $6,000

With a total purchase of $60,000 and a total annual charge of $83,200, the grand total cost for the first year would be $143,200.

As indicated by the ideal solution scenario, most of the annual costs come from the salary and training charges. Therefore, efficient personnel are the key for a successful implementation of this intermediate strategy. Of course, salary and training charges can be significantly reduced through the use of a web-based system. The web-based system would provide the essentially universal access that PMIS currently has (any TxDOT employee with a mainframe account can run PMIS reports) while not requiring installation of GIS on thousands of workstations. In fact, it might even be possible to leave the PMIS data native on the mainframe (where validation and storage already occur) and have live links to the data when needed by GIS.

Chapter 9. Pilot Project

9.1 The Need for a Pilot Project

A good approach to dealing with uncertainty is to undertake a pilot project to test the concepts and recommendations described in this report. There are several reasons to undertake a pilot project (Ref 6):

1) As an experiment, the purpose of which is to verify the key findings and critical recommendations in the real working environment and to obtain some first-hand estimates of the time, resources, and training required for implementing and operating the proposed GIS for PMIS.
2) As a demonstration, with which potential users of the system are shown what is available and what can be achieved.
3) As a temporary operation or production environment, with which agency data are processed to answer specific problems, to assess operational feasibility, and to determine organizational impacts.

9.2 Expert Task Group Meeting

On August 6, 1998, an Expert Task Group meeting (ETG) was held at CTR. The purpose of this ETG panel meeting was to brainstorm among the ETG members and collect expert opinions about the user requirements of GIS for pavement management. The group discussion was focused upon two main areas. The first topic was "Important Uses of GIS in Pavement Management." This discussion required each district or division engineer to list three important GIS uses for pavement management. The second discussion topic was "What Types of Issues Are Critical for Implementing GIS for PMIS?"

9.2.1 User Requirements for GIS-PMIS

During the meeting, each district pavement engineer was required to list three issues that were most important for GIS-PMIS, based on the engineer's daily business activities and discussions. The following is a summary of requirements for a GIS-integrated PMIS:

1) User-friendly interface and flexibility for users.
2) Statistical analysis.

3) Data integration.
4) A single LRS with multiple referencing methods.
5) The ability to extract subsets of data from databases with various methods.
6) Statistical summary (average value, deviation, distribution, high, low, average).
7) Good display ability.
8) DGPS.
9) Dynamic segmentation.
10) Pavement history.
11) Query.
12) Video, visual images.
13) Geometry/Layer.
14) Performance data.
15) Color-coded map for PMIS data.
16) Standard report with map.
17) Pavement maintenance information.
18) Trend data.
19) BRINSAP.
20) TIP.
21) Routine maintenance.
22) Special query at project level.
23) Speed, utilities, economy, material source, maintenance costs, soil type, performance.
24) Access to raw data.
25) Extra data from isolated locations.
26) Reference system capabilities.
27) Local method of description.

28) Analysis for future needs:
    a) aging algorithms.
    b) statistical analysis.
    c) multiple-year data display/view/query.
29) The ability to locate section with tie location reference system.
30) Data-defined dynamic segmentation.
31) Multiple condition query.
32) Data access limits.
33) Intranet, Internet.
34) Integration of various databases.
35) Job status.
36) Simplicity and ease of use.
37) Language that is easy to understand (plain language reports).

9.2.2 Some Important GIS Implementation Issues

Some important institutional issues for implementing GIS discussed during the meeting are as follows:

1) Attracting and retaining qualified FTEs.
2) Convincing the decision makers to accept the idea.
3) Keeping FTEs.
4) Laying a foundation first.
5) Including metadata as a part of the system.
6) Integrating standards to tie different databases together.
7) Setting up a permanent control station (points) as reference.
8) Accessing GIS.
9) Paying for hardware and software.
10) Collecting the right data with undocumented constraints.
11) Updating data in a timely manner.
12) Training and education.
13) Interpreting certain databases.
14) Purchasing the latest software.

15) Generating GIS reports accurately.
16) Collecting, storing, and maintaining data and determining where the money will come from.
17) Presenting information to administration in a more understandable format.
18) Transitioning from conventional pavement management to GIS-PMIS.

9.2.3 Miscellaneous

During the meeting, several district pavement engineers discussed the following issues that may be considered in the pilot project:

1) Web applications, Internet and Intranet. However, certain files have to be restricted among the TxDOT employees for security.
2) GIS software can be customized to suit the special requirements of users. District pavement engineers should be responsible for what interface they want at the district level. For the interface design, enough tools and buttons should be provided, and they should be easy to use.
3) Concurrent access to the database is also important for TxDOT, since it has so many employees.
4) A data collection unit with all the capabilities so that data can be collected as a single data file and updated in a timely manner. PMIS database structure could be redesigned so that it could be used for GIS with dynamic segmentation.

9.3 Pilot Project

The Odessa District was selected for this pilot project. The following tasks were completed:

1) Linkage of the existing PMIS data (Odessa District) with the Odessa District on-system highway base map using the dynamic segmentation function. Most highway segments are 0.5 miles long.
2) Spatial data conversion, manipulation, and integration. Soil, rainfall, and climate (temperature) are critical factors that may affect the performance of pavement. The soil and rainfall data were downloaded from the Texas Natural Resource Information System (TNRIS) FTP site first and then converted to the projection consistent with

the TxDOT on-system highway base map. Since there are no existing digital county-based rainfall data for Texas available, the climate base map has to be developed using some paper data (Ref 35).

3) Application development using Avenue, including linking multiple images with highway segments and some convenient query tools for users.
4) Linkage of the R-log image files to the GIS base map through the Control-Section Job (CSJ) number, with which the R-log file can be easily accessed.
5) Seamless integration and synchronization by location of maps, video/photo logging, pavement condition profiles, and PMIS data tables.

9.4 Recommended Pilot Projects for the Future

There are some uncertainties related to integrating GIS with PMIS that to need to be addressed. The following pilot projects are recommended for further exploration of the potential of GIS and related technologies:

1) Enhance the base map pilot with GPS reference points.
2) Train GIS support unit staff in the latest technology, including ARC/INFO, ArcView, SDE, and MapObjects, and in database design and applications development issues.

Introduce Internet/Intranet-based GIS and PMIS applications so that district/division users can access data and information maintained on a server via Web browsers.

Chapter 10. Summaries

Successful GIS implementation involves not only the information technologies themselves but also the personnel and skills needed. The organization and institutional arrangements that govern the patterns of management and information flow are also critical and must be managed interactively. Since GIS-related information technologies are updated rapidly, it can be difficult to predict the future. Thus, a GIS implementation plan is needed to improve the chances of successful implementation. The plan presented here can help reduce mistakes and integrate management of the various aspects of data issues, personnel, and GIS skills needed, creating a solid base for dealing with the unexpected. This chapter summarizes the completed tasks, major findings, and key recommendations for GIS implementation actions.

10.1 Principal Aspects

The principal aspects of this implementation plan are as follows:

1) An overall procedure for implementing GIS is discussed, and critical issues for successfully implementing GIS for TxDOT PMIS are identified.
2) A three-stage GIS implementation concept is employed in making recommendations for each GIS component.
3) PMIS activities that can be improved by GIS operations, as well as the corresponding GIS operations themselves, are identified.
4) The benefits of adopting GIS for PMIS for several levels of PMIS users (e.g., users at the area, district, and division levels) are identified.
5) The required accuracy level of a digital base map for PMIS is researched from the applications perspective. Current TxDOT digital base maps are evaluated.
6) Data collection, maintenance, sharing, and transferal methods are recommended and related technologies are discussed.
7) A computing environment for operating GIS for PMIS is recommended and related technologies are discussed.
8) Personnel and GIS skills needed for PMIS, training strategies, and possible training programs are recommended.

9) Several options for organizational structure and the locus of GIS expertise, as well as important institutional issues, are discussed.
10) Several approaches to integrating GIS with TxDOT PMIS are compared. Costs for operating a GIS and related technologies that are important for integrating GIS with PMIS are discussed.
11) A pilot study for implementing the recommended GIS software and PMIS data is conducted.

A list follows of major findings that have significant impacts on the implementation of GIS for PMIS, each briefly summarized:

10.2 Major Findings

1) There are two interacting stages for implementing a GIS for PMIS. The first is the planning and design stage, in which the existing PMIS resources and limitations are examined and the potential GIS activities are then identified and selected. The second stage is the management and operation of the recommended GIS activities according to the implementation plan.
2) Several issues are critical for successful GIS implementation. The first is the involvement of both management-level and technical personnel. The second is the use of multiple technologies related to the successful implementation of GIS. The third is related to advancing technologies. The fourth is data and system integration.
3) Generally, for each PMIS activity at both the network level and the project level, there are certain GIS operations that can greatly increase the benefits of PMIS. The primary benefits of integrating GIS with PMIS come from two major categories of GIS functions: 1) to provide a user-friendly basis so that a wide variety of data can be accessed easily, manipulated visually, analyzed spatially, and presented graphically; and 2) to serve as a logical, coherent, and consistent platform and a common location reference system so that these diverse databases can be integrated and shared among different divisions of a department.
4) TxDOT is now ready to actively use GIS, apart from supporting the development of the base map and some ad hoc applications. PMIS is a mainframe application system. The PMIS data are still stored as flat files in ADABAS that cannot be used in GIS

directly. Data transfer from ADABAS to PC or Unix is accomplished through ASCII files.

5) A base map contains geographic features used for locational referencing. The quality of a base map determines to a large extent the success of a GIS project. The accuracy level required for PMIS, both absolute accuracy and relative accuracy, was determined from the perspective of specific applications. The absolute accuracy level of an existing TxDOT digital base map (about 15 m) is satisfactory for TxDOT PMIS's main purpose of planning. The relative accuracy level of the digital base map needs to be examined further.
6) Global Positioning System (GPS) is a three-dimensional measurement system. Integrated with GIS, GPS has enormous potential for engineering surveys and PMIS. In comparison to conventional instruments, GPS can be a more accurate and efficient method for base map development and for the collection and updating of highway inventory data than the conventional instruments.
7) Digital Orthophoto Quadrangle Quarter (DOQQ) is a geographically accurate digital image of the earth produced from aerial photography using photogrammetric techniques. DOQQs offer a complete, accurate base map for many GIS applications. However, they are expensive to acquire and manage.

10.3 Key Recommendations

Based on this research, the following recommendations should be carefully observed when implementing a GIS:

1) Different applications require spatial data at different scales. No one scale can support all pavement-related applications satisfactorily. It is recommended that several different scale themes be developed for frequent uses.
2) All GIS data, spatial data, and associated attribute data suffer from inaccuracy, imprecision, and error to some extent. Data quality assurance and quality control (QA/QC) rules must be established to ensure the delivery of high-quality data.
3) Maintenance of GIS data should be assumed by an appropriate "data steward" who is most responsible for collection and dissemination of the data.

4) Both internal and external data sources should be examined for potential use. Internal sources can include any department, division, or specific office, whereas external sources may include federal and state agencies, universities, and private entities.
5) Products from ESRI are recommended as the standard GIS software for PMIS. They include the following: high-end GIS software ARC/INFO, the desktop software ArcView, and MapObjects for adding GIS functions to non-GIS applications.
6) Mixed DBMSs are recommended to support GIS applications for PMIS. Sybase SQL Server is recommended for enterprise-wide and workgroup applications. Sybase SQL anywhere is recommended for PC workstation applications that have the potential to expand beyond a single workstation, and for small workgroup applications. Microsoft Access should be used for individual workstation database applications. INFO is recommended for prototype GIS database applications on an as-needed basis.
7) Based on the level of GIS knowledge needed, there are likely to be three levels of GIS staff and users associated with PMIS: core staff, master users, and other users. Based on the organizational level at which they are positioned, there are likely to be three levels of GIS staff associated with PMIS: local GIS users, local GIS specialists, and a GIS application/data steward.
8) Training for the GIS support personnel is extremely important for the success of GIS. Early implementation of GIS within TxDOT will be more dependent on vendor-supplied training. However, the GIS support group in ISD should develop training specifications for in-house training.
9) The introduction of new information technologies must be accompanied by the necessary change in organizational structures and institutional arrangements.
10) A top-down, then bottom-up GIS management strategy should be adopted for GIS planning and implementation.
11) A database linkage approach should be used to integrate GIS with TxDOT PMIS so that various kinds of databases can be accommodated.

12) The current data collection procedures should be modified so that the PMIS data can be more effectively integrated with GIS.
13) The potential of the Internet and Intranet should be fully examined as a platform to improve the efficiency and effectiveness of GIS-oriented PMIS.

Appendices

Appendix A

The Improved PMIS Benefits for Different Users from Implementing GIS

	GENERAL	ELECTED REPRESENTATIVES	SENIOR MANAGEMENT	TECHNICAL-LEVEL PEOPLE
Benefits of PMIS	Awareness of the magnitude of the pavement investment. Better chance of making correct decisions. Improved intra-agency coordination. Improved technology use. Improved communication.	Justification of maintenance and rehabilitation programs. Assurance of best expenditure of tax funds. Less pressure for arbitrary program modifications. Objective answers to questions about effects of lower funds or lower standards.	Comparative view of network status (current and future). Objective answers to questions about funding level effects on status and implications of deferred work or lower standards. Justification of programs to elected representatives. Assurance of best use of available budget. Definition of the management fee (percent of budget).	Improved recognition of various agency elements. Increased awareness of available technology. Improved communication among design, construction, maintenance, planning, and rehabilitation. Satisfaction from providing the best value for available funds.

Appendix A

The Improved PMIS Benefits for Different Users From Implementing GIS (continued)

	GENERAL	ELECTED REPRESENTATIVES	SENIOR MANAGEMENT	TECHNICAL-LEVEL PEOPLE
Improvements From Implementing GIS for PMIS	Facilitation of information sharing and communication among different divisions. Reduction of data redundancy. Improvement in organizational integrity. Better integration of different software, hardware, systems, and technologies. Cost reduction in data, systems development, and maintenance. Enhancement of productivity and improved efficiency. More effective computerized common location reference system. User-friendly interface.	Information that is easier to obtain and more meaningful (visually investigated data). Better decision-making.	The ability to retrieve the expected new information more efficiently and effectively. Information that is easier to obtain and more meaningful (visually investigated data). Better decision-making. More efficient and effective communication at the public and legislative levels.	More efficient and accurate collection of data. Identification of omitted or wrong pavement attributes. Verification of spatial accuracy. More efficient and effective retrieval of the expected new information. Reduction of data input and data storage requirements. Information that is easier to obtain and more meaningful (visually investigated data). Better decision-making. More efficient and effective communication at the public and legislative levels.

Appendix B

Ideal GIS-PMIS Activities (Network Level) and Related Improvements

NETWORK LEVEL PMIS ACTIVITIES	POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS
Segmentation	GIS OPERATIONS: Dynamic segmentation, thematic mapping, classification and reclassification of data.
	Improvements: Reduction of data input and data storage requirements, information that is easier to obtain and more meaningful (visually investigated data)
Data acquisition and processing	GIS OPERATIONS: GPS, geocoding, access and retrieval of data, data import and export, spatial data exchange, handling of raster and vector data and conversion between them, search and sorting of data, map projection, on-screen display.
	Improvements: More efficient and accurate collection of data, identification of omitted or wrong pavement attributes, verification of spatial accuracy, make information easier to obtain and more meaningful (visually investigated data)
Identification of available resources	GIS OPERATIONS: and retrieval of data, search and sorting of data, classification and reclassification of data, p and-click query, logic query, polygon overlay, thematic mapping, geocoding.
	Improvements: Information that is easier to obtain and more meaningful (visually investigated data), better decision-making, more efficient and effective retrieval of the expected new information

Appendix B

Ideal GIS-PMIS Activities (Network Level) and Related Improvements (continued)

NETWORK LEVEL PMIS ACTIVITIES	**POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS**
Summarization of current status	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, dynamic segmentation, network overlay, polygon overlay, point-and-click query, logical query, thematic mapping, report layout
	Improvements: Reduction of data input and data storage requirements, more efficient and effective retrieval of the expected new information, information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on public and legislative levels, better decision-making
Identification of present and future needs	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, dynamic segmentation, network overlay, polygon overlay, point-and-click query, logic query, thematic mapping, report layout
	Improvements: More efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements

Appendix B

Ideal GIS-PMIS Activities (Network Level) and Related Improvements (continued)

NETWORK LEVEL PMIS ACTIVITIES	**POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS**
Identification of candidate project for improvement	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, point-and-click query, logic query, dynamic segmentation, network overlay, thematic mapping, layout & report
	Improvements: Better comprehension of the complex relationships among many decisions, information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on public and legislative levels, better decision-making, more efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements
Generation of MR&R alternatives	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, dynamic segmentation, network overlay, polygon overlay, point-and-click query, logic query, thematic mapping, layout & report
	Improvements: More efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements, better comprehension of the complex relationships among many decisions, information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on public and legislative levels, better decision-making

Appendix B

Ideal GIS-PMIS Activities (Network Level) and Related Improvements (continued)

NETWORK LEVEL PMIS ACTIVITIES	POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS
Technical and economic analysis	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, dynamic segmentation, network overlay, polygon overlay, point-and-click query, logic query, thematic mapping, layout & report
	Improvements: More efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements, better comprehension of the complex relationships among many decisions, information that is easier to obtain and more meaningful (visually investigated data), better decision-making
Prioritization of MR&R alternatives	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, network overlay, polygon overlay, point-and-click query, logic query, thematic mapping, layout & report
	Improvements: More efficient and effective retrieval of the expected new information, better comprehension of the complex relationships among many decisions, make information that is easier to obtain and more meaningful (visually investigated data), better decision-making

Appendix B

Ideal GIS-PMIS Activities (Network Level) and Related Improvements (continued)

NETWORK LEVEL PMIS ACTIVITIES	**POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS**
Budget planning and distribution	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, network overlay, polygon overlay, point-and-click query, logic query, thematic mapping, layout & report
	Improvements: More efficient and effective retrieval of the expected new information, better comprehension of the complex relationships among many decisions, information that is easier to obtain and more meaningful (visually investigated data), better decision-making
Development of MR&R programs	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, network overlay, polygon overlay, point-and-click query, logic query, thematic mapping, layout & report
	Improvements: Better comprehension of the complex relationships among many decisions, information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on public and legislative levels, better decision-making, more efficient and effective retrieval of the expected new information

Appendix B

Ideal GIS-PMIS Activities (Network Level) and Related Improvements (continued)

NETWORK LEVEL PMIS ACTIVITIES	**POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS**
Summarization of future status	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, dynamic segmentation, network overlay, polygon overlay, point-and-click query, logic query, thematic mapping, layout & report
	Improvements: More efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements, information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on the public and legislative levels
Justification of the budget requests	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, point-and-click query, logic query, thematic mapping, layout & report
	Improvements: Better comprehension of the complex relationships among many decisions, information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on the public and legislative levels, more efficient and effective retrieval of the expected new information

Appendix B

Ideal GIS-PMIS Activities (Network Level) and Related Improvements (continued)

NETWORK LEVEL PMIS ACTIVITIES	POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS
Effects of less capital	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, point-and-click query, logic query, thematic mapping, layout & report, etc.
	Improvements: Better comprehension of the complex relationships among many decisions, information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on the public and legislative levels, more efficient and effective retrieval of the expected new information
Effects of deferring work or lowering standards	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, point-and-click query, logic query, thematic mapping, layout & report
	Improvements: Better comprehension of the complex relationships among many decisions, information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on the public and legislative levels, more efficient and effective retrieval of the expected new information

Appendix B

Ideal GIS-PMIS Activities (Network Level) and Related Improvements (continued)

NETWORK LEVEL PMIS ACTIVITIES	**POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS**
Effects of budget requests on future status	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, point-and-click query, logic query, thematic mapping, layout & report
	Improvements: Better comprehension of the complex relationships among many decisions, information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on the public and legislative levels, more efficient and effective retrieval of the expected new information
Effects of increased load limits	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, point-and-click query, logic query, thematic mapping, layout & report, etc.
	Improvements: Better comprehension of the complex relationships among many decisions, information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on the public and legislative levels, more efficient and effective retrieval of the expected new information

Appendix B

Ideal GIS-PMIS Activities (Network Level) and Related Improvements (continued)

NETWORK LEVEL PMIS ACTIVITIES	POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS
Effects of the implementation of MR&R	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, point-and-click query, logic query, thematic mapping, layout & report, etc.
	Improvements: Information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on the public and legislative levels, more efficient and effective retrieval of the expected new information
Updating of data	GIS OPERATIONS: GPS, access and retrieval of data, storage of data, search and sorting of data, classification and reclassification of data, dynamic segmentation, data import and export, on-screen display, etc.
	Improvements: More efficient and accurate collection of data, identification of omitted or wrong pavement attributes, reduction of data input and data storage requirements, information that is easier to obtain and more meaningful (visually investigated data)

Appendix B

Ideal GIS-PMIS Activities (Network Level) and Related Improvements (continued)

NETWORK LEVEL PMIS ACTIVITIES	POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS
Feedback of information to improve model	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, point-and-click query, logic query, thematic mapping
	Improvements: More efficient and effective retrieval of the expected new information, information that is easier to obtain and more meaningful (visually investigated data)
Updating of MR&R programs	GIS OPERATIONS: Access and retrieval of data, storage of data, classification and reclassification of data, dynamic segmentation, network overlay, polygon overlay, point-and-click query, logic query, thematic mapping, layout & report
	Improvements: More efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements, better comprehension of the complex relationships among many decisions, information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on the public and legislative levels, better decision-making

Appendix C

Ideal GIS-PMIS Activities (Project Level) and Related Improvements

PROJECT LEVEL PMIS ACTIVITIES	POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS
Subsectioning	GIS OPERATIONS: Dynamic segmentation, thematic mapping, classification and reclassification of data
	Improvements: Reduction of data input and data storage requirements, information that is easier to obtain and more meaningful (visually investigated data)
Acquisition and processing of data	GIS OPERATIONS: GPS, geocoding, access and retrieval of data, data import and export, spatial data exchange, handling of raster and vector data and conversion between them, search and sorting of data, map projection, on-screen display
	Improvements: More efficient and accurate collection of data, identification of omitted or wrong pavement attributes, verification of spatial accuracy, information that is easier to obtain and more meaningful (visually investigated data)

Appendix C

Ideal GIS-PMIS Activities (Project Level) and Related Improvements (continued)

PROJECT LEVEL PMIS ACTIVITIES	POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS
Summarization of current status	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, dynamic segmentation, network overlay, polygon overlay, point-and-click query, logical query, thematic mapping, report layout
	Improvements: More efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements, better comprehension of the complex relationships among many decisions, information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on the public and legislative levels, better decision-making
Generation of alternatives	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, dynamic segmentation, network overlay, polygon overlay, point-and-click query, logic query, thematic mapping, layout & report
	Improvements: More efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements, information that is easier to obtain and more meaningful (visually investigated data), better decision-making

Appendix C

Ideal GIS-PMIS Activities (Project Level) and Related Improvements (continued)

PROJECT LEVEL PMIS ACTIVITIES	POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS
Technical and economic analysis	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, dynamic segmentation, network overlay, polygon overlay, point-and-click query, logic query, thematic mapping, layout & report
	Improvements: More efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements, information that is easier to obtain and more meaningful (visually investigated data), better decision-making
Selection of best alternatives	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, dynamic segmentation, network overlay, polygon overlay, point-and-click query, logic query, thematic mapping, layout & report, etc.
	Improvements: More efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements, information that is easier to obtain and more meaningful (visually investigated data), better decision-making

Appendix C

Ideal GIS-PMIS Activities (Project Level) and Related Improvements (continued)

PROJECT LEVEL PMIS ACTIVITIES	POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS
Summarization of future status	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, dynamic segmentation, network overlay, polygon overlay, point-and-click query, logical query, thematic mapping, layout & report
	Improvements: More efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements, information that is easier to obtain and more meaningful (visually investigated data), better decision-making, more efficient and effective communication on the public and legislative levels
Implementation	GIS OPERATIONS: GPS, access and retrieval of data, storage of data, search and sorting of data, classification and reclassification of data, geocoding, on-screen display, thematic mapping
	Improvements: More efficient and accurate identification of omitted or wrong pavement attributes, verification of spatial accuracy, information that is easier to obtain and more meaningful (visually investigated data), better decision-making

Appendix C

Ideal GIS-PMIS Activities (Project Level) and Related Improvements (continued)

PROJECT LEVEL PMIS ACTIVITIES	POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS
Effects of implementation	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data, dynamic segmentation, network overlay, polygon overlay, point-and-click query, logical query, thematic mapping, layout & report
	Improvements: Information that is easier to obtain and more meaningful (visually investigated data), more efficient and effective communication on the public and legislative levels, more efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements
Updating of data	GIS OPERATIONS: GPS, access and retrieval of data, storage of data, search and sorting of data, classification and reclassification of data, data import and export, on-screen display, thematic mapping
	Improvements: More efficient and accurate collection of data, information that is easier to obtain and more meaningful (visually investigated data)

Appendix C

Ideal GIS-PMIS Activities (Project Level) and Related Improvements (continued)

PROJECT LEVEL PMIS ACTIVITIES	POTENTIAL PRIMARY GIS OPERATIONS TO IMPROVE THE PMIS AND RELATED IMPROVEMENTS
Reschedule measures	GIS OPERATIONS: Access and retrieval of data, storage of data, classification and reclassification of data, point-and-click query, logic query, dynamic segmentation, network overlay, thematic mapping, layout & report
	Improvements: More efficient and effective retrieval of the expected new information, reduction of data input and data storage requirements, information that is easier to obtain and more meaningful (visually investigated data), better decision-making, more efficient and effective communication on the public and legislative levels
Feedback and improvement of models	GIS OPERATIONS: Access and retrieval of data, search and sorting of data, classification and reclassification of data

Appendix D

External Data Providers

Agency	Data Available
Texas Natural Resources Information System (TNRIS) (512) 463-8337 http://www.tnris.state.tx.us/	Most GIS data produced by the various state agencies are cataloged at TNRIS. Some data are actually stored on the TNRIS server. Often TNRIS will provide a link to where the data reside.
Texas Parks and Wildlife Department (TPWD) (800) 792-1112 http://www.tpwd.state.tx.us/	Recreational facilities, biological distributions
Texas Natural Resource Conservation Commission (TNRCC) (512) 239-1000 http://www.tnrcc.state.tx.us/	Topography, hydrography, energy transmission features, water utility, land use/land cover, state-owned lands
Texas General Land Office (GLO) (512) 463-5001 http://www.glo.state.tx.us/	Political and administrative boundaries, biological distribution
United States Geological Survey (USGS) (703) 648-4000 http://www.usgs.gov/	Digital elevation models, digital line graphs, digital raster graphics, NAPP photography
Texas Water Development Board (512) 463-7847 http://www.twdb.state.tx.us/	Topography, hydrography, energy transmission features, land use/land cover, surface geology, floodplains, water wells, environmental features, generalized soils
Railroad Commission of Texas (512) 463-7288, (800) 735-2989 http://www.rrc.state.tx.us/	Oil and gas wells, energy transmission features, original Texas land survey

Appendix E

0-1747 Expert Task Group Meeting

August 6, 1998

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