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16. Abstract

A geographic information system (GIS) is a tool for effectively managing and analyzing tremendous amounts of geographic information. It employs the essential principle of geography to organize in formation and express relationships between real-world phenomena. In recent years, GIS has become increasingly important in supporting decisions made in all sectors of government, including state departments of transportation (DOTs). Because GIS is a technology that is complex, interactive, and evolutionary, its development and implementation demand careful study of such issues as needs, benefits/costs, specifications, and implementation plans.

The Texas Department of Transportation (TxDOT) has been a lead er in managing highway transportation systems. The GIS pavement management information system (PMIS) project will develop a comprehensive guide for implementing the most effective GIS capabilities to support TxDOT pavement management and other transportation-related management. This research will provide comprehensive recommendations for various issues involved in incorporating GIS into the Texas PMIS.

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REVIEW OF CURRENT GEOGRAPHIC INFORMATION SYSTEMS TECHNOLOGY FOR TxDOT PAVEMENT MANAGEMENT INFORMATION SYSTEM

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Research Report Number 1747-1

Research Project 0-1747
Recommend a Geographic Information System (GIS) for the Pavement Management Information System (PMIS)

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. DEPARTMENT OF TRANSPORTATION
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by the

CENTER FOR TRANSPORTATION RESEARCH
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May 1998

IMPLEMENTATION STATAEMENT

The information presented in this report may be used by district personnel interested in GIS/GPS technology or in pavement management systems. This interim report has no implementation items per se; the final report will contain the specific implementation plan.

DISCLAIMERS

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Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Pavements are carrying increasingly more traffic as Texas and the rest of the nation compete in an ever-expanding global economy. At the same time, while pavements are becoming so much more important, the funds available to maintain them have become more restricted. To make the most efficient and effective use of limited state money, the Texas Department of Transportation (TxDOT) is implementing a Pavement Management Information System (PMIS). PMIS is an automated system for storing, retrieving, analyzing, and reporting information useful in pavement-related decision making within TxDOT.

Even though PMIS is an automated system that can quickly retrieve and analyze pavement information, its incorporation with the capabilities of geographic information systems (GIS) has been delayed owing to concerns over cost and departmentwide standardization. Currently, efforts to adopt a GIS for TxDOT are being made at both the department level and the district level. The Information Systems Division (ISD) has established a team to address the requirements, standards, and recommendations for a departmentwide GIS; in the meantime, the Odessa District of TxDOT has a pilot project that is studying several GIS software packages for use with the PMIS to support various decisions in pavement management.

GIS is a tool that allows the effective management and sophisticated analysis of tremendous amounts of information. This tool employs the essential principle of geography to organize information and express relationships between real-world phenomena. In recent years, GIS has become increasingly important in supporting decisions made in all sectors of government and the economy, including state DOTs. Since GIS is a technology that is complex, interactive, and evolutionary, its development and implementation demand careful study of such issues as needs, benefits/costs, specifications, and implementation plan.

TxDOT has been a leader in managing highway transportation systems. The GIS-PMIS project will develop a comprehensive guide for implementing the most efficient and effective GIS capabilities to support TxDOT pavement management and other transportation-related management. This research is aimed at providing comprehensive and quality recommendations for various issues involved in incorporating GIS into the Texas PMIS.

1.2 IMPORTANT CONCEPTS IN GIS IMPLEMENTATION

There are many reasons for using GIS to support the decision-making process in pavement and other transportation infrastructure management (Simkowitz, Zhang 96). The most important reasons generally fall into two major functional groups:

(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 so that diverse databases can be integrated and shared among different divisions of a department.

GIS is a technology that is complex, evolutionary, and expensive. To minimize the economic risks, potential issues must be carefully addressed through needs analysis, specification development, and pilot implementation before initiating any full-scale implementation. In this regard, important concepts and issues that are vital in recommending a GIS for use with PMIS in TxDOT are discussed below.

1.2.1 GIS as an Integration Platform

Transportation management systems have been developed and implemented by state DOTs in one form or another. However, most of the systems were developed and operated as stand-alone or application-specific systems. Owing to the changing characteristics of computer hardware and software, these systems were usually implemented in various configurations. The data structures also varied from one system to another, ranging from the simplest flat files to sophisticated relational databases. The incompatibilities among these systems have caused serious problems in the data sharing and management cooperation demanded by various divisions with state DOTs. Many researchers, in response, introduced the concept of integrated systems.

The advantages of such integrated systems are obvious. Substantial benefits can be potentially achieved through the implementation of an integrated system. These advantages and/or benefits include, but are not limited to, the following: (1) free flow of information, (2) elimination of redundant data, (3) better management solutions, and (4) cost reduction in system development and maintenance. The concept of an integrated transportation management system is illustrated in Figure 1.1, where GIS is the integration platform using location as the integrator.

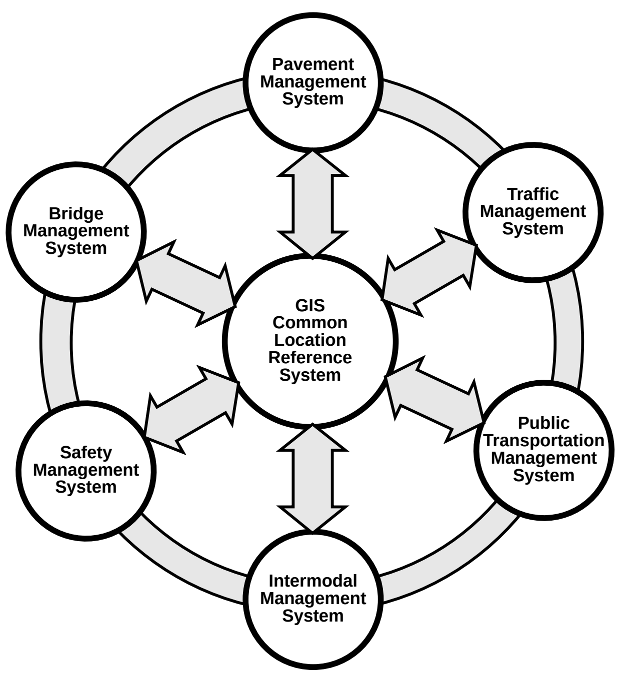


Figure 1.1 Concept of the integrated transportation management system

1.2.2 Locational Reference System

The location referencing system (LRS) is an important part of a pavement management system. Traditionally, different methods of referencing have been used by different state DOTs and/or different divisions in a state DOT. For example, a study conducted by the New Mexico DOT in 1989 found that 10 LRSs were used in its own department. These methods were usually not compatible with each other, making communications among these divisions very difficult. Thus, a common location reference method was needed so that all highway networks could be cross-referenced by all divisions within a state DOT. The two most commonly used methods of referencing infrastructure networks are route-milepost and node-link.

The route-milepost method is most often used for highway networks. In this method, a unique name or number is assigned to each route. With the defined starting point of the route set, mileposts are then given along the length of the route. The Texas Reference Maker (TRM) system developed by TxDOT is based on the concept of route-milepost.

The node-link method has been used widely for all kinds of infrastructure networks. The method defines a network by representing the intersections of a network as nodes and the sections between these nodes as links.

A geographic information system (GIS), which uses a coordinate system to define the location of features in a network, has proved to be the most effective computerized common location reference system. In fact, many transportation and public works agencies have already adopted GIS in their location reference systems.

1.2.3 Videologging, Photologging, and Multimedia Capabilities

Traditional information management systems were developed to handle tabulated data. The advent of GIS technology makes it possible for geographical data to be spatially manipulated and analyzed. In addition, present multimedia technology makes available the incorporation of video, sound, images, and text — all of which can be manipulated and visualized simultaneously to support pavement management decision making. The integration of multimedia with GIS not only greatly enhances the capability of PMS, but also has the potential for a wide spectrum of other engineering applications in transportation infrastructure management. The Odessa District (TxDOT) has launched a pilot project to incorporate pavement images into GIS to support decision making. Research conducted at The University of Texas at Austin has also successfully integrated multimedia technology with GIS in support of pavement and other infrastructure management, as illustrated in Figure 1.2.

1.2.4 Differential Global Positioning

The global positioning system (GPS) is the Department of Defense's satellite navigational system. GPS receivers make extremely accurate timing measurements by means of orbiting satellites, which broadcast their position in the orbit. By trilateration, the receivers' position relative to the earth can be calculated.

There are, however, practical limitations in the positional accuracy of stand-alone receivers, owing both to atmospheric errors and to intentional errors that have been placed in the system by the military. Consequently, in order to achieve a horizontal positional accuracy of 2 meters (6.5 feet) or less, differential-GPS (D-GPS) must be used. D-GPS improves accuracy by having a GPS receiver at a known location rebroadcast its correction observed to the receiver either in real time or by postprocessing.

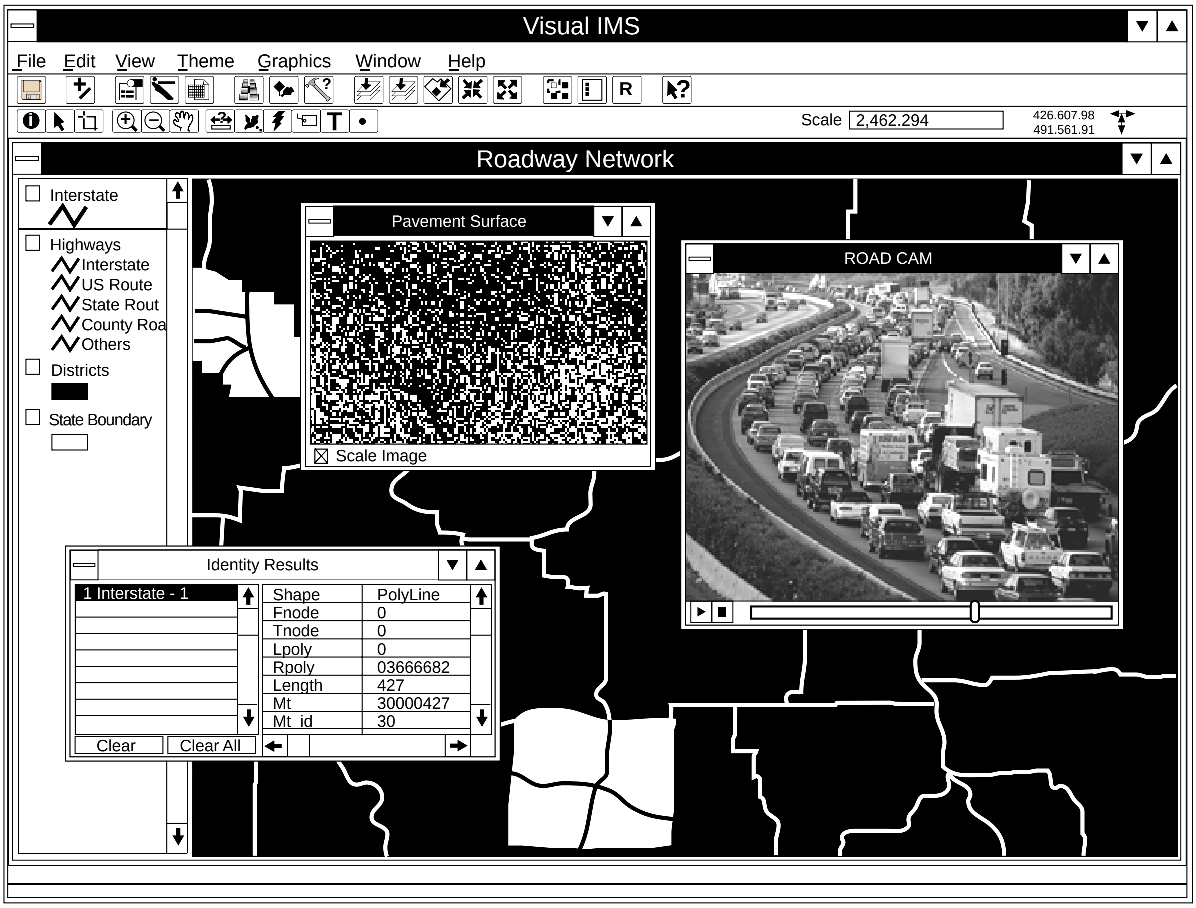


Figure 1.2 The seamless integration of multimedia technology with GIS makes it possible for information in various formats, such as tabular data, videos, sounds, images, drawings, and text, to be used simultaneously to support decision making in pavement management

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 for implementation. Representing a promising technology is a subscription service, John Chance and Associates in Houston, that provides real D-GPS corrections broadcast by satellite anywhere in the U.S. The subscription to this service costs about $800 per year. (TxDOT is already a subscriber.) The L-band receiver, which costs $4,500 provides excellent accuracy throughout Texas. The research team, using a Trimble Geoexplorer handheld receiver and an

ACCQPOINT differential correction FM receiver, is able to collect position and attribute information on notebook computers. The FM scanning receiver receives the same differential correction from 20 base stations but are broadcast as part of the FM carrier signal. The FM receiver for differential correction is cheaper and lighter than satellite receivers, but the measurements must be within range of the FM broadcast station. Currently only 90 percent of Texas is covered by the vendor. Postprocessed differential correction is possible for the base mapping function. Recently, ACCQPOINT has closed its operations, and FM differential correction is available only from DCI. Additional DGPS discussion is provided in Chapter 5.

1.2.5 Dynamic Segmentation

Dynamic segmentation is the ability to store attribute data in a single storage item for multiple and partial segments of graphic elements. For example, if 10 kilometers (6.2 miles) of MoPAC highway are resurfaced in 1995, that information is stored at the start and endpoint; the software understands that each segment or partial segment in between has that attribute associated with it. Otherwise, that attribute database will have to have 20 entries of resurfacing for each one-half kilometer (0.31 mile) segment of the highway. Figure 1.3 shows how different dynamically segmented data can be used.

The question of whether dynamic segmentation will be required will be an important one in analyzing the needs and capabilities of the GIS software. Not all GIS software supports dynamic segmentation. If used effectively, dynamic segmentation can reduce the data input requirements and data storage requirements. Although the power-user may be able to access the data correctly, the low-end users may not be, depending on the level of dynamic segmentation supported by the software used.

Currently, both ESRI ARC/INFO and Intergraph MGE support dynamic segmentation, though the ArcView and VistaMap products support dynamic segmentation differently. Bentley GIS currently does not support dynamic segmentation, though they are negotiating with someone to add this capability to their product. SAS/GIS will not support dynamic segmentation.

1.2.6 Computational Environment

Given the current trend toward computer networking and the fact that integrated transportation management 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 computer networks. Major benefits that can accrue 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. Client/server architecture can serve as an ideal environment for data sharing and information exchange, which state DOTs are increasingly demanding. TxDOT is planning to retool its computers to accommodate client/server architecture using Microsoft Windows NT as its operating systems. This means that any software recommendations should be compatible with the Windows NT environment.

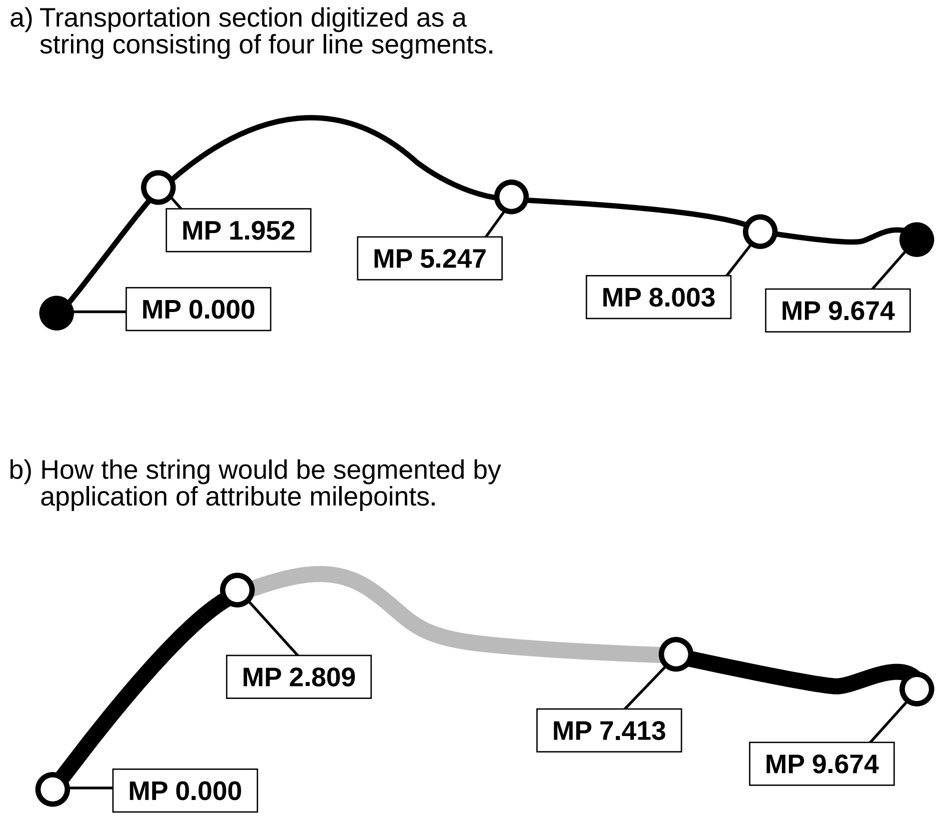


Figure 1.3 Concept of dynamic segmentation

CHAPTER 2. GIS CONCEPTS AND SOFTWARE

2.1 BASIC CONCEPTS OF GIS

As briefly reviewed in Chapter 1, geographic information systems (GIS) are expected to play an important role in the management operations of transportation infrastructure in the immediate and long-term future. This chapter describes basic GIS technology through a discussion of the concepts, components, and structure of a GIS. The development of GIS for pavement and infrastructure management is also discussed.

2.1.1 Definition of GIS

GIS is a marriage of mathematics and computer technology. Spatial mathematics was developed in the 1930s and 1940s, while computer technology expanded rapidly in the 1960s and 1970s. In the 1980s, user-friendly PCs and workstations having sophisticated graphics capabilities became available to a wide range of users at an affordable cost. However, to be useful, a computer requires job-specific software. Thus, computer software has developed from the many different data paradigms listed below, with GIS representing the latest one:

Spreadsheet: Puts numbers on computers and structure summaries
Word processor: Puts words on computers
Database: Structures numbers and words into records, and puts them on computers;
CAD: Puts drawings on computers
GIS: Structures drawings and records into intelligent geographically referenced maps and joins them on computers

Clearly, a GIS is not simply a computer software package for making maps, although it can create high-quality maps in various scales, projections, and colors. A GIS is a special kind of database management system, one with powerful analysis capability. The distinct advantage of a GIS is its unique capability of identifying the spatial relationships among map features.

A GIS does not store a map in any conventional sense; nor does it store a particular image or view of a geographic area. Instead, what a GIS stores is the database from which the user can create his or her desired views or maps and conduct analyses to suit a particular purpose.

2.1.2 Components of a GIS

Several components comprise a GIS, as illustrated in Figure 2.1. The main components of any GIS are its database models. These data models, through either abstraction or simplification, represent the real world. Included in the database models are a geographic database and an attribute database. The descriptive component of the geographic element is maintained in the attribute database, while the positional component of the element, which is described by its geographic coordinates and by its topological relationship to other elements, is maintained in a geographic database.

One of the main functions of a GIS is to establish the relationship between the location of features in the geographic database and their corresponding descriptions in the attribute database. The so-called spatial data operation performs the linkage and analysis between geographic data and attribute data by means of a georelational data structure. A georelational data structure is a hybrid data model that represents locational data in a topological mode and the attribute data in a relational model (Morehouse, 1985).

Some do not consider the user to be a component of a GIS; however, the user does in fact becomes part of the GIS whenever complicated analyses have to be carried out, such as in the case of sophisticated spatial analyses and modeling. These usually require not only skills in selecting and using GIS tools, but also intimate knowledge of the data being used.

2.1.3 Basic Characteristics of Spatial Data and Management

Spatial data have three basic characteristics (Dangermond, 1983):

(1) the positional location (i.e., that location within geographic space where it resides);

(2) the attributes that describe the actual phenomenon or characteristics (e.g., the variable, its classifications, value, name, etc.); and

(3) variation through time.

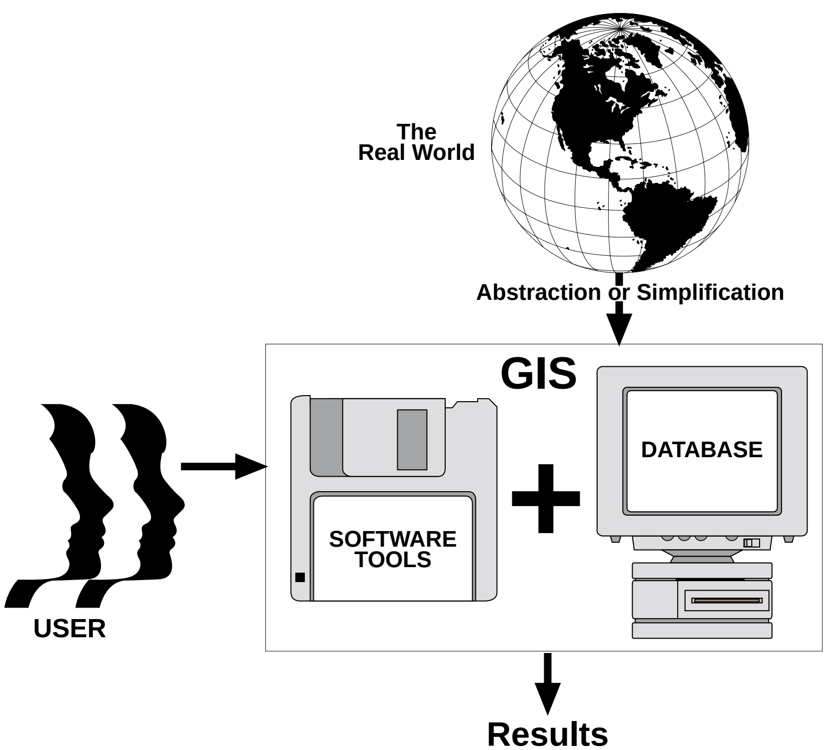


Figure 2.1 Components of a GIS (after ESRI 90)

Figure 2.2 illustrates the relationship of these three elements: location data, attribute data, and variation through time. It can be observed that the management of spatial data can become quite complex because location data and attribute data often change independent of one another with respect to time. Accordingly, effective spatial data management requires that location data and attribute data be independent of one another. That is to say, those attributes can change character but retain the same spatial location, or vice versa.

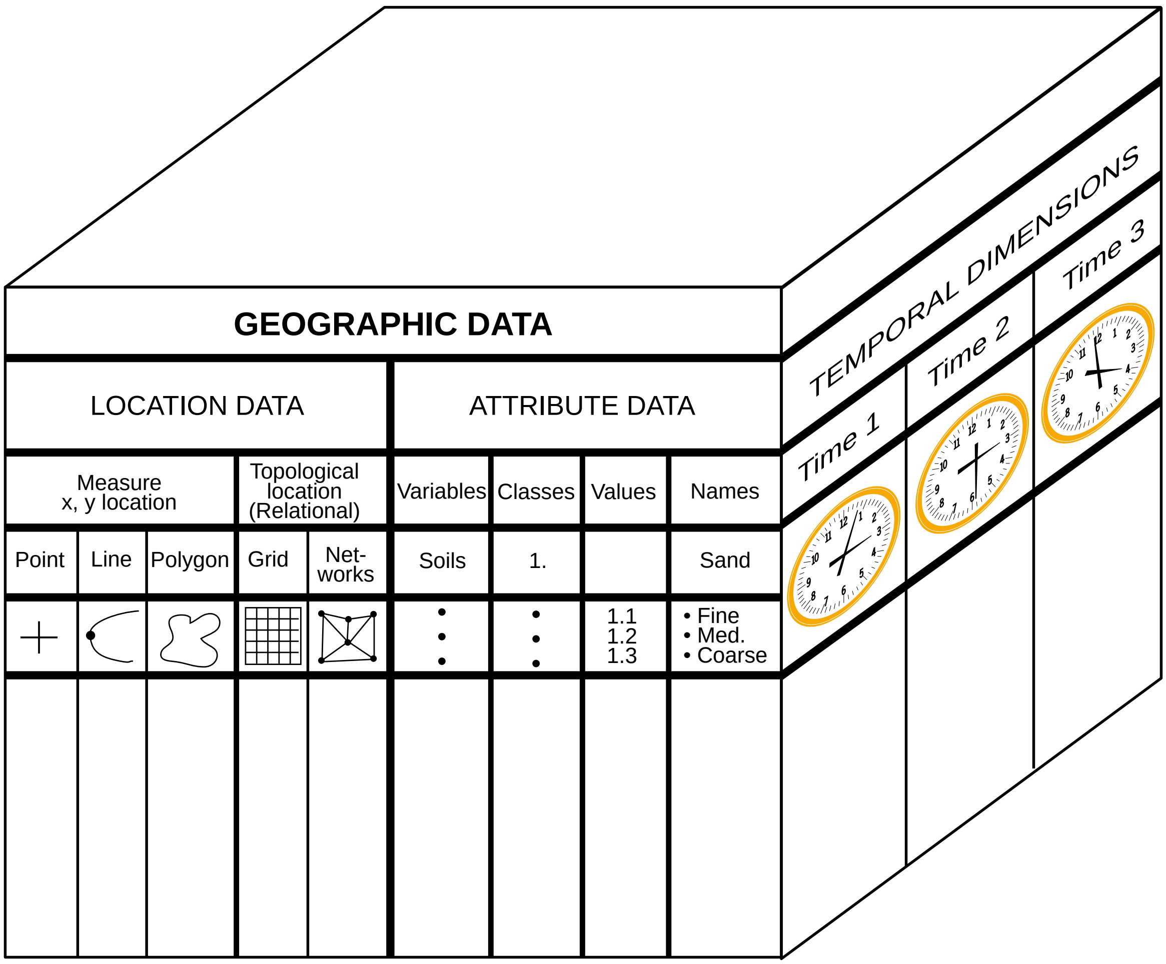


Figure 2.2 Conceptual illustration of characteristics of spatial data (Dangermond, 1983)

To structure a database for geographic information processing, the data management must occur on both location data and nonlocational (attribute) data. Usually there are two ways to handle this problem:

(1) location data are considered to be an additional attribute associated with geographic characteristics;

(2) the geographic location of a characteristic is kept separately from the other attribute data associated with this characteristic, but they can be related to each other with a common item (e.g., segment ID) of the databases.

The latter approach allows for more flexibility with respect to handling data changes — specifically, changes associated with time.

2.1.4 The Geographic Database

The geographic database can be structured into three formats:

(1) grid (raster) format,

(2) vector format, and

(3) triangulated irregular network (TIN) format.

While the TIN structure is better suited for topographic data analysis and is often offered as a separate option in various GIS packages, the grid and vector structures are usually used in the planning and analysis fields (Dueker, 1987).

The grid structure involves the use of a grid mesh to define a regular but arbitrary polygon framework for storing geographic information. The grid acts as a matrix of (x, y) coordinates to represent changes in geography. Figure 2.3 illustrates how an original polygon map overlaid on a grid can be abstracted into row/column values expressing geographic variation. The advantages of such a system are apparent when performing map overlays: They can be performed without preprocessing, as when satellite digital imaging or scanned aerial photographs are used for data input. Disadvantages include increased display time, which is directly proportional to the desired map resolution, and an inherent inability to explicitly represent feature boundaries accurately (Stiefel, 1987).

Data in vector format can be structured topologically, facilitating the storage and retrieval of geographic data and the recording of spatial relationships of geographic features. Figure 2.4 shows how a typical polygon/network map can be abstracted into nodes, links or line segments, and polygons. By numbering these links and associating them with nodes and as polygons on the right and left, a basic map notation system can be derived (Dangermond, 1983). Since geographic features in vector-based GIS are represented by lines, their resolution is limited only by the resolution of output devices. However, map overlaying involves determining areas of overlap between basemap and overlay map elements by comparing polygon area and determining points of intersection. The time taken for this operation is a function of map complexity and of the computer processing speed. In addition, scanned photographs and satellite images have to be converted into vector format before they can be analyzed by a vector-based GIS (Fernando, 1989).

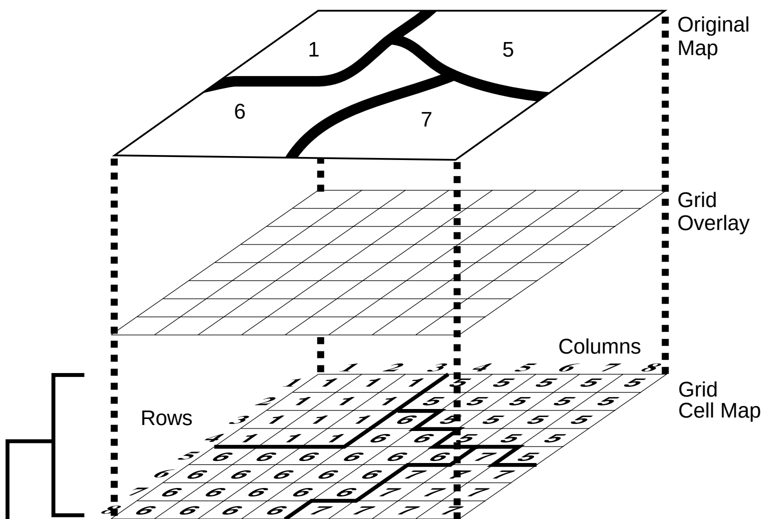
2.1.5 The Attribute Database

As discussed previously, attribute data refer to all descriptive nongeographic information (e.g., variables, values, names, classes, etc.) that identifies a geographic feature. All GISs utilize some kind of database management system (DBMS) to facilitate the handling of attribute data. The management systems include formatted data entry, data editing, data processing and manipulation, data query, and report generation.

The three best-known approaches for structuring dBases are:

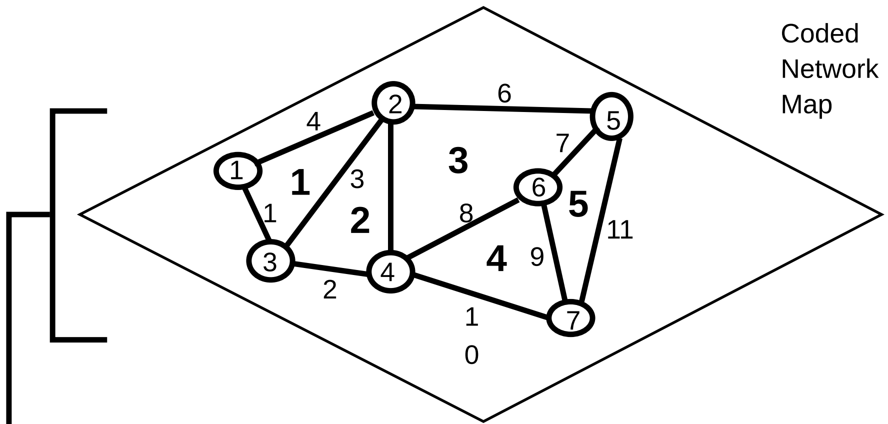
(1) the hierarchical approach,
(2) the relational approach, and
(3) the network approach.

In a hierarchical DBMS, attribute data are organized using a hierarchical data structure where all information related to a geographic feature is linked together by pointers stored in the data record (Stiefel, 1987). This structure is useful in applications where a rigid data structure is desirable.



Row	Column	Value
1	1	1
1	2	1
1	3	1
1	4	5
1	5	5
1	6	5
•	•	•
•	•	•
•	•	•
•	•	•

Figure 2.3 Illustration of transforming map into grid database files (Dangermond, 1983)



Link #	Right Polygon	Left Polygon	Node 1	Node 2
1	1	0	3	1
2	2	0	4	3
3	2	1	3	2
4	1	0	1	2
5	3	2	4	2
6	3	0	2	5
7	3	3	5	6
8	4	3	6	4
9	5	4	7	6
10	4	0	7	4
11	5	0	5	7

Topologically Coded Network and Polygon File

Node #	X Coordinate	Y Coordinate
1	23	8
2	17	17
3	29	15
4	26	21
5	8	26
6	22	30
7	24	38

Figure 2.4 Illustration of transforming map into vector files (Dangermond, 1983)

In a relationally structured DBMS, all feature information is kept in tables where the relationships between entities are maintained by indexes that point to data fields. Related data associations are formed according to specific data interrelationships. The relational approach, although slower in data retrieval than its hierarchical counterpart, offers a more flexible data structure (Fernando, 1989).

With a network-based DBMS, data are represented by records and links, as in a hierarchical structure. However, a network is a more general structure than a hierarchy because a given record occurrence may have any number of immediate superiors (as well as any number of immediate dependents). The network approach allows a DMBS to model a many-to-many correspondence more directly than does the hierarchical approach.

2.1.6 The Georelational Data Structure

One of the important functions of a GIS is to establish the relationship between the location of features to the characteristic descriptions of those features — in other words, to relate the location of features in the geographic database to corresponding records of descriptions and additional information about those features in the attribute database. The linkage of a feature's locational data to its attribute data is called a georelational structure (Morehouse, 1985). According to Morehouse's definition, a georelational data structure is a hybrid data model that represents locational data in a topological model and represents attribute data in a relational model. In order to establish such a georelational structure, a one-to-one relationship is required between the locational record of a feature in the locational database and the descriptive record of that feature in the attribute database (Dueker, 1987). It is this linkage of a one-to-one relationship that allows a feature's attribute values to be displayed on the map.

2.1.7 Two Basic Types of GIS

The two types of GIS are based on the structure format of the geographic database discussed previously. These include: (1) raster GIS, and (2) vector GIS.

In a raster GIS, spatial information is represented in the form of regular grid cells. The advantages of raster GIS are apparent in performing map overlay, though it cannot explicitly represent feature boundaries. While it has the potential for land-use mapping, it is not often used in transportation applications (Fletcher, 1992).

The geometric elements in a vector GIS are put on a Cartesian plane. Point, line, and polygon, as described below, are the three basic units to define any map features:

point : Point feature is represented by a discrete location defining a map object whose boundary or shape is too small to be shown as a line or area feature. Points have position.

line: Line feature is a set of ordered coordinates that, when connected, represent the linear shape of a map object too narrow to be displayed as an area. Lines have magnitude and direction.

polygon: Polygon feature is a closed figure whose boundary encloses a homogeneous area. Polygons are closed connections of connected lines.

Bus stops can be indicated as points, pavement segments can be represented with lines, and lakes can be defined by polygons. The combination of points, lines, and polygons can describe any map feature. Vector GIS is appropriate for application in the management and analysis of transportation facility infrastructure.

Both raster GIS and vector GIS have their advantages and disadvantages. Table 2.1 provides a brief comparison of raster GIS and vector GIS with regard to their major characteristics and potential areas of application (Fletcher, 1992).

2.1.8 GIS for Pavement and Infrastructure Management

There are several reasons for using GIS technology in pavement and infrastructure management. First of all, with the development of computer technology, more and more users desire a management system that can access, manipulate, analyze, display, and report information on road network and other infrastructure graphically. This is regarded as preferable to the traditional systems that process information in tabular format.

Second, the dramatically decreasing cost of computer hardware makes GIS technology affordable to more users than ever before. GIS can be run on most stock PCs.

Table 2.1 Comparison of raster GIS and vector GIS

Raster GIS	Vector GIS
• Divide study area into cells (each cell a single value) • Space filling — all locations in the space have to be referenced • Every location in the study area corresponds to a cell in the raster • Simpler data model	• Discrete objects connecting line segments • Vector objects do not necessary fill space — not all locations in the space have to be referenced (but polygons exhaust space) • Tells where everything occurs; gives location to an object • More complex model
<u>Most Used</u> • Natural boundaries	<u>Most Used</u> • Man-made infrastructure
<u>Advantages</u> • Simple • Relatively fast • Convenient for image	<u>Advantages</u> • Good cartographic precision • No data redundancy
<u>Disadvantages</u> • Sacrifice details • Edge effects (jagged edges)	<u>Disadvantages</u> • Computationally intensive • More complicated • Data conversion — available data may be cell based

Third, various government agents or private companies have produced a multitude of ready-to-use digital geographical data. These data are usually available to users at a very low cost or even at no cost. Appropriate utilization of these data with GIS technology will obviate the time-consuming process of generating X and Y coordinates to produce a map. Furthermore, these digital geographical data are usually real-world latitude/longitude coordinates, which are useful for map manipulation and utilization of such technology as Global Positioning Systems (GPS).

Finally, it is worthwhile to address the problem by taking a look at a coordinated municipal infrastructure management system. For effective and efficient management of the municipal infrastructure, a centralized database having a common location reference system is extremely important for providing communication among different subsystems. Usually all the subsystems cannot be established simultaneously. It is important to use GIS technology to generate a common location reference environment to develop each subsystem so that the developed subsystem will be consistent with future subsystems.

2.2 GIS SOFTWARE

Today there is a wide range of GIS software packages that are marketed as tools for developing GIS applications. The most widely accepted GIS packages in the transportation community are the GIS families from Environmental Systems Research Institute, Inc. (ESRI) and Intergraph. Other new GIS products that have potential for the transportation community include Bentley GIS and SAS/GIS. Both ESRI's GIS products and Intergraph's GIS are used extensively at the Center for Transportation Research for various transportation research projects.

2.2.1 ESRI GIS Product Family

As one of the leading GIS software manufacturers, ESRI provides a family of flexible GIS software products designed for use by different levels of users within different computational environments. All the software architectures in ESRI's GIS family can be integrated with 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 capabilities. The open data architecture of ARC/INFO and ArcView allows the use of data obtained from most of the database management systems in the GIS application. Table 2.2 summarizes the key features of ARC/INFO, ArcView, and PC ARC/INFO.

2.2.2 Intergraph GIS Family

Key products of the Intergraph GIS family are MGE and VistaMap. MGE is a fully functional GIS package based on the Microstation core (but one having an open architecture system). There are certain advantages in using the MGE product: It is Windows compliant, it is an integrated suite of software that runs on Windows NT, it has the ability to import and export in other formats, and it can run different relational databases, including Oracle, Infomix, Ingres, Sybase, and RDB, on different servers. Given its complexity, MGE is more difficult to learn than some GIS software. However, the data files are binary compatible among UNIX, Windows, and Macintosh platforms. Utilities are also included for converting data from such other GIS applications as ARC/INFO, MapInfo, Atlas*GIS, etc., into MGE format. VistaMap is a read and analysis package that ensures that users cannot change the graphic data. It is similar to ERSI's ArcView. In fact, VistaMap automatically imports files in different projections and displays them simultaneously in the projection of the first file. GeoMedia, an updated product, will replace VistaMap with enhanced functionality this summer.

Table 2.2 Key features of ARC/INFO, ARCVIEW, and PC ARC/INFO

Software Product/ Characteristic	ARC/INFO	ArcView	PC ARC/INFO
Supported Hardware	Leading UNIX, Workstations, VAX Computer	Intel-based and Macintosh Personal Computers, UNIX Workstations, VAX Computers	Intel-based Personal Computers
Supported Operating Systems	UNIX, VMS, Windows NT*	Windows 3.1, NT, UNIX, System 7, Open VMS	DOS, Windows
Supported DBMSs	ORACLE, INGRES, SYBASE, INFORMIX, INFO	dBASE, ASCII Text, INFO, Leading SQL Databases	dBASE and Compatibles
Script Language	ARC Macro Language (AML)	Avenue	Simple Macro Language (SML)

*To be released soon.

2.2.3 Bentley GIS

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 under the UNIX environment. With its SQL Manager, Microstation GeoGraphics allows users to create and manage links between map features and nongeographical attributes from a wide variety of databases, including Microsoft Access, Microsoft SQL server, Oracle, and Informix. It works with MGE files and has a smaller package of spatial analysis tools than MGE. However, it is a fully functional GIS and is sort of an "MGE Light" GIS software.

2.2.4 SAS/GIS

SAS Institute, Inc., has recently released its GIS capability under the name of SAS/GIS. The SAS/GIS software package maintains both attribute data and spatial data. It allows the analysis results from SAS to be used directly for displaying and mapping. Sophisticated spatial analysis capability is not available with SAS/GIS.

CHAPTER 3. PRELIMINARY REVIEW OF IMPLEMENTATION ISSUES

3.1 PARADIGM SHIFTS OF COMMUNICATION

Human communication has undergone two paradigm shifts (epochs): “nonverbal to verbal” and “verbal to historic;” a third shift — from “historic to digital” — is currently underway. Each of these three epochs is marked by the mode of its communication and how the communication is recorded. The communication mode and record type for each epoch is summarized in Table 3.1 (Klein, 1992).

Table 3.1 Paradigm shifts of communication ages (after Klein, 1992)

Age (EPOCH)	Communication Mode	Record Type
	No Words (Signals)	Instinct
Nonverbal	Spoken Words	Recollection (Memory)
Verbal (Oral)	Written Words	Written Document (Book)
Written	Magnetic	Dynamic Document (Electronic copy)
Digital		

The shift from the “nonverbal” epoch to the “verbal” epoch accelerated human cultural evolution. The shift from “verbal” to “historic” changed human communication from a story-telling mode to a written mode. With this shift, knowledge could for the first time be precisely “remembered” beyond the life of the originator. In the present “digital age,” which began in the 1940s, archived record keeping shifted from manual to digital processing; the result is that, today, both knowledge and experience can now be magnetically archived. Furthermore, knowledge and experience cannot only be precisely remembered, but also dynamically assembled and interpreted for further applications (Klein, 1992). Examples of such achievement include the development of artificial intelligence (AI) and expert systems.

This new epoch, the “digital age,” fundamentally changed the way people communicate. Digitally (magnetically) archived information of past experience improved, among other things, the decision-making process. Geographic information systems (GIS), which are a recent extension of this technology, has the capability of integrating and interpreting cartographic as well as nongraphic information to support management decision processes at different levels and in various fields.

3.2 CHARACTERISTICS OF THE DIGITAL AGE

The digital age is defined by certain characteristics that have had an evolutionary effect on traditional ways of managing data and making decisions (Klein, 1992). The characteristics of this new epoch, with particular emphasis on GIS, are discussed below.

3.2.1 Computation

The primary and most obvious characteristic of the digital epoch is the dramatic decrease in the time required to perform a computation. However, many data management and decision-making processes were not significantly or widely affected by this advantage until the cost of an individual computation had been greatly reduced through the advent of personal computers (PCs) (Klein, 1992).

The average cost of a single computation can be determined by all computations performed at any one time divided by the total human effort required to produce the equipment and to provide the support activity (e.g., electricity, data entry, overhead, etc.) (Klein, 1992). Figure 3.1 conceptually shows the evolutionary process of the average cost of a single computation through time (Klein, 1992). As illustrated, the cost to perform the first computation was infinitely large. As technology improved, the average cost of a single computation was gradually reduced. This reduction, however, was gradual until the proliferation of personal computers (PCs) in the 1980s, when the cost dropped dramatically. As indicated, with further improvement in technology and the continued proliferation of PCs, the average cost of computation will eventually become infinitely small (Klein, 1992).

3.2.2 Data Archival

Compared to the "Historic Age," the digital format of data archival has two significant advantages. One is the dramatic increase of data handling speed and the other is the greatly improved durability of data and the analysis results from these data. Basemap data, attribute data, analysis results, and recommendation plans produced today can be reproduced thousands of years from now without any deterioration. The detail, precision, and colors of the maps will be exactly the same as the day they were first produced.

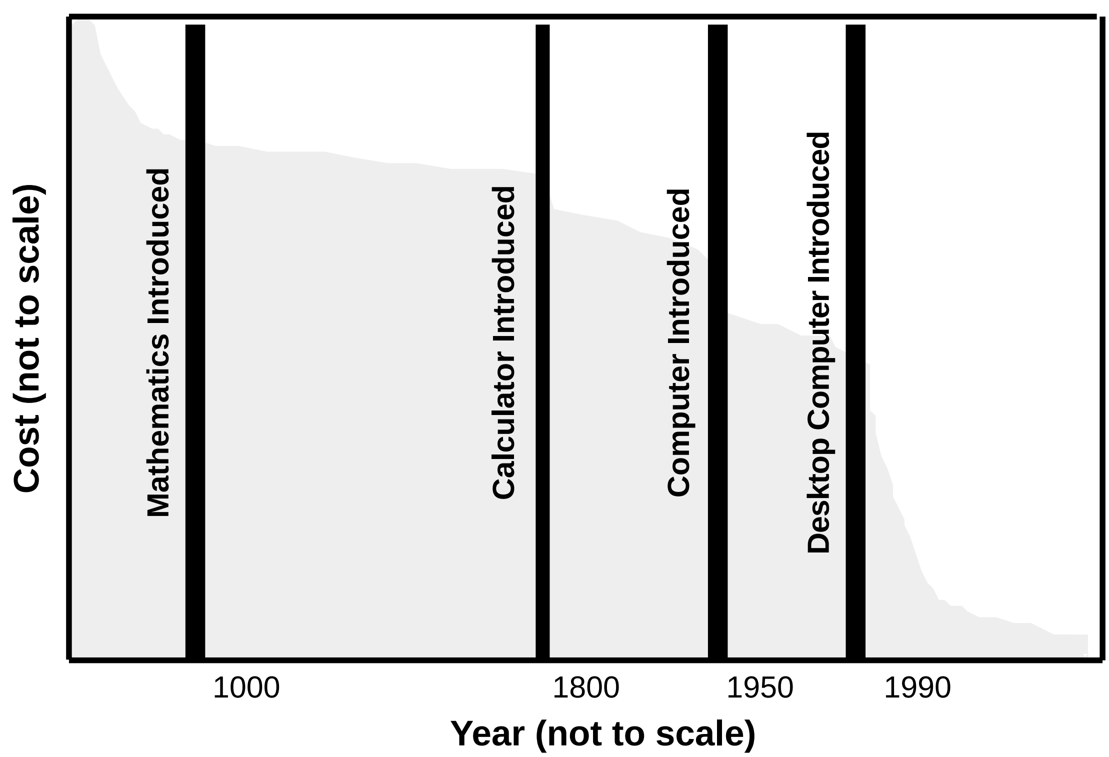


Figure 3.1 Conceptual illustration of decreasing computation costs (after Klein, 1992)

3.2.3 Data Retrieval

Digital data changed the traditional ways of producing and reproducing maps. Once the map data have been put in digital format, they can be retrieved with far greater ease and lower cost than traditional manually maintained map sheets. The improving technology and decreasing cost of storage media make digital geographical data accessible to more users than ever before. Ready-to-use digital geographical data, as discussed in Chapter 4, can be obtained from various local, regional, and federal agencies or from private businesses at a relatively low cost.

3.2.4 Data Display

Associated with the advancement of computer technology, graphical display devices were and are continually being improved to present data in an easily understood graphical format. The traditional way of presenting data in a tabular format has been changed. The costs of large format display devices are also continually decreasing. These advancements make it technically and economically feasible to bring the real world into computers to support various decision-making processes.

These characteristics discussed previously make the implementation of GIS more feasible both technically and economically than at any other time in history. Digital data communications might also eventually drive the implementation of GIS technology.

3.3 ADOPTION PROCESS OF GIS

Like the diffusion of any other technological innovation, there is an adoption or diffusion process for GIS technology. It is important for the decision makers to understand such a process so that the best implementation plans and strategies can be generated to meet both short-term and long-term needs.

3.3.1 Diffusion Concept

Diffusion is the process by which a product, idea, or service moves through a potential market or through a group of potential users. The diffusion for many innovations follows a sequence that begins slowly, then gradually speeds up. When the speed reaches a certain maximum value it slows down again and eventually approaches zero. As a percentage of the total number of adoptions versus time coordinates, a normal bell-shaped curve is produced. If the percentage of adoptions is changed to the accumulated percentage of adoptions, the diffusion process produces an S-shaped curve. Figures 3.2(a) and 3.2(b) illustrate such processes.

The adoption process can also be interpreted as a technological life cycle. One technology life cycle can be recognized as a six-stage cycle (Figure 3.3): (1) decision to adopt, (2) actual adoption, (3) "honeymoon," (4) increasing dissatisfaction, (5) review of alternatives, and (6) subsequent adoption of a new or revised product. The other technology life cycle can be described as a step-by-step improvement process, such as the development of pavement management systems (Figure 3.4) (Haas and Hudson, 1982). Clearly, the latter is preferred for the adopted technology.

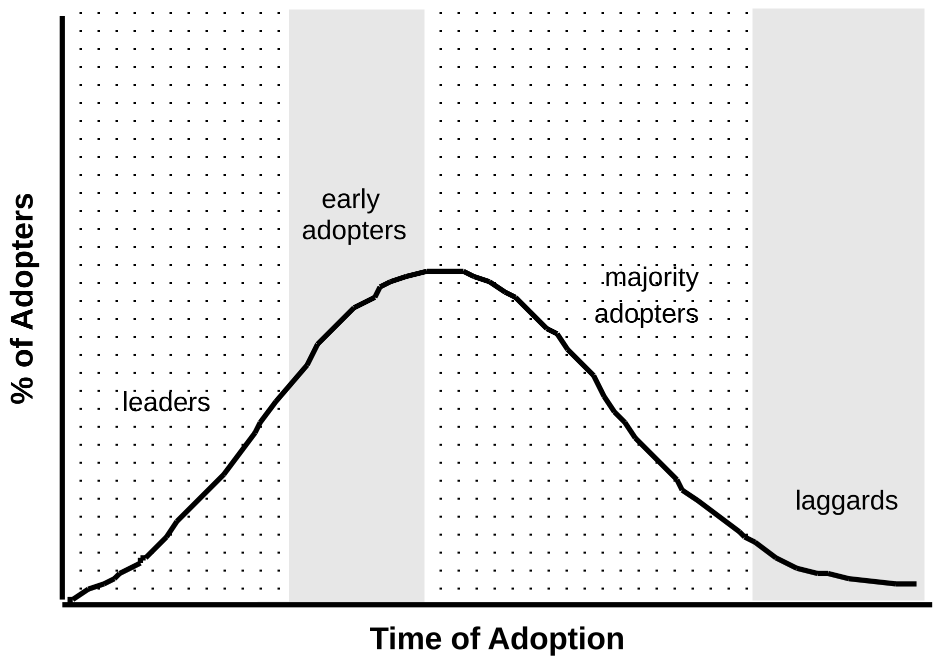


Figure 3.2(a) Adoption curve (after Lane 90)

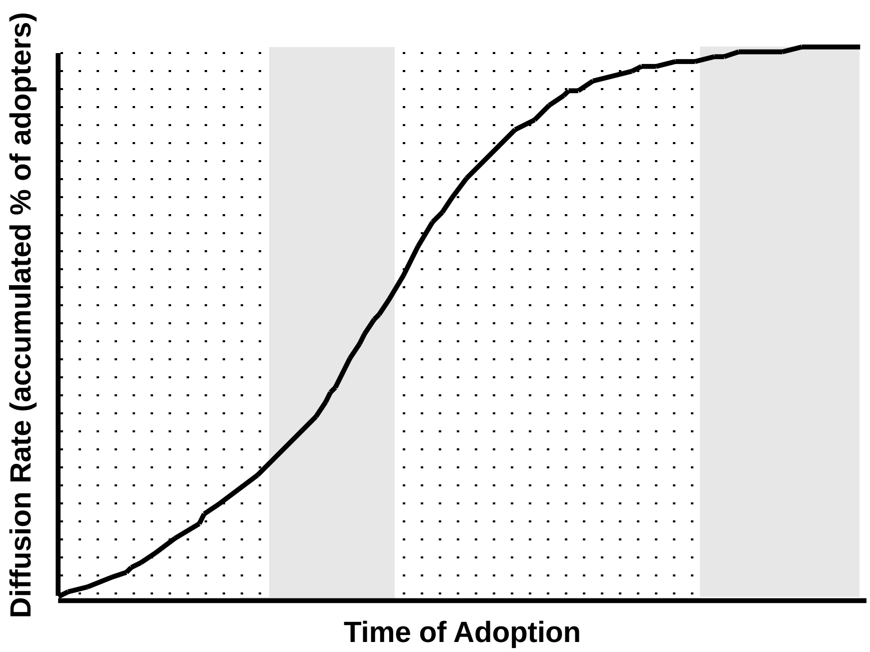


Figure 3.2(b) Diffusion curve (after Lane 90)

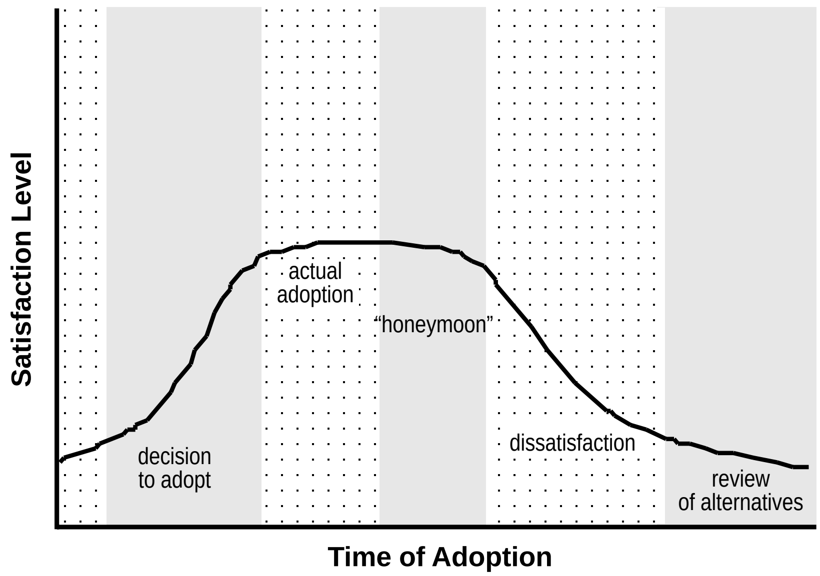


Figure 3.3 Conceptual illustration of adoption life cycle (after Lane 90)

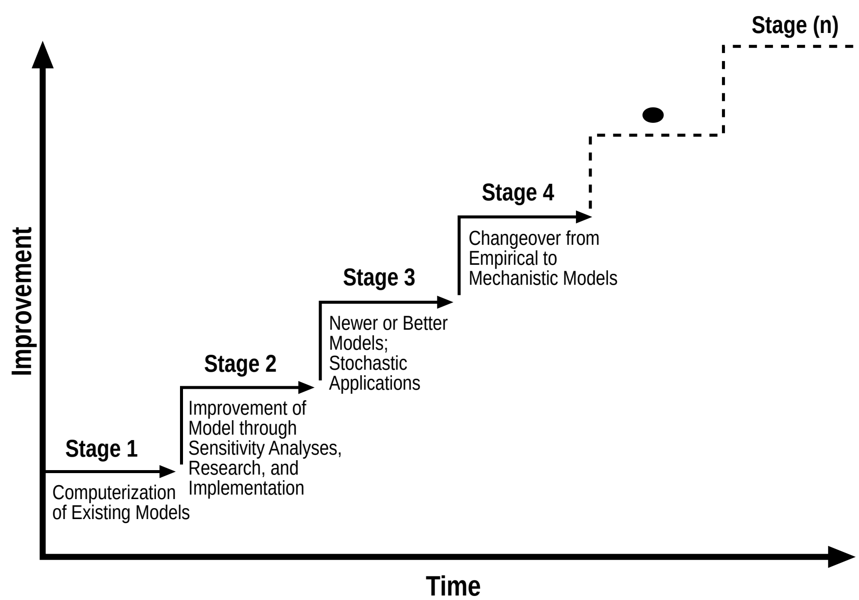


Figure 3.4 Step-by-step improvements in PMS development (after Haas, 1982)

3.3.2 Basic Elements of Diffusion Process

Various factors affect the characteristics of the diffusion process. Some factors stimulate the adoption and others retard the adoption. Carriers, barriers, and leaders are the three basic elements of the diffusion process identified by Rogers and other diffusion researchers (Lane, 1989). These three elements are described below.

Carriers: Carriers are factors that assist or encourage adoption of new technology. Among the most commonly observed factors are:

1. Money: the availability of funds is always a key issue for the adoption of any new technology. New technology cannot be adopted without proper funding.
2. Management directives: good and scientific management directives normally encourage the adoption of new technology.
3. Service or product failures: previous service or product failures can allow new technology to be considered to replace old technology.
4. Presence of champions: champions occurring in a field can prompt the adoption of new technology in order to achieve success.
5. Actions of competitors: the adoption of new technology by competitors often influences an agency to adopt new technology.
6. New market creation: new technology is likely to be accepted at the time when a new market is created.
7. New management approaches: the change of management approaches will stimulate the adoption of new technology.
8. Staff ideas: staff ideas normally play an important role in technology changes.
9. Literature searches: literature usually documents technology improvement and introduces ideas for adopting new technology.
10. External assistance: assistance from external sources such as technology vendors, universities, etc., will accelerate the adoption of new technology.
11. New technology: implementation of certain new technologies will require the adoption of certain other new technologies.
12. Legal orders (laws, ordinances, etc.): new technology adoption is forced through the issuance of legal orders.

Barriers: Barriers are factors that slow or stop the process of innovation. These barriers are described below.

1. Lack of communication: technology development in one’s field is not fully realized or understood.
2. Turf battles: different divisions in an agency try to protect their own “territory,” which makes new technology impossible to be implemented.
3. Lack of fiscal reserves: new technology cannot be adopted and implemented without sufficient funds.
4. Outdated technology: innovation cannot be carried with outdated facilities.
5. Ignorance of one’s field: intensive interest plays an important role in innovation or adoption of new technology.

Leaders: Early innovators in an area are called leaders, while those who tend to lag behind are called laggards. The factors affecting the difference between leaders and laggards most often include:

1. Education or experience: a well-educated person with rich experience normally has a stronger desire for innovations and adoption of new technologies.
2. Professional expertise: deep knowledge in one's field will always stimulate innovation or adoption of new technology.
3. Awareness of technology: fully understanding existing technologies will help to evaluate and adopt new technology.
4. Negotiating or managing skills: success and innovations are to some degree related to one's negotiating or managing skills.
5. Views about innovation: positive view of innovations will always encourage innovations and adoption of new technology.

3.3.3 Variables Affecting the Adoption of GIS

Lane studied the factors affecting the adoption of information systems in the state departments of transportation (DOTs) based on diffusion theory (Lane, 1989). The study was based on responses from twenty-six state DOTs to a questionnaire covering four large information systems, including computer-aided drafting and design (CADD), geographic information systems (GIS), roadway data, and capital project management.

Six categories of variables that might affect the adoption of computerized information systems in state DOTs have been identified. These variables may well have the same effect on the adoption of GIS in urban and city areas:

1. System characteristics (functionality): the functionality of a particular system is a measure of how well the system serves the user's needs. While those systems with a high measure of functionality are likely to survive and to be maintained, those with a low measure of functionality are subject to be updated or replaced.
2. Agent characteristics: the size and spending capital of an agency have been proposed as having positive effects on the rate of diffusion in some studies.
3. Management characteristics: knowledge of current literature in one's field of work, conference attendance, and the length of time at a position within the same agency (Lane, 1989) are all considered as having an effect on innovation.
4. Degree of interaction: the degree of interaction of the agent with nearby universities and communication with other similar agents or groups have been used as explanatory variables in some diffusion studies (Lane, 1989).
5. Vendor characteristics: vendor's attitude and assistance may also play a part in adopting a system (Lane, 1989). After-sale service and support, product price, and other similar issues will often influence the adoption of a product.
6. Governmental factors: the availability of government funding can prompt the adoption of a system that otherwise would be deemed too costly to be adopted. The introduction of a government mandate can also accelerate the adoption of a system (Lane, 1989). As an example, the Federal Highway Administration (FHWA) has required each state DOT to implement a Pavement Management System (PMS) no later than 1993.

3.4 PERSONAL COMPUTERS VERSUS WORKSTATIONS

Personal computers (PCs) and high performance workstations are the two types of computers that are used in most civil engineering offices. The first issue to be addressed in implementing a GIS is whether to select a PC or a workstation as the platform. While both PCs and workstations have their advantages and disadvantages, the choice should be made with the consideration of needs assessment and overall costs/benefits analysis. The characteristics and performance of PCs and workstations are discussed and compared below.

3.4.1 Power to Handle Applications

Although PCs have evolved into powerful machines for solving complex engineering problems, the data sets they can handle are smaller than those processed by a workstation (Tonias, 1992). This is not due to computer hardware, but rather to the operating system of the PC, or specifically, DOS. While the development of 386/486 level PC opened the door for addressing huge amounts of memory, the DOS limitation of 640k bytes still exists (Will, 1992). This is not to say that PCs have low value for engineering applications; in fact there are a wide variety of engineering application packages written for PCs. All the top GIS vendors, such as ARC/INFO, GisPlus, and AtlasGIS, have GIS packages especially designed for PCs. Also, a number of third-party vendors have developed DOS memory extenders that allow the PC application developer to take advantage of the large address space of the 386/486 chip (Will, 1992). Other vendors have developed C and FORTRAN compilers, as well as graphical device drivers that also utilize the memory extender software.

3.4.2 Costs

Workstations, without question, offer a platform that can perform operations much faster and handle data sets larger than PCs, but the downside for workstations is the cost. The cost of a workstation is usually twice that of a PC, although the differential is shrinking (Will, 1992). Besides the hardware cost differential, there is also a software cost differential. For example, the cost of ACR/INFO for a PC station is less than $6,000, while its counterpart for workstations costs from $18,000 to $88,000 depending on the CPU. In addition, the intensive competition of the PC market makes a wide variety of PC products available to users at inexpensive costs.

3.4.3 Performance

Performance is judged by the number of instructions the computer can handle per second, usually in units of millions of instructions per second (MIPS). Most 486-based PCs today offer 5 to 8 MIPS while most workstations run at 17 MIPS and up (Will, 1992). The performance of some workstations has almost quadrupled with recent technology advancement. But, given their ease of operation, PCs are still excellent machines for most engineering uses.

3.4.4 Portability of Software

Another differential between PCs and workstations is the portability of software. Though it has memory limitations, DOS for PCs has been standardized among almost all PC manufacturers. UNIX, the operating system for most workstations, however, is not. This fact brings out the issue of software portability. For example, the PC version of the GIS package can be executed on almost any PC without regard to its manufacturer. However, for workstations this is not always the case.

3.5 COMPUTER HARDWARE AND DATA STORAGE

3.5.1 Workstations

The current state of the art of computer hardware for workstations is an Intel Pentium Pro 200 Mhz processor with 16 KB Level 1 internal cache, 256 KB Level 2 internal cache, support for dual processors, PCI bus, 128-bit memory architecture, 64 MB 60ns ECC DIMM memory, 10/100Base-T PCI LAN interface, Ultra SCSI controller, 2.1GB Ultra SCSI disk drive, 16X CD-ROM, 64-bit PCI graphics accelerator, high resolution monitor, 3-year limited warranty (1-year on-site, next-business-day; 2-year carry-in parts and labor), and Windows NT Workstation 4.0 operating system. Additional memory may be added based on application needs. Additional processing power can be achieved by adding a second processor.

The near-term future for workstations will be the Intel Pentium Pro II processor with MMX technology. Dual-processor support will again be supported. Quad-processor support is expected. The other workstation hardware is not expected to change dramatically in the near future.

The long-term future for workstations is the P7 processor being jointly developed by Intel and Hewlett Packard. This processor is expected to be twice as fast as the Pentium Pro II processor. Dual- and quad-processor support will again be supported. Six-processor support is expected. Other workstation hardware is not expected to change dramatically in the long-term future.

3.5.2 Servers

The current state of the art of computer hardware for servers is a Dual Intel Pentium Pro 200 Mhz processor with 16 KB Level 1 internal cache, 256 KB Level 2 internal cache, support for quad processors, PCI bus, 128-bit memory architecture, 128 MB 60ns ECC DIMM memory, 100Base-T PCI LAN interface, Ultra SCSI controller, 2.1GB Ultra SCSI disk drive, 16X CD-ROM, 64-bit PCI graphics accelerator, high resolution monitor, 3-year limited warranty (1-year on-site, next-business-day; 2-year carry-in parts and labor), and Windows NT Server 4.0 operating system. Additional memory may be added based on application needs.

The near-term future for workstations will be the Intel Pentium Pro II processor with MMX technology. Quad-processor support will again be supported. Six-processor support is expected. Other workstation hardware is not expected to change dramatically in the near future.

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3.5.3 Data Storage

The current state of the art of computer hardware for data storage is a PCI RAID controller with up to six disk drives (when using RAID 5, the available storage is the capacity of the five drives while the sixth drive provides hot swappable on-line repair of single drive failures without taking the system off-line or down), high performance 1" high disk drives with 4 GB storage, high performance half-height disk drives with 9 GB storage, high performance full-height disk drives with 23 GB storage, Iomega 100 MB removable media Zip drives, Iomega 1 GB removable media Jazz drives, 4mm tape drives with hardware compression, 8mm tape drives with hardware compression, Digital Linear Tape, and network CD-ROM servers that can support up to 250 CDs online.

The near-term future of data storage technology is not expected to change.

The long-term future for data storage is the approximate doubling of storage capacity within a given height, increased use of Digital Linear Tapes (because of their large data storage capacities), and the use of Digital Versatile Disks (DVD), which is the newest CD-ROM replacement standard with 7-14 times the storage capacity.

3.6 PRACTICAL ISSUES OF GIS IMPLEMENTATION

Previous sections have introduced background information useful in justifying the various decisions for GIS implementation. The following sections present practical principles and considerations for implementing this technology.

3.6.1 Basic Principles at the Age of Technological Change

It should be realized that this is an age of major and rapid technological change (NCHRP, 91). These changes will affect various aspects of the decision-making process, including transportation infrastructure management. To successfully develop plans and strategies for the implementation of GIS capabilities, it is important for the agency to closely follow two general principles that have been identified by the NCHRP under project 20-27 (NCHRP, 91). These are:

(1) GIS or any other new technology should be adopted and exploited on the basis of need rather than on technology availability. The reason for adopting such a technology should be that it meets some specific, well-defined need, rather than that it is a new technology or it is likely to serve some "good" but ill-defined purpose. Need-driven strategies require good knowledge to make intelligent decisions about the timely adoption of new technologies. Technologies should be adopted at the time they have become sufficiently cost-effective and reliable for certain needs rather than when they may meet some short-term needs but may be abandoned when another prospective technology becomes sufficiently cost-effective and reliable. Some knowledge of technology diffusion as discussed in the pervious section will be definitely helpful on this issue.

(2) Data integration may play the most important role for the effective exploitation of GIS technology. While GIS technology has reached a mature state, the effective use

of it depends largely on data integration issues. GIS should no longer be treated as a special case and implemented for isolated applications on isolated equipment; rather, it should be connected to the agency's general data environment so that information can be shared or exchanged among different divisions.

3.6.2 Platform Selection

Section 3.3 has provided the basic characteristics and performance comparison of PCs and workstations. Besides the various advantages and disadvantages of these two types of machines, the selection of platform should also consider the size of the city and the volume of data that is going to be processed. The volume of data to be processed is generally proportional to the size of the city. While high performance PCs might be a good choice for most cities, workstations should be expected for some cities where PCs are not effective enough to handle extremely large volumes of information.

Another issue associated with platform selection is the assessment of existing resources. Before acquiring any new facilities, existing computer capabilities and existing database characteristics should be fully evaluated so that there will be no redundant facility or extra work for data transformation.

It should be pointed out that geographical information systems usually involve huge volumes of geographical data and necessary attribute data manipulations. The hard disk of newly acquired equipment should be sufficiently large to both store these data and perform other routine applications.

3.6.3 Selection of Software

Currently within the international GIS software market there are at least 300 software products — most of which differ widely in both function and capability — labeled as "GIS" (GIS World, 1991). The implementation of GIS technology does not mean benefits can be obtained from any product labeled "GIS," since the label is often used for marketing purposes (NCHRP, 1991). The National Cooperative Highway Research Program (NCHRP) Research *Results Digest No.180* identified eleven functionally separable modules that a GIS usually possesses. They are:

(1) modules for data input and editing;
(2) modules for managing databases containing locational, geometric, and topological data about spatial entities;
(3) modules for managing descriptive attribute data;
(4) modules for integrating data from diverse databases, in particular, by means of "overlay" operations;
(5) modules for performing aggregation and generalization operations on geographic data;
(6) modules performing analytic (e.g., allocation) operations on geographic data;
(7) modules for map generation;
(8) modules for map printing;
(9) modules for electronic map display, with user control of zooming, cropping, windowing, suppressing and adding of different kinds of details;

(10) modules for querying and report generating; and
(11) application development utilities, e.g., macro languages.

It is suggested that these function guidelines be followed in evaluating and selecting any GIS package for potential use in pavement or infrastructure management.

3.7 A CONSIDERATION OF COST/BENEFIT ANALYSIS

Although in most fiscal environments a cost/benefit analysis is needed to convince decision makers of GIS's overall worth, in fact, it is difficult to sum all the costs and benefits of implementing such a technology as GIS. One of the major reasons is that it is difficult to precisely quantify some of the benefits. This section uses some results from a case study to provide some general ideas about the costs and benefits of implementing a GIS application.

The case study results provided by Fletcher (Fletcher, 1992) were based on the implementation of a GIS application in the City of Newton, Massachusetts. Costs and benefits are first estimated and then sketched.

Cost Estimates: The costs include the purchase of both hardware and software, data processing, staff training, etc., which are estimated in Table 3.2.

Benefit Estimates: The benefit estimates are presented in Table 3.3. As mentioned earlier, some of the benefits cannot be precisely quantified.

Cost-Benefits Sketch: Based on the cost and benefit estimates presented in Table 3.2 and Table 3.3, a simple cost-benefit analysis is illustrated in Figure 3.5.

From the cost-benefit illustration, it can be seen that the cost is larger than the benefit during the initial 3 years. In the long run, however, the benefits derived from implementing GIS are exceedingly higher than costs, not considering those benefits that cannot be precisely quantified.

Table 3.2 Cost estimation for implementing a GIS (Fletcher 92)

Basic setup costs	
New workstation	$25,000
Digitizer/plotter	$15,000
GIS software	$22,000
Street line data	$20,000
Attribute data	$20,000
Training costs	$10,000
Other support	$10,000
Total	$122,000
Annual maintenance costs	
Software and hardware	
Maintenance fees	$6,000
Other support fees	$5,000
Total	$11,000

Table 3.3 Benefit estimation for implementing a GIS (Fletcher, 1992)

Quantifiable	
Save 1/4 technician salary (per year)	$10,000
Better, cheaper data maintenance	$30,000
Total	$40,000
Less Quantifiable	
More timely response to requests	
Better response in emergency situations	
Long-term benefits in agency efficiency	
Liability avoidance	

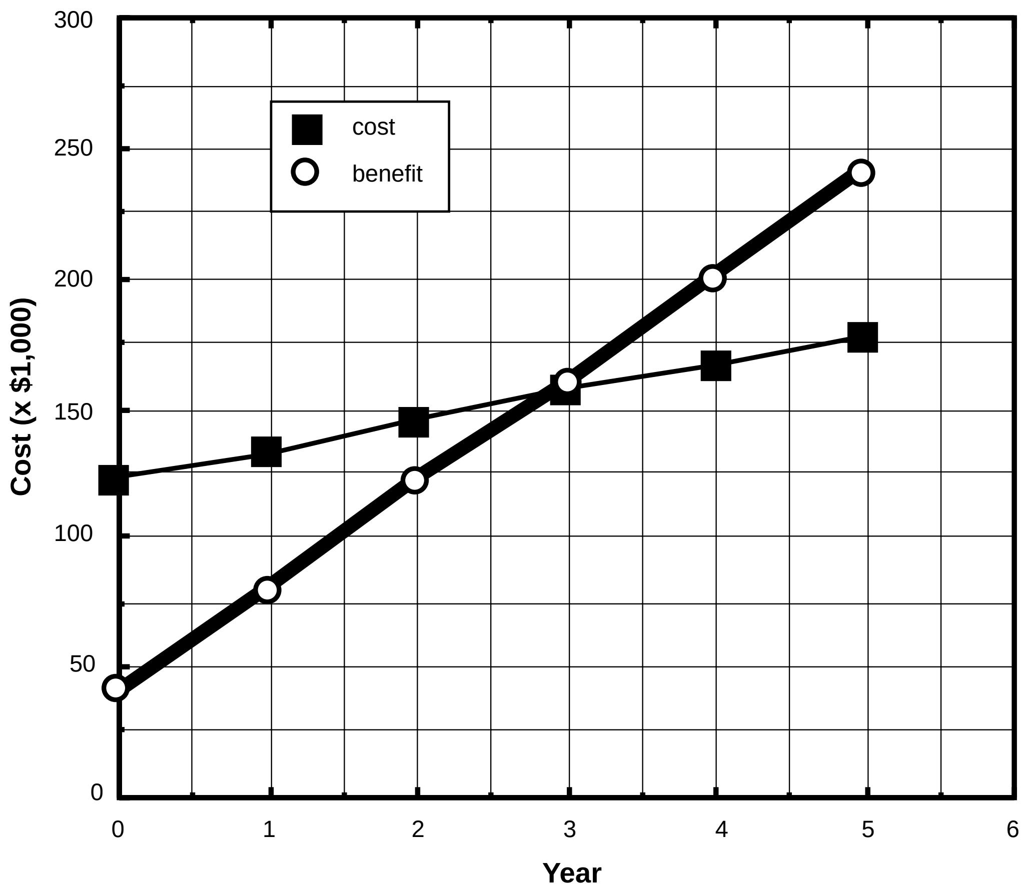

Figure 3.5 An illustration of cost/benefit analysis (Zhang, 1993)

Although the example presented is not a detailed cost/benefit analysis, it does provide some general ideas for justifying the implementation of a GIS.

CHAPTER 4. GIS USE IN STATE DOTS

4.1 ANALYSIS OF GIS-T SURVEY

Given their effectiveness as both a common location reference system and a powerful database management and analysis tool, geographic information systems (GIS) have been developed and implemented by most state DOTs in the U.S. However, these systems were usually implemented with widely varying software and hardware in various configurations. Thus, a state-of-the-art overview regarding GIS technology and the applications of GIS in state DOTs will be helpful in understanding current GIS technology, the advantages and disadvantages of different GIS software packages, and their suitability for PMIS. The Geographic Information Systems for Transportation (GIS-T) group conducted a survey regarding the state of the art of GIS applications in state DOTs. This survey, which covers all fifty states in the United States, reports on software, hardware, operating systems, staffs, application areas, map scales, and related technologies presently used in state DOTs. A similar survey conducted by the Center for Transportation Research (CTR) at The University of Texas at Austin emphasized GIS application for pavement management in state DOTs. While the GIS-T survey is summarized in this section, the CTR survey results are presented in section 4.2 of this chapter.

Figure 4.1 shows common hardware used for GIS in state DOTs. As seen in the figure, hardware having the highest use rates in state DOTs include Intergraph (31%), PC (30%), and UNIX (30%), which includes SUN, DEC, and HP. IBM RISC and VAX are not widely used in state DOTs. With the development of computer hardware and the introduction of some related technologies, such as Windows NT and Client/Server architecture, PCs serving as clients will be used more extensively in the near future.

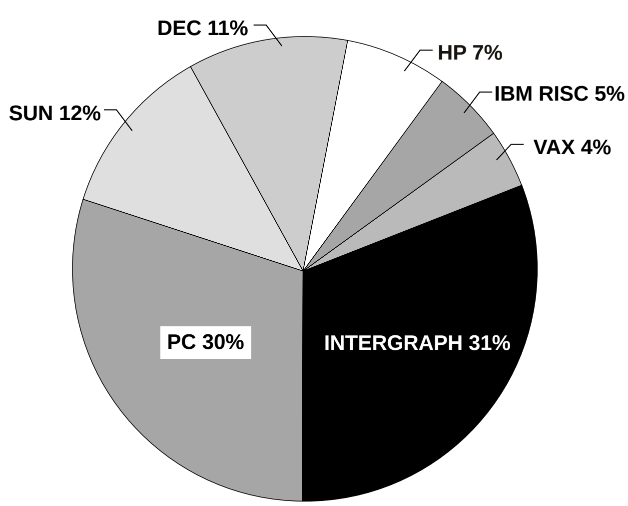

Figure 4.1 Hardware used for GIS in state DOTs

Figure 4.2 shows the GIS software used in state DOTs. Most state DOTs use software packages available on the market; only 2% of the responding state DOTs indicated that they developed GIS software packages by themselves. The most extensively used software packages are the GIS families from ESRI (Environmental Systems Research Institute, Inc.) and Intergraph. ARC/INFO (31%) and ArcView (22%) come from ESRI and MGE (27%) comes from Intergraph. Microstation is a CAD software produced by Bentley.

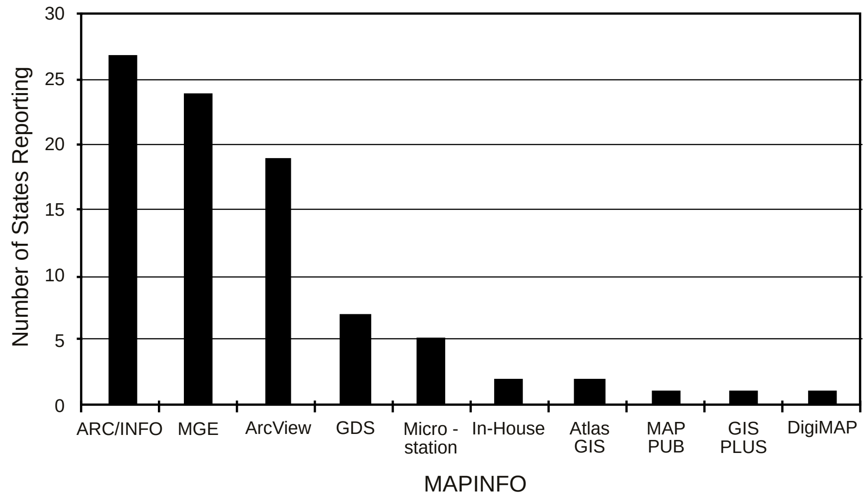

Figure 4.2 Software used for GIS in state DOTs

The survey indicates that 88% of state DOTs use the basemap in GIS. As seen in Figure 4.3, most of the GIS map scales used in state DOTs are 1:24000 (40% of state DOTs) and 1:100000 (22% of state DOTs). Some state DOTs use more than one basemap scale.

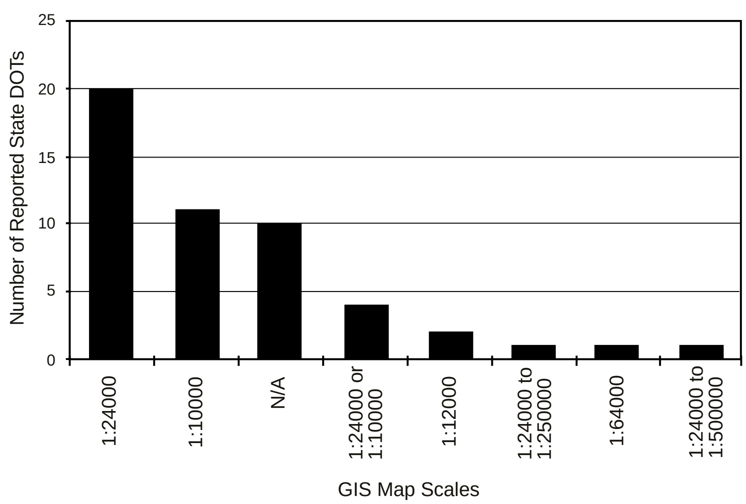

Figure 4.3 GIS map scales used in state DOTs

Figures 4.4 and 4.5 show the number of GIS staff employed in each state DOT. Most state DOTs (74%) employ only 1 to 10 staff working on GIS. Thirty-eight percent of state DOTs employ only 1 to 5 staff working on GIS, while 36% of state DOTs employ 6 to 10 staff working on GIS. Only 18% of the reporting state DOTs employed more than 11 staff.

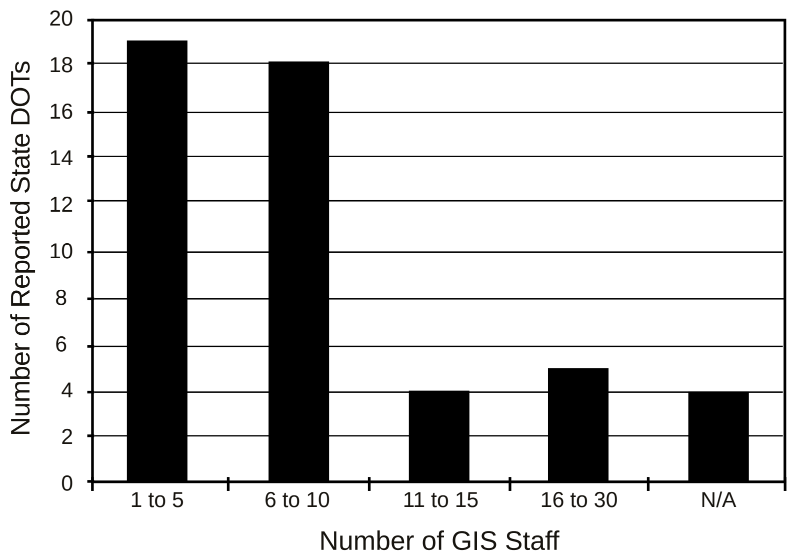

Figure 4.4. GIS staff numbers in state DOTs

Figure 4.5 shows the percentage of state DOTs using Windows 95 and NT for GIS. Presently, only 36% of state DOTs have used Windows 95 and NT. Sixty-four percent of state DOTs used other operating systems, such as DOS, UNIX, Windows 3.1, or VMS.

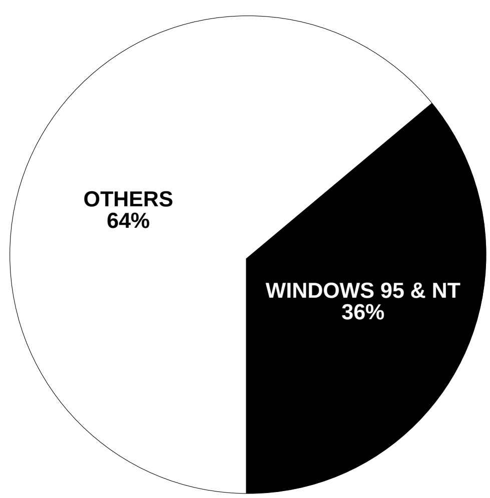

Figure 4.5 Percentage of state DOTs using Windows 95 and NT for GIS

Several technologies are closely related to the implementation of GIS. Figure 4.6 shows the related technologies used in state DOTs. The most extensively used technologies include GPS (30% of state DOTs), VIDEO LOG (22% of state DOTs), ROADLOG (22% of state DOTs), PHOTOLOG (15% of state DOTs), and SIGN LOG (11% of state DOTs).

Table 4.1 lists the application areas of GIS in state DOTs. Pavement management is the most common applications area of GIS in state DOTs, having been reported by 20 state DOTs, followed by bridge management, reported by 19 state DOTs. Both accidents and HPMS (highway performance management system) are ranked third, having been reported by 17 state DOTs.

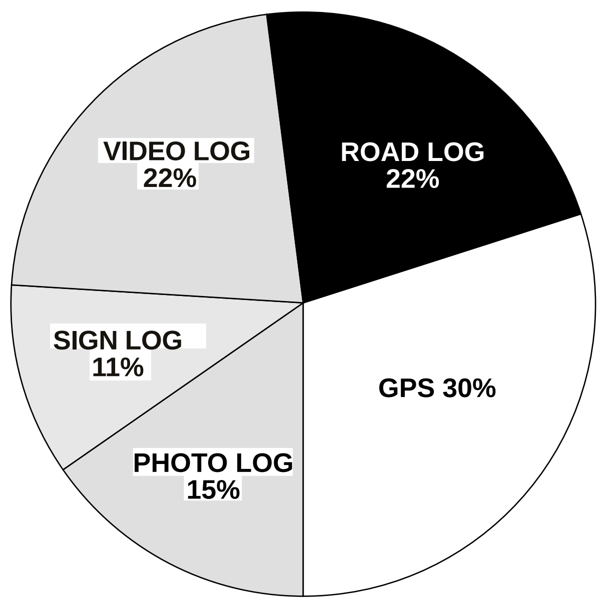

Figure 4.6 Related technologies used in state DOTs

Table 4.1 Reported application areas of GIS used in state DOTs

Application Areas of GIS Used in State DOTs	Number of Respondents
ACCIDENTS	17
ADT	8
BIKE	2
BRIDGE	19
CLEAN AIR MODELING	0
CONGESTION MANAGEMENT	6
CONSTRUCTION	4
CORRIDOR PLANNING	7
DEMOGRAPHICS	1
ECONOMIC EVALUATION	1
ENVIRONMENTAL	8
FACILITIES MANAGEMENT	0
HPMS	17
HIGHWAY INVENTORY	9
HIGHWAY SAFETY	6
HYDROLOGY	5
INCIDENT MANAGEMENT	2
ISTEA	8
INTERAGENCY SUPPORT	7
LAND USE	0
MAINTENANCE	5
NETWORK APPLICATIONS	3
NHS	7
PAVEMENT MANAGEMENT	20
PROGRAM DEVELOPMENT2	3
PROJECT MANAGEMENT2	8
RIGHT OF WAY	4
ROADWAY GEOMETRICS	3
ROUTING	2
TRAFFIC OPERATIONS	0
TRAFFIC MONITORING	7
TRANSPORTATION PLANNING	7
TRANSIT SERVICE	2
WEATHER CONDITIONS	4
NETWORK APPLICATIONS2	3
PROGRAM DEVELOPMENT	3
PROJECT MANAGEMENT	8
MULTIMODAL	0
INTERMODEL PLANNING	7
INVENTORY APPLICATIONS	3

Table 4.2 lists the main functions of GIS within state DOTs. Mapping/Display is the most common function of GIS, as reported by 26 state DOTs. Dynamic Segmentation/Linear Reference Systems and Basemap development are two other functions that are used extensively, as reported by 13 state DOTs. Planning is the third function, having been reported by 12 state DOTs.

Table 4.2 Reported functions of GIS used in state DOTs

Functions of GIS Used in State DOTs	Number of Respondents
BASE MAP DEVELOPMENT	13
DATABASE QUERY SYSTEM	9
DATA INTEGRITY	3
DATA MANAGEMENT	9
DECISION SUPPORT	8
DYN.SEG./LINEAR REF SYS.	13
FUNCTIONAL CLASSIFICATION	7
GIS DISTRIBUTION	2
MAPPING/DISPLAY	26
MODELING	7
PLANNING	12
SYSTEM PLANNING	2

4.2 ANALYSIS OF CTR SURVEY

In order to understand GIS applications in pavement management systems and to provide background information for TxDOT, an information booklet was developed by CTR and sent to some state DOTs. Twenty-one responses were received and developed into a database. This analysis concerns GIS software, hardware, operating systems, staffs, application areas, map scales, and related technologies used in state DOTs.

With regard to the percentage of state DOTs using GIS, most state DOTs (95% of responses) have used GIS at different stages. Only 5% of state DOTs reported that they hadn’t yet used GIS. These percentages suggest that most state DOTs have realized GIS capabilities to support their missions of pavement management and other transportation-related management.

Figures 4.7 and 4.8 show the number of years state DOTs have been using GIS in general applications and in PMS, respectively. As seen from the figure, most state DOTs have used GIS more than 2 or 3 years, and some of the state DOTs have used GIS in pavement management systems (PMS) less than 3 years.

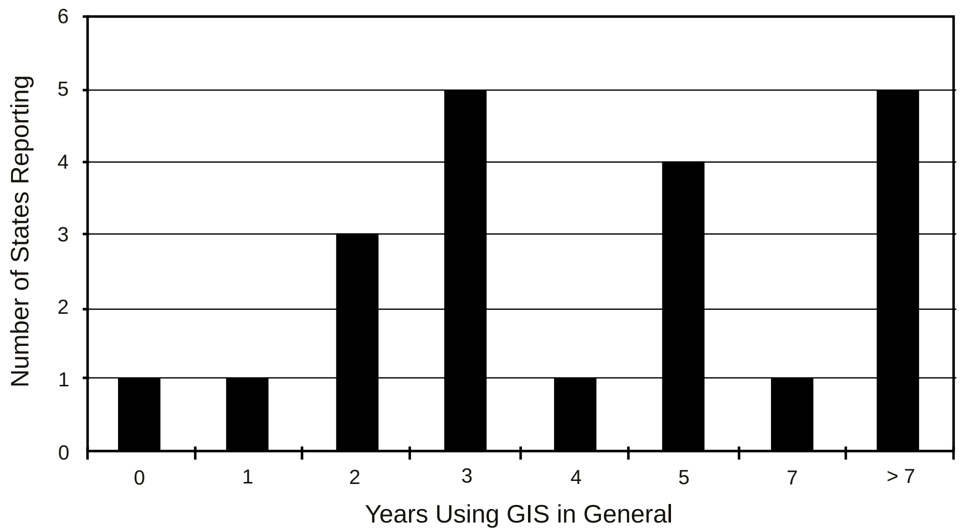

Figure 4.7 Reported years of state DOTs using GIS in general

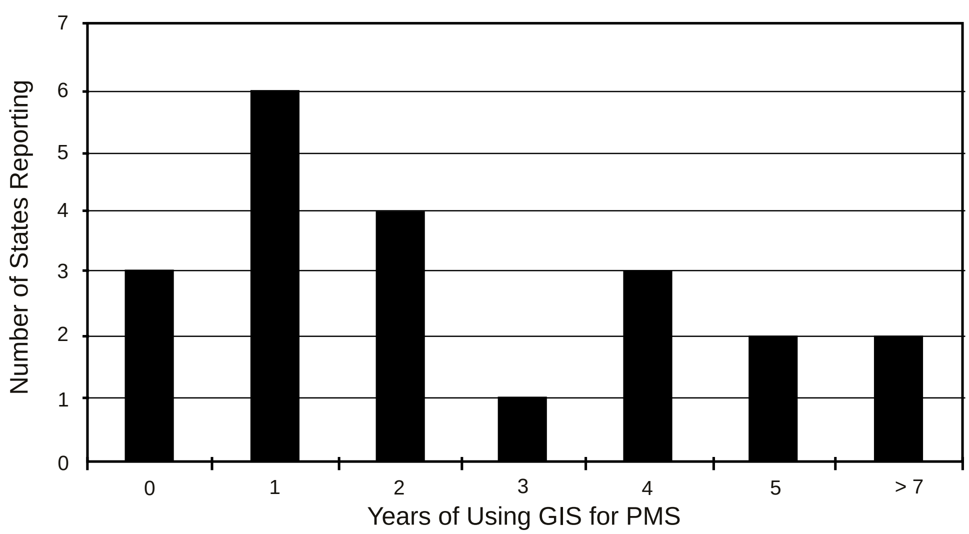

Figure 4.8 Reported years of state DOTs using GIS in PMS

Figures 4.9 and 4.10 show the number of staff employed by state DOTs in general and in PMS, respectively. Most state DOTs have more than two GIS specialists in general. Some state DOTs employ eight GIS specialists in general. However, in PMS, most state DOTs have fewer than two GIS specialists, and some state DOTs have no GIS specialists in PMS.

Figure 4.11 shows the reported GIS software packages presently used by state DOTs. As seen in the figure, the GIS software packages from the ESRI family (ARC/INFO, ArcView, and PC ARC/INFO) are the most extensively used, followed by the Intergraph family (MGE and GeoMedia) in state DOTs. Software with the highest response rates is ARC/INFO and ArcView, 23% and 22%, respectively. MGE ranks third, at 14%. MicroStation is a product of Bentley, a company in the CAD market.

It can be concluded from Figure 4.12 that most responding state DOTs (90%) are satisfied with GIS software packages presently. However, only 48% of these state DOTs expect that present software packages will satisfy future needs throughout the next 5 years, of which only 19% of responding state DOTs plan to change — for various reasons — their software packages to meet future needs (obstacles to GIS application in state DOTs will be listed later).

Figure 4.13 shows the current operating systems used in state DOTs. Windows NT and UNIX are operating systems having the highest response rates, at 37% and 33%, respectively. Windows/DOS was third, at 26%. Few responding state DOTs use VMS or VAX. However, as seen in Figure 4.14, an overwhelming majority of state DOTs reported that Windows NT would be the first choice if they decide to change the operating system.

Table 4.3 lists the computer CPU used for GIS applications in state DOTs. As seen from the table, Pentium processors produced by Intel, rated from 66Mhz to 200Mhz, are used most extensively in state DOTs. As seen in Figure 4.15, only 38% of the responding state DOTs plan to change their hardware configurations in the next 3 to 5 years.

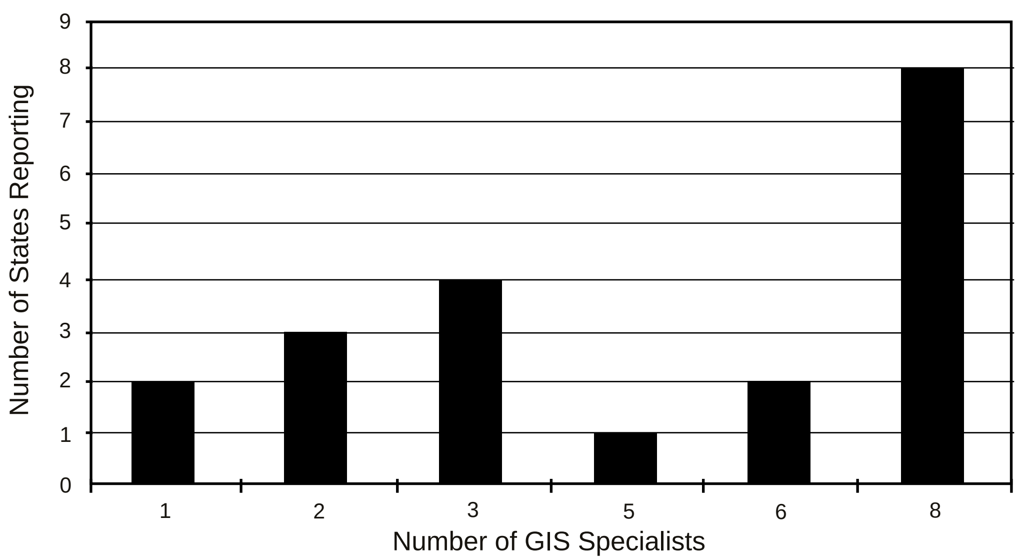

Figure 4.9 Number of GIS specialists employed in state DOTs in general

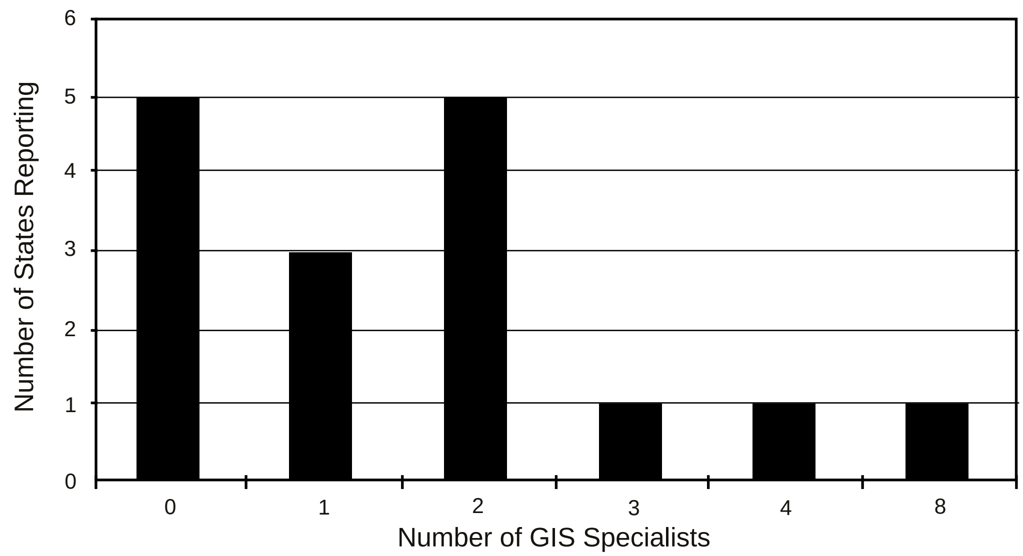

Figure 4.10 Reported number of GIS specialists employed in state DOTs in PMS

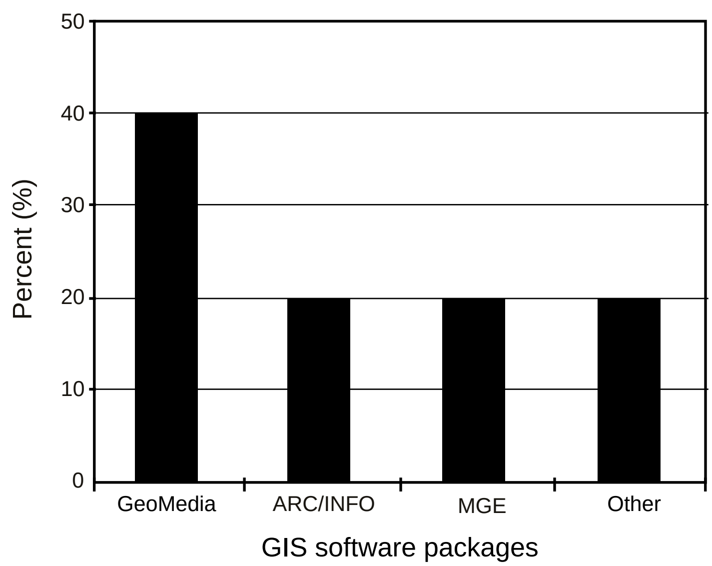

Figure 4.11 Reported GIS software packages used in the U.S.

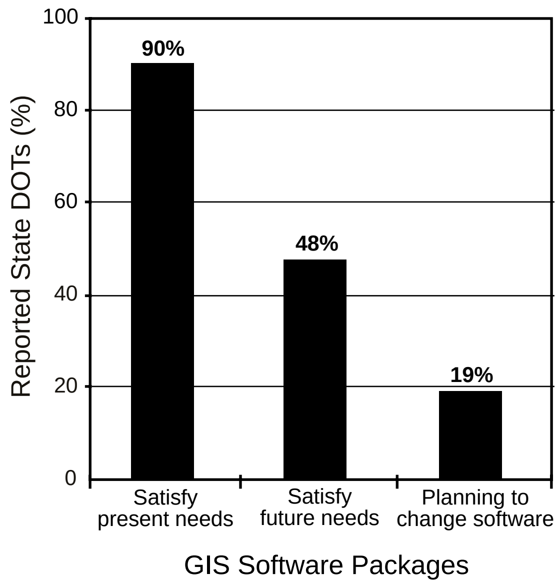

Figure 4.12 Reporting state DOTs that consider GIS software packages satisfy present needs

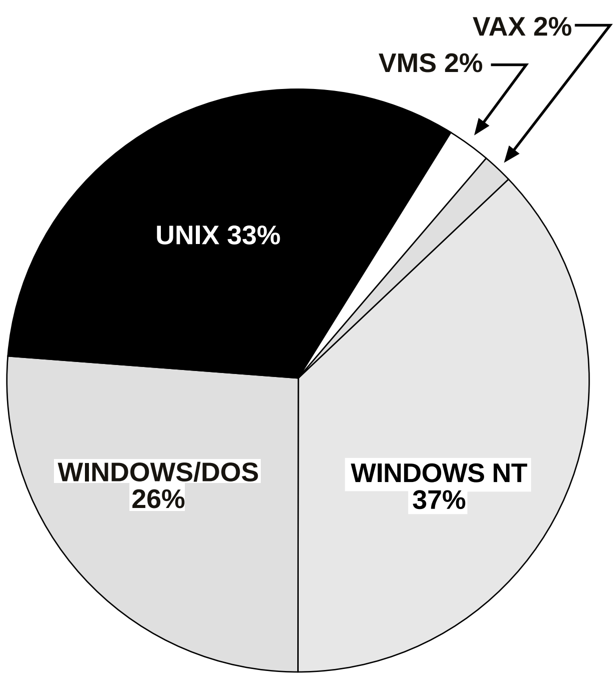

Figure 4.13 Reported percentage of operating systems used for GIS

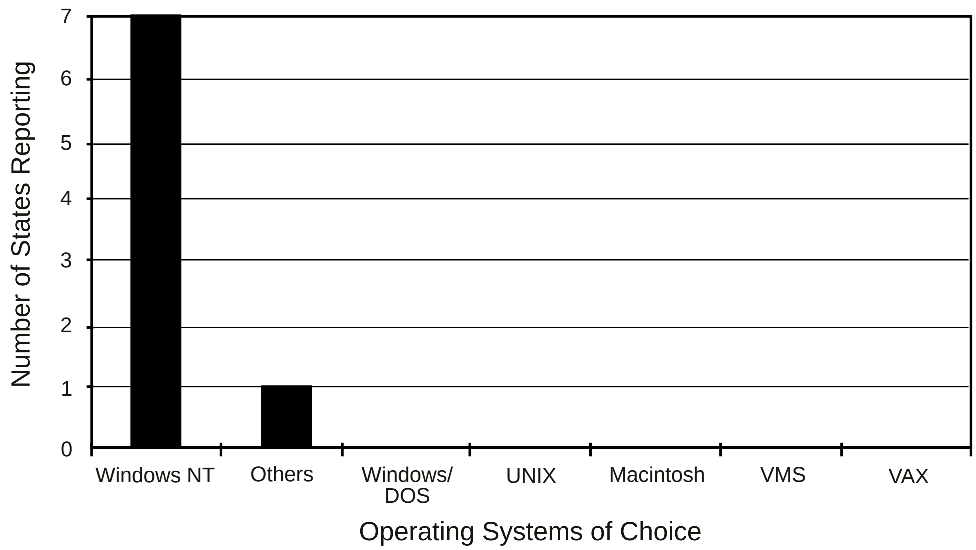

Figure 4.14 First choice of state DOTs if changing the operating systems

Table 4.3 Computer CPU used for GIS applications in state DOTs

CPU	No. of Respondents
DEC ALPHA	1
DGAVHON 33MHZ CPUCOM	1
IBM RS6000(UNIX-256MHZ)	1
PENTIUM 133	5
PENTIUM 166	3
PENTIUM 66-200	1
PENTIUM PRO 200	5
Minimum PENTIUM 100	1
Grand Total	18

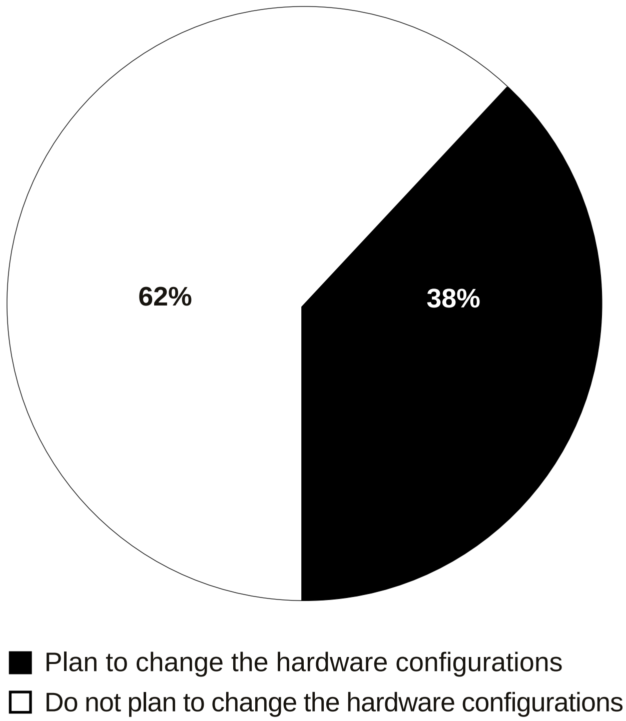

Figure 4.15 Reported state DOTs planning to change hardware configurations in the next 3 to 5 years

Figure 4.16 shows the major application areas of GIS in state DOTs. As seen in the figure, pavement management was the most commonly used area of GIS in state DOTs, having been reported by 17 state DOTs, followed by highway safety management, reported by 11 state DOTs. Bridge management was the third, having been reported by 10 state DOTs. Traffic congestion management, public transportation management, and intermodal transportation facilities management were also application areas of GIS in state DOTs.

Figure 4.17 shows the major functions of GIS for PMS. As seen from the figure, the major functions of GIS for PMS with the highest response rates were map generation (22%), color coding of pavement conditions (21%), use as a location reference system (18%), spatial analysis (15%), interactive query (14%), and use as an integration platform (7%). This distribution illustrates that most state DOTs are still in the preliminary stages of GIS implementation.

Dynamic segmentation is the ability to store attribute data in a single storage item for multiple and partial segments of graphic elements. According to the survey result, about 90% of the respondents reported that their GIS supports dynamic segmentation.

Figure 4.17 shows the main sources of GIS basemap used for PMS: in-house development (56%), government data warehouse (28%), and contracted development (16%). No responses reported the commercial data publisher as a source of basemap.

Figure 4.18 shows the resolution of the GIS basemap used in state DOTs. As seen in the figure, 10 state DOTs reported that their resolution of basemap was 1:24000 and 3 state

DOTs reported that the resolution of basemap was 1:100000. Some state DOTs used more than one resolution of GIS basemap.

Figure 4.20 shows the accuracy of the GIS basemap used in state DOTs. The positional accuracy of plus or minus 5.01 to 15 m was reported by 6 state DOTs, followed by 1 to 5 m (4 state DOTs), 15.01 to 50 m (4 state DOTs), and more than 50 m (3 state DOTs). Only 1 state DOT reported that the accuracy of GIS basemap was less than 1 m.

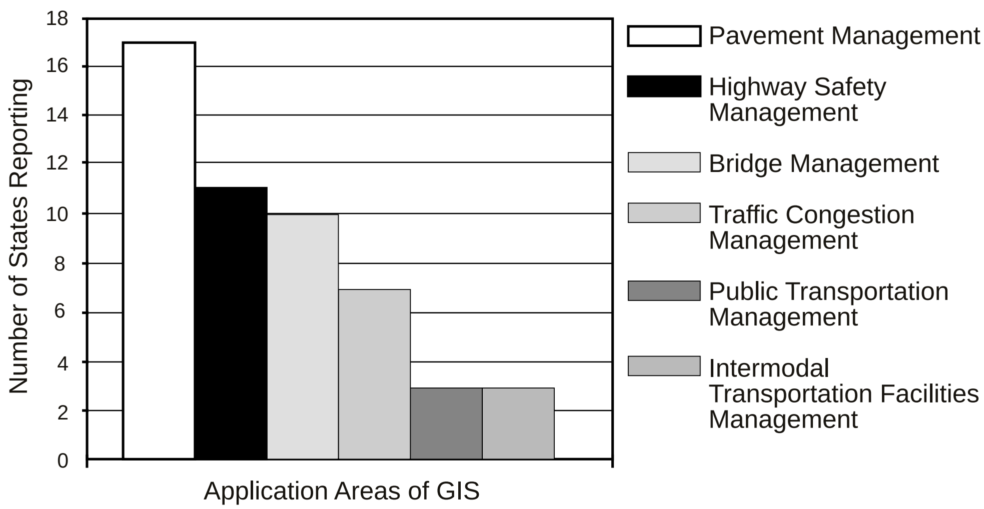

Figure 4.16 Major application areas of GIS in state DOTs

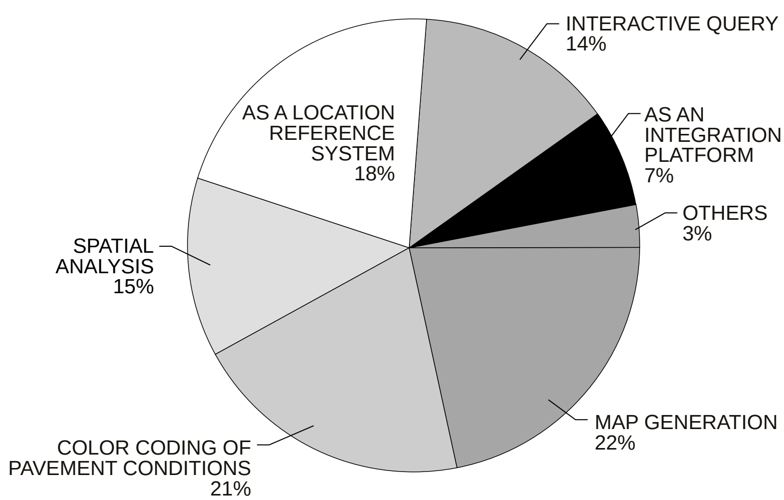

Figure 4.17 Major functions of GIS for PMS for state DOTs

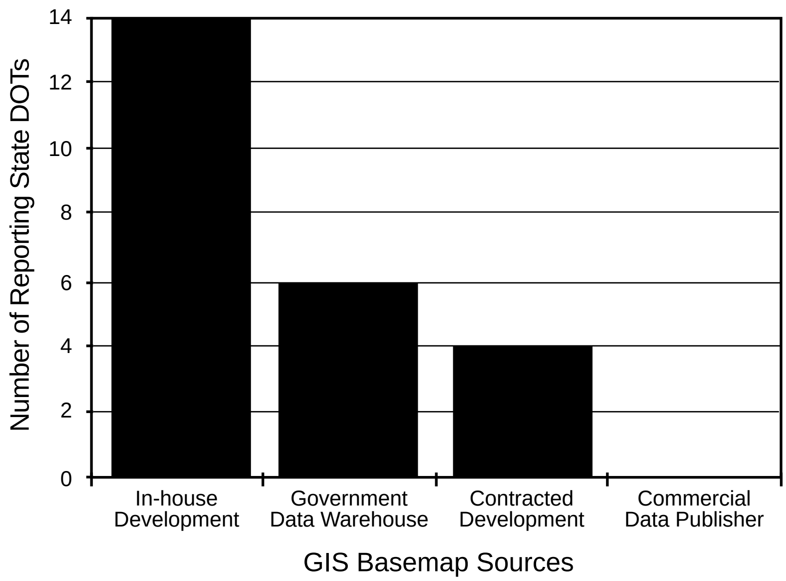

Figure 4.18 Reported sources of GIS basemap

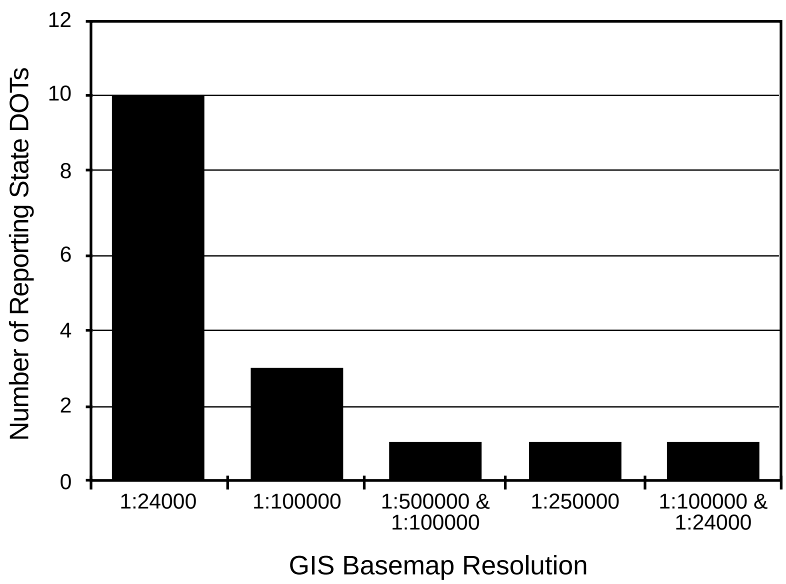

Figure 4.19 The resolution of GIS basemap used in state DOTs

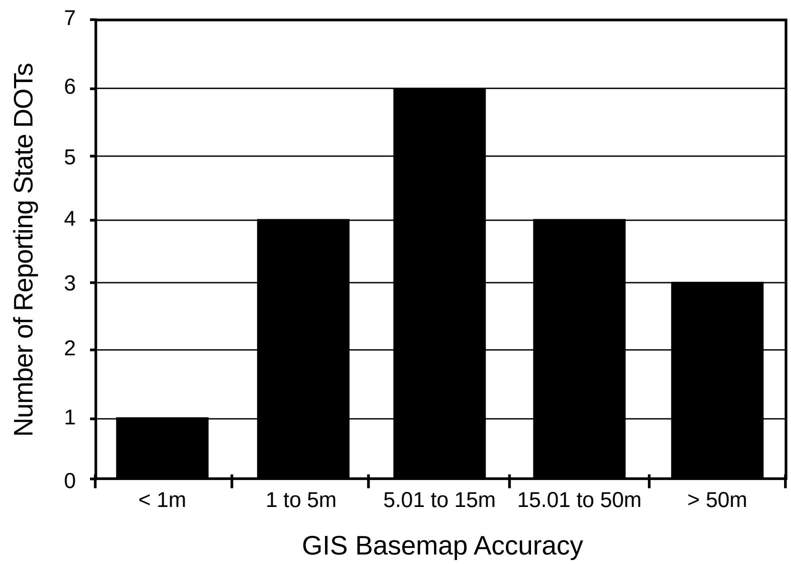

Figure 4.20 The accuracy of GIS basemap

As seen in Figure 4.21, the most extensively used relational database management systems (RDBMS) were Oracle (45%), followed by MS ACCESS (13%), dBase (13%), INFORMIX (12%), and ADABAS (4%).

As seen in Figure 4.22, 44% of the respondents reported that the interface between GIS and PMS was database linkage, while 25% of the respondents reported that the interface between GIS and PMS was seamless software integration.

Figure 4.23 shows the related technologies used in state DOTs. As seen in the figure, 32% of the responding state DOTs used Global Positioning Systems (GPS) technology and 27% of the responding state DOTs used Differential Global Positioning Systems (DGPS). Multimedia technology, such as VIDEOLOGGING (27%) and PHOTOLOGGING (14%), were also reported as having been used in GIS by some state DOTs.

From Figure 4.24 it can be concluded that the following issues are the main difficulties in GIS application: institutional issues (37%), lack of trained GIS specialists (32%), insufficient funds (12%), and difficulties in getting digital map data (7%). Other specific issues were also reported by several state DOTs (12%).

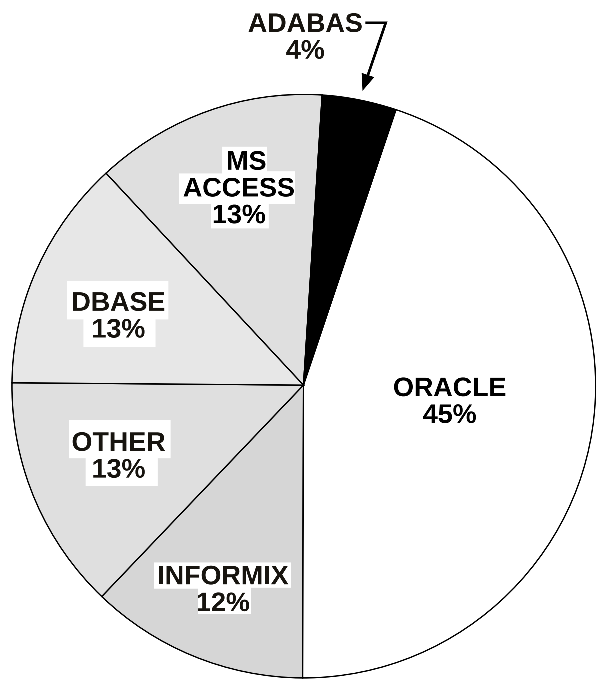

Figure 4.21 RDBMS used for PMS in state DOTs

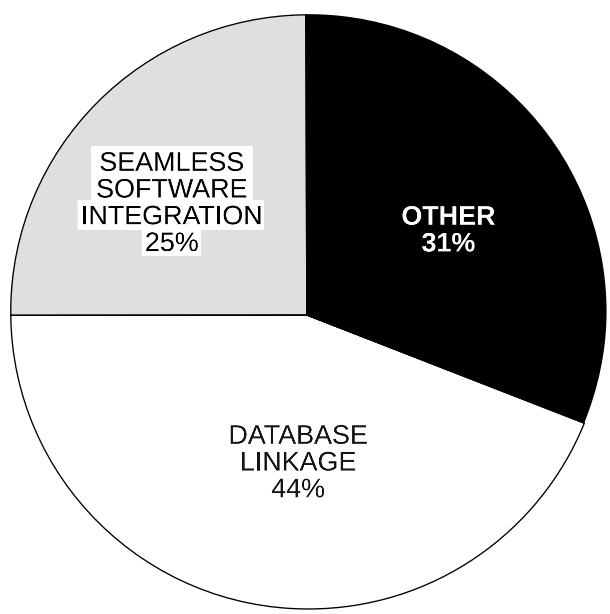

Figure 4.22 The interfaces between GIS and PMS in state DOTs

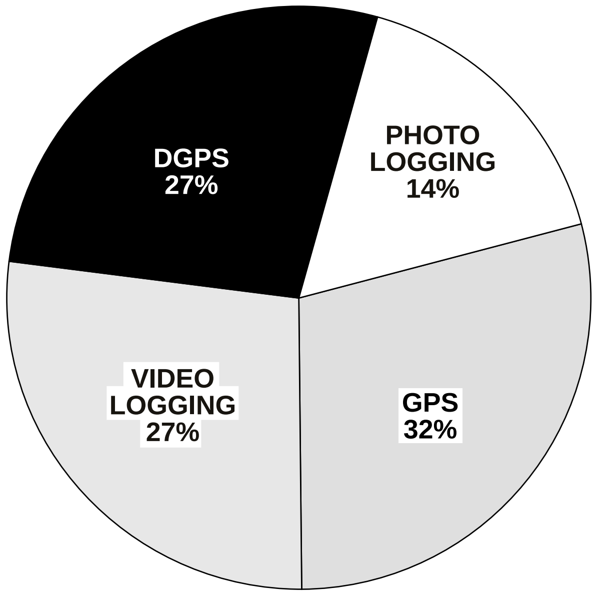

Figure 4.23 New technologies related to GIS currently used in state DOTs

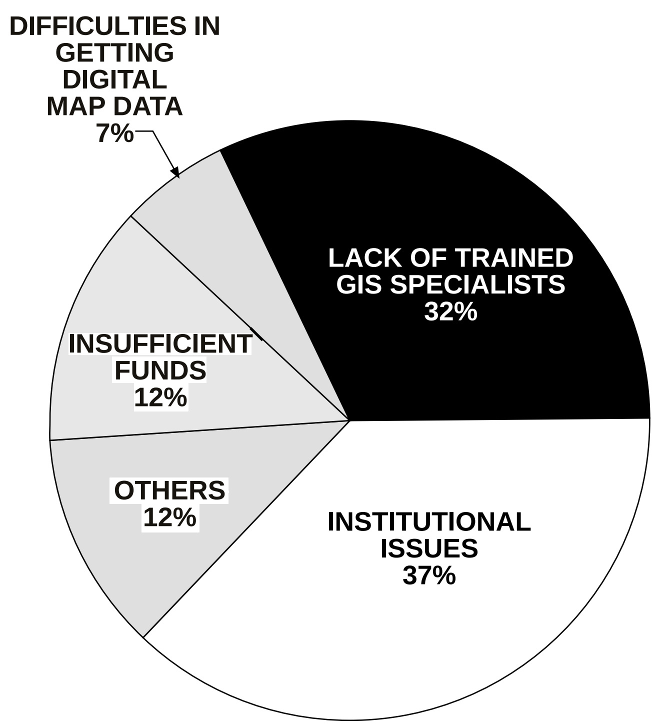

Figure 4.24 Major difficulties in GIS applications in state DOTs

CHAPTER 5. OTHER RELATED TECHNOLOGIES

5.1 INTRODUCTION

No technical area — including pavement management — can be effective if it remains static (Hudson, 1997). Owing to changing user demands and changing technology, the practice of pavement management is always full of opportunities for improvement and advancement. Although the practice of systematic pavement and infrastructure management began only three decades ago, the approach, the methodology, and the technique for pavement management have evolved along with recognized need and the development of new technologies. The most important breakthroughs in pavement and infrastructure management were the application of the systems approach and of computer technologies (Hudson, 1968; Hutchinson, 1968; Haas, 1970; NCPWI, 1988; NRC, 1993; Haas, 1994). These breakthroughs established the basic concepts and principles implied in the term *pavement management systems* (Haas, 1982; Hudson, 1994; Zhang, 1996; Hudson, 1997).

Over the past 5 years, the most noticeable change occurring within pavement management systems has perhaps been the shift from traditional stand-alone systems to integrated systems. At the same time, technology has advanced greatly over the past 10 years, especially in the areas of computer processing speed and storage capacity, automation of data collection, spatial data analysis and visualization, and data management and communications. These advances in technology have made the development and implementation of integrated IMS viable. Specific technologies that will have a major impact on the future of integrated IMS are discussed in the following sections.

5.2 GLOBAL POSITIONING SYSTEM (GPS)

A global positioning system (GPS) is a satellite-based navigational system that allows the position of a location anywhere on the earth to be determined using a GPS receiver and a clear path to four or more GPS satellites. GPS receivers make extremely accurate timing measurements by means of orbiting satellites that broadcast their position in the orbit.

5.2.1 Background

The first space-based navigation system was the Navy Navigational Satellites System (NNSS), also called the TRANSIT system. The TRANSIT system consists of six satellites orbiting the earth at altitudes of 1074 nautical km (580 nautical miles). It was initially developed by the U.S. military primarily for the purpose of navigating vessels and aircraft. Civilian use of the TRANSIT system was eventually authorized and now provides global, but intermittent, coverage for thousands of users in both navigation and surveying.

Under a 1973 directive of the U.S. Department of Defense (DOD), the present NAVigation System with Timing and Ranging (NAVSTAR) Global Positioning System was developed to replace the TRANSIT system. The NAVSTAR GPS satellite constellation consists of twenty-one satellites plus three active on-orbit spares launched into orbit in six orbital planes that are 20,183 nautical km (10,898 nautical miles) above the earth. The NAVSTAR GPS provides full 24-hour, three-dimensional global positioning coverage. Although the satellites and ground support equipment are financed by the DOD, the navigation signals from these satellites are available to all users around the world free of charge (Logsdon, 1992; HW, 1993).

5.2.2 Major Segments of GPS

The global positioning system can be broken down into the three major parts or segments illustrated in Figure 5.1: (1) the space segment, (2) the user segment, and (3) the control segment.

The purpose of the space segment is to transmit precisely timed signals and the satellites' ephemeris constants to an unlimited number of users around the world equipped with GPS receivers to fix their positions, velocities, and/or their exact timings. The function of the control segment is to track the satellites for the orbit and clock determination and to upload the data message to the satellites. The control segment consists of a master control station, worldwide monitor stations, and ground control stations. The purpose of the user segment is to pick up the satellite signals from four or more satellites, and to process them to obtain accurate positioning solutions. A GPS receiver can be divided into three major components: (1) the antenna, with its associated electronics for picking up the satellite signals; (2) the receiver-processor unit for processing the signals to calculate positions; and (3) the control-display unit for displaying information and providing a convenient interface between the GPS and the user.

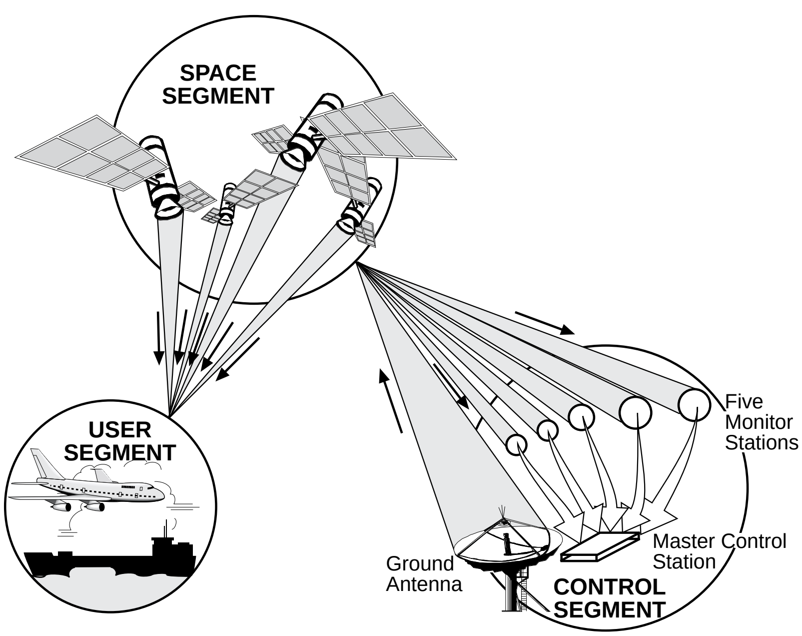

Figure 5.1 Three major segments of the GPS

Various GPS receivers are available for navigation, GIS data collection, and survey. These receivers provide varying accuracies and offer different features over a wide range of prices. Table 5.1 summarizes three grades of GPS receivers, distinguished according to the method of differential correction, accuracy, cost, sensitivity, and number of channels. The physical configuration of field GPS receivers can be broadly categorized into three groups: handheld, backpack, and PCMCIA card. All of these can provide position measurements with 100-meter (328-ft) (without differential corrections) to 1-meter (3.28 ft) level (with differential corrections) accuracy.

Table 5.1 A summary of three grades of GPS receivers and their capabilities

Navigation	GIS	Survey		Method of Correction		
None	None	Post-process	Real-time	Post-process	Real-time	
Accuracy	100 m	100 m	5 m	5 m	<1 m	<1 m
Data Collection	2 min	2 min	10 min	2 min	90 min	15 min
GPS cost	>$1,000	$3,000 - $5,000	<$10,000			
Number of Channels	3	6	12			

(Note: 1 meter = 3.28 ft)

5.2.3 Accuracy of GPS Positioning

The accuracy level that can be achieved is perhaps one of the biggest concerns in using GPS for pavement management. Figure 5.2 shows the six basic levels of GPS accuracy based on the type of signals being processing (i.e., C/A-code or P-code), their status with respect to selective availability (degraded or undegraded), and whether or not differential GPS and/or carrier-aided techniques are employed (Logsdon, 1992).

Each accuracy level is represented on the figure as a horizontal strip expressing a Rayleigh distribution, with a span from 5% to 90%. The small circles near the center of each horizontal strip mark the circular error probable value (CEP value) for that particular mode of positioning. CEP is equal to the median value, or 50% confidence level value; in other words, it is a circle that contains 50% of all randomly varying statistical samples occupying a two-dimensional region. What should be noted from the figure is that the average GPS positioning accuracy levels range from as small as 0.5 cm (0.2 in.) for a carrier-aided, site-fixed, static positioning solution, to as large as 100 meters (328 ft) without differential.

Given that a GPS is virtually a free (with the exception of the purchase of the receiver) resource with broad potential, its application has been extended to such engineering areas as pavement, infrastructure and facility management, GIS data collection, vehicle routing and navigation, and engineering mapping. These applications have become more viable as additional base stations for differential corrections are established throughout the U.S. The accuracy level of 1 to 5 meters (3.28 to 16.4 ft) for position coordinates can be achieved after the differential corrections. It is clear that GPS technology will play an increasingly important role in modern pavement management.

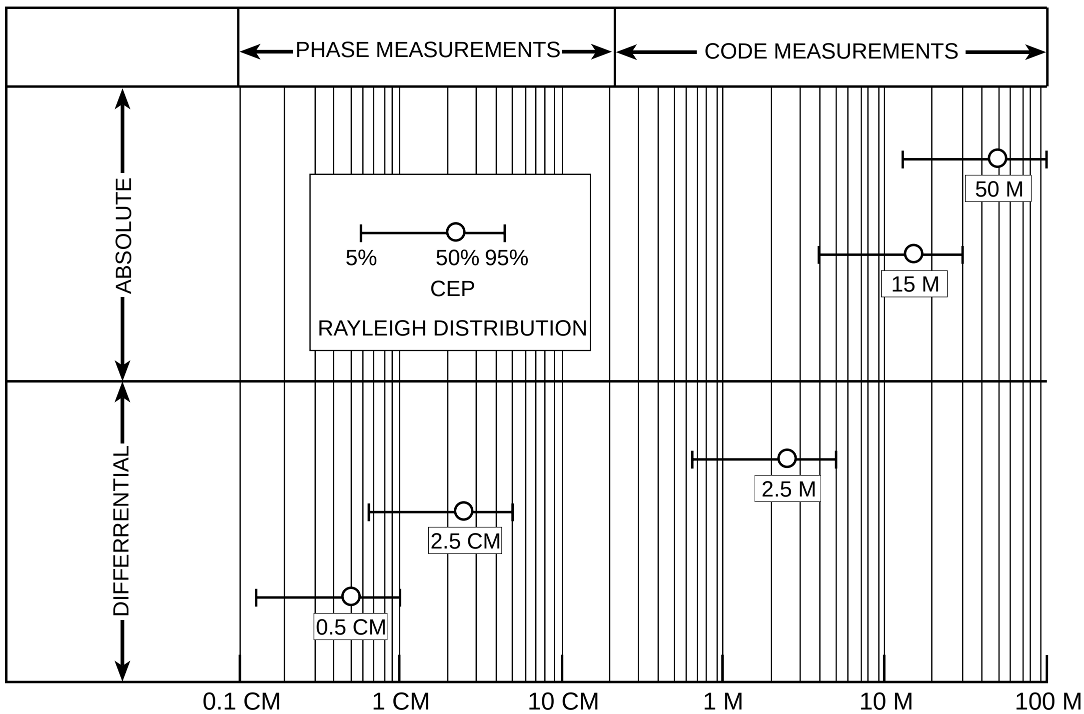

Figure 5.2 Six basic levels of GPS accuracy

5.2.4 Differential GPS Correction in Texas

There are several options and methods of differential correction available for GPS users in Texas. The methods include postprocessing and real-time kinematic differential GPS. The options involve providing your own base station, using free government base stations (e.g., TxDOT or U.S. Coast Guard), or purchasing a subscription service. Postprocessed data are rather routine and most users are familiar with the procedures. However, care must be taken in that when proprietary receiver data formats are used, compatible data are also required for postprocessing. Also, an important consideration is how the differential is corrected. The best accuracy is achieved when the base station calculates its position using the exact satellites as the roving receiver.

The ideal situation is to have real-time kinematic differential correction. Basically, a base station or a group of base stations collect GPS from known locations and calculate a differential correction factor based on the man-made selective availability and atmospheric errors. The real difference is how this differential correction is broadcast to the roving receiver. Surveyors routinely set up their own base station and use line-of-sight radios to broadcast the correction to the roving receiver. However, the limitations include the line-of-sight transmitter/receiver and having a known location.

The U.S. Coast Guard operates — primarily for maritime GPS users — a free differential correction service near major shipping channels. The Coast Guard broadcasts the differential correction on a specific frequency: If you are in range of the Coast Guard beacon and have a receiver capable of receiving that correction frequency, you can get fairly good differentially corrected positions. Many GPS manufacturers will supply GPS receivers with the U.S. Coast Guard beacon receivers. The Lower Colorado River Authority is interested in having additional U.S. Coast Guard beacons built inland for inland Texas waterways. However, currently less than one-third of the state can be covered by the U.S. Coast Guard beacons.

Another popular method is to broadcast the differential correction on the carrier signal of FM radio stations. Last year there were two large subscriber groups providing such a service — one in Texas and another that was national. ACCQPOINT, the Texas group, claimed that it had 90% coverage in Texas before the company went out of business last year. One of the authors of this report was an ACCQPOINT user last year and was satisfied with the service in the Dallas/Fort Worth area but was not very satisfied with the reception in the Austin area. Even though ACCQPOINT was using a local FM station in Austin, it seems as if there are several areas of the city where a good GPS signal could be achieved, though not a consistent differential signal.

DCI is the national company selling the differential correction as a yearly subscription service. However, it does not have an FM station in Austin currently broadcasting the differential correction. The research team estimates that less than half the state could receive the DCI differential correction. This service would have the same line-of-sight problems that ACCQPOINT had with its FM broadcast. Accordingly, there will be areas of limited or poor reception, resulting in a lack of consistent differential correction.

The best and only real-time kinematic differential correction is the Omnistar system provided by John Chance and Associates in Houston, Texas. Basically, this system is using more than twenty ground base stations to calculate differential corrections; it broadcasts them via satellite communication links to the roving GPS receiver. The communication satellites are in geostationary orbit — that is, at an altitude higher than the lower orbiting Navistar GPS satellites. Therefore, if you are in Texas, you are in range of a geostationary communications satellite from Omnistar. The Omnistar system also uses at least three base stations in Texas and allows the GPS receiver to receive a customized differential correction signal based on the GPS receivers' location. The Omnistar system is the only system capable of real-time differential correction statewide in Texas. The Omnistar system is recommended in the TxDOT GIS/GPS architecture. The Omnistar system should provide 2-meter (6.5-ft) accuracy 95% of the time.

The Federal Aviation Administration (FAA) is spending $460 million to implement a Wide Area Augmentation System (WAAS), and even more for an airport Local Area Augment System (LAAS). Hughes Aerospace, recently acquired by Raytheon, has the contract to implement the WAAS. The FAA requirements are rather rigorous with respect to system reliability. The WAAS is envisioned as a replacement to all other navigation systems and must have a 4-meter (13.12-ft) accuracy 99.999% of the time. The 2-meter (6.5-ft) accuracy should be available better than 98% of the time. Although full implementation of the WAAS is not envisioned until after 2001, Raytheon is on schedule to start broadcasting Stage 1 WAAS by March of 1999. The WAAS is functionally the same as the Omnistar system in that they both use nationwide coverage of ground base stations and transmit a differential correction from geostationary communication satellites. The difference is that the WAAS will be a free service paid for by the FAA; consequently, a special, separate satellite communications receiver will not be necessary. The WAAS differential correction signal will be broadcast on the same frequency as the L1 GPS carrier signal. Once commercially available GPS receivers are built to take advantage of the WAAS, a second receiver will not be necessary. What is not clear is how long it will take commercial GPS manufacturers to start making WAAS-capable receivers and at what price. However, based on the competition among receiver manufacturers, the research team expects that it will happen soon after the WAAS begins consistent broadcasting.

5.2.5 Integration of GPS with GIS

GPS can be integrated with GIS in either static mode or in a real-time condition to support pavement management, depending on the nature of the application. Static integration means that the position data files exported from a GPS receiver device during postprocessing can be read directly into the GIS in order to generate geographical features or themes. Many GPS receiver devices have software that can produce output files of locational coordinates in various ASCII or other GIS-readable formats. The advantage of GPS data in ASCII format is that users are able not only to look up the locational coordinates, but also to perform postprocessing and differential corrections to the data for better accuracy at a later date.

Real-time integration, as indicated by the name itself, means that a GPS receiver is directly connected to a computer for interfacing with GIS. The key issue for real-time integration is the instantaneous data communication and conversion between GPS and GIS. For example, ArcView's GIS open architecture and Interapplication Communication (IAC) tools allow GIS to be linked with almost all GPS products in real-time through a user-friendly interface. Real-time integration is particularly useful for field data collection, location identification, and vehicle navigation.

The combination of differential GPS and portable GIS can make field data collection more accurate and less expensive, as compared with traditional procedures of data collection. There is no doubt that GPS technology has added a new dimension to pavement management.

5.3 VIDEOLOGGING, PHOTOLOGGING, AND MULTIMEDIA TECHNOLOGY

The migration of technology from analog (continuously variable signals) to digital (discrete, binary signals) has taken place steadily not only in telecommunications, but also in the computer industry. This migration has a direct impact on the way data and information for pavement management is handled in public works agencies.

Tabular data, maps, engineering drawings/pictures, and videos are the most commonly used data and information formats used in pavement management. Although tabular data have been computerized for a long time, maps and drawings are still maintained and used in hard-copy format by most of the public works agencies. Visual information is usually captured and viewed in analog format via either 16mm film or via the more recent broadcast-quality video devices. For example, the first pavement video inventory, developed by the Connecticut Department of Transportation, uses analog-based laser disc systems. Arizona and Arkansas later started their roadway video inventory, also using laser disc or Super-VHS video (Hanley, 1992; Wang, 1995).

There are two main drawbacks with hard copy or analog-based information: (1) It is difficult and sometimes impossible to access simultaneously all the data and information associated with a specific element of the transportation infrastructure system, and (2) it is difficult or infeasible to share these data among all divisions within an agency or to transfer them to other associated agencies.

Today, multimedia technology can be used to support infrastructure management decision-making. By employing GIS and its integration with multimedia technology, a computerized management system, initially capable of handling only tabular data, would have the capabilities of creating, storing, manipulating, analyzing, and transmitting simultaneously a wide variety of digitized data and information, including maps, graphics, sound, video, and text. The integration of multimedia with GIS not only greatly enhances the capability of pavement management systems; it also has the potential for a wide spectrum of other engineering applications. For example, the Odessa District (TxDOT) has launched a pilot project to incorporate digital roadway images into GIS to support decision making in its transportation infrastructure management.

5.4 ADVANCES IN DATABASE TECHNOLOGY

Owing to the large amount of space required to store necessary data and information for pavement management, data sharing is increasingly demanded by all sectors of government agencies for more efficient data use and management. In addition, a fundamental requirement of an integrated management system is the concept of enhanced data sharing and information exchange among related subsystems and their corresponding components. In response to these needs, database technology has advanced from centralized systems to more flexible distributed systems, from hierarchical databases to more efficient object-oriented databases, as illustrated in Figure 5.3.

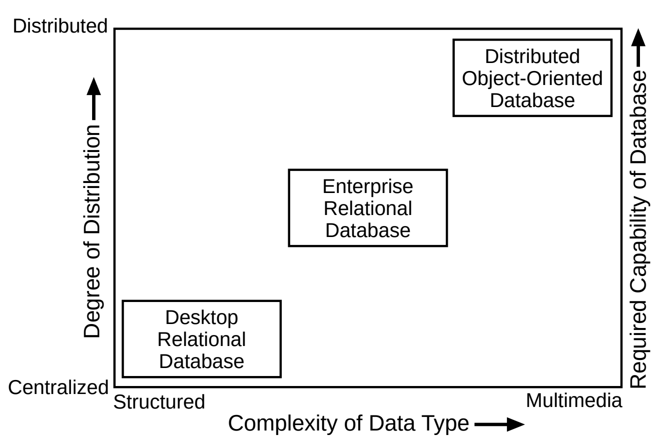

Figure 5.3 Complexity of data type and required capability of database

Based on its nature, data relevant to pavement management usually falls into two categories:

(1) traditional data collected with conventional means and stored in alphanumeric forms (e.g., character strings, numbers, ASCII files, etc.), and

(2) multimedia data, such as image, video, and sound, produced with modern equipment (e.g., videologging) and stored usually as objects.

Traditional data are usually managed in flat files, hierarchical databases, or relational databases. By providing a consistent and nonredundant structure of data, relational database systems have improved the development process of management systems where intensive data use is required. The high-level linguistic features and the facilities for controlled data sharing associated with relational databases make it possible to develop integrated management systems more easily than before. Furthermore, the integrity of data is better controlled through a set of highly tuned data formatting and access routines.

However, traditional relational databases cannot meet the requirements of effective and efficient management of these newer object-oriented data. The solution for this would be the newly emerged object-oriented databases (Schaaf, 1991; NCHRP, 1994; Zdonik et al., 1990; Larson, 1995). Unlike relational databases, which use a value-based model where an object is usually stored as a record and identified by a subset of its attributes (usually in the form of data fields) called a "unique key," object-oriented databases store information as objects and are characterized by their ability to make references through an immutable object identity. A current workable framework for the sharing of all kinds of data may use both relational databases and object-oriented databases.

For a system that has databases in separate geographical locations, distributed database systems are becoming increasingly popular for solving the problems of data sharing and information exchange. A distributed database system does not depend on any centralized computer; instead, data are accessed and shared among the workstations directly through automated protocols via network connections when necessary. For example, a national distributed database system has been proposed for the Federal Highway Administration's Long Term Pavement Performance (LTPP) Information Management System (IMS) (Rowshan, 1997). Although the distributed database systems eliminate the costs of central database management, acceptable performance requires relatively powerful workstations and high-speed network connections. Also, substantial efforts must be made during the IMS software development stage to control the database modification procedure so that consistency can be maintained among all workstations.

5.5 DIGITAL ORTHOPHOTOGRAPHY

Digital orthophotography involves a raster photographic image that is usually produced through aerial photography. These images can then be displayed in registration with vector map features in a GIS environment to support pavement management. Although aerial photography has been routinely used in hard-copy format for various pavement management purposes, the practical use of digital orthophotography was impeded in the past by (1) limited disk capacity for storing the huge raster images and (2) the limited computer memory required for displaying the images. However, recent advances in low-cost and high-volume hard disk capacity have made computer storage space no longer a problem for digital orthophotography implementation.

5.5.1 The Concepts of Orthophotography

An orthophoto is a photograph with images of ground features in their true map positions; it is similar to a vector map created photogrammetrically from aerial photography. This means an orthophoto provides two tools in one: a picture and a scaleable map. Thus, unlike conventional images, an orthophoto as a map can be used to make direct measurements of distances, angles, positions, and areas. Orthophoto differs from photo enlargement, which has varying scales as a result primarily of aircraft tilt, terrain relief, and camera lens distortion. In the orthophoto, a photogrammetric process removes the effects of tilt, relief, and lens distortion.

There are two kinds of orthophotos produced by the same methodology but by different equipment. A conventional orthophoto is created using mechanical image exposure to remove image displacements, a process that yields only hard copies. A digital orthophoto is a computerized version of a conventional orthophoto, an ortho-rectified raster image that is composed of picture elements (i.e., pixels). A digital orthophoto is a continuous-tone raster image. All pixels are "on" but in varying intensities of black, white, and gray. The intensity values range from 0 to 255. Digital orthophotos are created by using a computer image process to remove image displacements; in this way, digital orthophotos allow users to work not only with hard copies, but also with computerized maps.

5.5.2 Steps for Creating Digital Orthophotos

In practice, a five-step process to create digital orthophotos has been proposed as follows:

(1) Aerial photography should be taken during weather conditions suitable for taking clear photographs and at a scale appropriate for the accuracy and resolutions required. The aerial camera should be equipped with forward motion compensation, which ensures precise exposure and sharply defined photos.

(2) In preparing for an aerial flight, sufficient ground control points must be identified or established to orient the photographs to known coordinates and ground features. Then, through a process of aerotriangulation calculations, some points can be added to densify the ground control.

(3) Next, the aerial photographs can be scanned and converted into continuous-tone, digital raster images. Photographs should be scanned at a very high resolution to ensure high image quality. In the future, digital cameras may eliminate the need for image scanning.

(4) Aerial photographs are used to form a digital elevation model (DEM) that represents a topographic surface. The DEM will be used to correct the scale differences across the aerial imagery created by elevation changes, and remove the relief distortion. The DEM must be both accurate and dense enough to adequately define the terrain.

(5) Finally, the raster images are overlaid with the DEM and corrected, based on ground coordinates, so that the effects of relief distortion and terrain elevation differences can be removed. The resulting image is now an accurate, rectified raster image of the aerial photography.

The quality of digital orthophotos is important for GIS managers who will use the imagery in daily operations. The quality of digital orthophotos can be grouped into two categories: (1) spatial accuracy and (2) image quality. Spatial accuracy refers to the location of the picture element with reference to its true location. Image quality includes defects and tonal differences, etc. Many factors, such as DEM, image-processing software, the computer screen, and the output device, can affect the quality of digital orthophotos.

5.5.3 Applications of Orthophotography

Digital orthophotos are an accurate backdrop for many geographic information system (GIS) applications. In addition to enhancing the visual display of information, for the first time this base map can be used to add or correct the locations of features from the computer screen. Like other GIS base-mapping alternatives, digital orthophotos may not be appropriate for all applications. However, digital orthophotos may be a cost-effective base mapping option for GIS managers (e.g., county appraisers, public works managers) who need a detailed, accurate base map. Digital orthophotos provide a powerful yet cost-effective tool for meeting land use planning information needs. Besides serving as an accurate backdrop, digital orthophotos serve three other functions within GIS:

(1) *Update Other Attributes*. This function requires that GIS has a screen-digitizing function.

(2) *Quality Control*. Digital orthophotos can correct the errors of other attributes.

(3) *New Mapping*. Digital orthophotos can be used to identify locations not present on any existing map.

5.5.4 Practical Use of Digital Orthophotos

Although aerial photography has been routinely used in hard-copy format for various pavement management purposes, the practical use of digital orthophotography was impeded in the past by (1) the limited disk capacity for storing the huge raster images and (2) the limited computer memory for displaying the images.

However, recent advances in low-cost and high-volume hard disk capacity has made computer storage space no longer a problem for digital orthophotography implementation. A digital orthophotography image covering 932 sq. km (360 sq. miles) of San Diego County at 0.15 meters (0.5 ft) needs 55 GB of storage space, which is now affordable for most public works agencies. Second, the problem of display memory has been solved by the recent breakthrough method implemented in a software called DODI (Digital Orthophoto Display Interface) (Thorpe et al., 1994). The basic theory of the DODI method is that data are partitioned by geographical area and by scale. Area partitioning allows the imagery for a portion of the area to be accessed without retrieving the imagery of the entire area. Only those portions or tiles that overlap the region of interest are loaded into the memory and displayed on the screen. The objective of the DODI method is to reduce the amount of memory required by relying on the display software to seek directly the section of the tile required for display. As an example, the 18 GB digital orthophotography imagery of Dallas County has been integrated with GIS using the DODI software.

Undoubtedly, digital orthophotography will become an important addition to GIS in supporting pavement management, where it will be used as an accurate landbase allowing users to view the pavement and related features they are interested in. Digital orthophotography can also serve as a convenient and cost-effective way to verify and update existing pavement inventory information.

5.6 CLIENT-SERVER ARCHITECTURE

The development of computer network technology has made it possible for data and information stored in one computer (server) to be accessed by or transferred to a remote computer (client). The client/server architecture can serve as an ideal environment for the data sharing and information exchange that are increasingly demanded within transportation and public works agencies.

5.6.1 Benefits of Networking

Given the recent advances in computer networking, and given 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 computer networking technology. Major benefits from computer networking include:

(1) Software and File Sharing: Compared with individually licensed copies, many software manufacturers provide networkable versions of the same software packages at considerable lower costs. Data and files stored on one computer can be accessed by many other computers on the network.

(2) Hardware Resource Sharing: Through networks, such computer hardware resources as printers, plotters, and data storage devices can be shared by all users on the network.

(3) Database Sharing: Databases, especially large databases, usually consume a lot of disk storage space. A network allows many users to simultaneously access database files housed by the server computer and to manipulate them without damage to the data.

(4) Workgroups Structure: Through networks, individuals from diverse departments located in different physical areas can be organized to work for special group projects under the supervision of specific managers.

More specifically, the benefits of GIS client/server architecture over traditional GIS configurations can be summarized as follows:

(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 centralized administration and database control, client/server technology greatly simplifies administration of databases 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 handled 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.

5.6.2 Alternative Implementation Architecture

Client/server architecture can be implemented on a variety of computer platforms with proper configuration. While the basic components of all architectures are the same, the main difference lies in the extent to which the computing power is centralized or decentralized. A client/server system is half centralized and half distributed. In a centralized computer system, all IMS software and data reside on a single mainframe computer, and all users have to dial in to the mainframe in order to use the IMS. In a distributed system, a centralized computer is not required and data are shared among workstations through automated protocols as needed.

Centralized Client/Server: In centralized client/server architecture, all data are managed by a central database that resides on a central computer, the server. Used as a collection and distribution point for data, the server's only role is database management. All other software for reporting and analyzing resides on the client workstations. Since data collection, storage, and maintenance for pavement management are expensive, a centralized data server with a corporate database would save substantial development and support costs.

On the other hand, since the analysis capability of the IMS is resident on the client workstations, it is important to standardize all software modules of IMS so that they are fully compatible with each other.

Decentralized Client/Server: Decentralized client/server architecture is characterized by the addition of local area networks (LANs). The LANs act as clients relative to the central database server and as servers relative to workstations of individual users. Although LAN hardware and software represent additional costs compared with the centralized client/server architecture, the decentralized system can reduce the data communication costs. The decentralized client/server architecture is especially useful for a department whose divisions have established LANs (or are going to establish their LANs).

Distributed Databases: Distributed database systems are becoming increasingly popular for solving the problems of data sharing and information exchange in pavement management. The system does not depend on any centralized computer; instead, data are accessed and shared among the workstations directly through automated protocols as necessary. Although the distributed database systems eliminate the costs of central database management, acceptable performance requires relatively powerful workstations and high-speed network connections. Also, substantial efforts must be made during the IMS software development stage to control the database modification procedure so that consistency can be maintained among all workstations.

5.6.3 Practical Integration with GIS

Software vendors have recently released an intermediary software — a software layer residing between the client and the server to help manage and deliver data — to implement the client/server model. These "middleware" products provide an advanced tool for supporting high-performance client/server access to spatial data by multiple users in an enterprise environment.

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.

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

Taking advantage of the Windows NT platform, FRAMME (Facilities Rulebased Application Model Management Environment), Intergraph's premier AM/FM/GIS software, has proven attractive to many users. FRAMME is supported by Sybase, Oracle, Informix, Ingres, RDB, and DB2.

The client-server architecture is integrated with ESRI GIS at two levels. The first level is, as previously described, the peer-to-peer networking through which data and information can be easily shared among a group of users who use similar computers in a local area network (LAN). The second level is integrated in a way whereby Visual IMS serves as a client to directly access data stored on dedicated servers. One example is to access ARC/INFO data stored on a UNIX workstation from within Visual IMS. Since ArcView does not have the built-in capability to mount remote file systems, networking software must be used to mount remote file systems for data access.

ArcView software operates in three basic environments: Windows (NT, 3.1, Workgroups 3.11), UNIX, and Macintosh. Network technologies enable other computing platforms to function as file servers even if they do not support the running of ArcView. The discussion here will focus on six server systems: UNIX (NFS), Windows NT, Server Version 3.5, Novell, Banyan, Windows for Workgroups, and Macintosh. Figure 5.4 summarizes the requirements for connecting a Visual IMS client to different file system servers.

The UNIX network file system (NFS), originally developed by Sun Microsystems Inc., is an industry-standard specification for supporting distributed file systems. NFS is based on and requires the TCP/IP network protocol. Many NFS-based products have been developed by different companies to provide network access to file systems for UNIX and other operating systems. For instance, for a PC to access UNIX file systems, NFS products can map the remote UNIX file system to a logical driver on the PC. Windows NT, Windows for Workgroups, Novell, and Banyan are four commonly used PC network systems. A PC network usually has a central and dedicated file server; and PCs in the network can access data by directly connecting to the server, as the network operating systems make the remote data on the server appear local. A Macintosh network requires a dedicated Macintosh computer as a network server and software for both server and workstations. It uses the AppleTalk Filing Protocol (AFP), similar in concept to NFS, as the network protocol.

Computer networking is a relatively new and complex technology. This chapter has discussed a practical procedure for making IMS work in the client/server environment. Most of the transportation and public works agencies are already in the process of retooling their computer systems to accommodate client/server architecture. It can be forecast that client/server-based computer networking will play an increasingly important role in the practice of pavement and other transportation infrastructure management.

In summary, client/server architecture can serve as an ideal environment for data sharing and information exchange for integrated transportation infrastructure management, which are increasingly demanded by public works agencies. For example, the Texas Department of Transportation (TxDOT) and other state DOTs are in the process of retooling their computers to accommodate client/server architecture, using Microsoft Windows NT as the operating system.

Client / Server	PC Windows			UNIX	Macintosh
	Windows 3.1	**Windows for Workgroups 3.11**	**Windows NT**		
UNIX (NFS)	PC-NFS	PC-NFS	• Chameleon NFS (Net Manage) • PC-NFS for NT (Intergraph)	Native UNIX NFS	• MacTCP • LAN Workplace for Macintosh
Windows NT Server V3.5	Not Accessible	Windows for Workgroups 3.11	Native NT	Chamleon NFS Server	Add-on to NT server V3.5
Netware Server	NetWare Client Software	NetWare Client Software	• Services for NetWare • NT Requestor	NetWare NFS	NetWare for Macintosh
Banyan	Banyan Client Software	Banyan Client Software	Banyan Client for NT	Banyan Client for UNIX	MacLAN Connect DOS Version
Windows 16-bit OS	LANtastic	Windows for Workgroups 3.11	Not Accessible	N/A	MacLAN Connect
Macintosh	Products from Miramar Systems	N/A	N/A	Partner	Native Macintosh file systems

Figure 5.4 A summary of software requirements for connecting ESRI software to different file system servers

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