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Management Guide for Implementation of Geographic Information Systems (GIS) in State DOTs

A digest of the essential findings from a special report generated in NCHRP Project 20-27, "Adaptation of Geographic Information Systems for Transportation," prepared by Alan Vonderohe, Larry Travis, Robert Smith, and Victor Tsai, University of Wisconsin, Madison, and Myron Bacon, Consultant.

THE PROBLEM AND ITS SOLUTION

GIS has been successfully applied in many fields outside of the transportation industry. However, the full capabilities of GIS for transportation have yet to be realized. The primary objective of this research was to develop a top-level design and implementation plan for GIS-T that is responsive to current and projected technological capabilities and constraints as well as to economic, social, and institutional needs, and that will have immediate and favorable impact on GIS endeavors in transportation. NCHRP Project 20-27 resulted in three documents: (1) a Final Report that details a top-level system design and implementation plan for Geographic Information Systems for Transportation (GIS-T); (2) this Management Guide, intended for technical managers within transportation agencies; and (3) a brief version of this Management Guide, intended for upper managers at the Bureau Chief or Division Chief level.

The purpose of this Management Guide is (1) to provide a basic understanding of GIS and GIS-T; (2) to describe the factors involved in successful planning and implementation of GIS-T; (3) to provide a basic understanding of how GIS-T can benefit transportation agencies; and (4) to describe benefit-cost considerations and methods for evaluating the success of GIS-T implementation.

FINDINGS

The work reported herein is intended to provide a basis on which individual transportation agencies can develop or revitalize—and then proceed with—plans to exploit GIS technology to the fullest in both the near-term and long-term futures. The driving considerations behind the research have been the following:

1. Current and expected future demands for information management and analysis in support of transportation agency missions;
2. The need for data and systems integration within transportation agencies and across multiple units of government;
3. Technology trends; and
4. Organizational considerations and constraints.

Although details are provided on the functionality and interrelationships of the recommended system components and on the recommended approach to GIS-T implementation planning, the results are general in nature and should be considered as guidelines rather than as specifications.

The contents of this Management Guide appears on the following page. Additional information derived from this project can be found in Research Results Digest 180, *Implementation of Geographic Information Systems (GIS) in State DOTs* and NCHRP Report 359, *Adaptation of Geographic Information Systems for Transportation.*

CONTENTS

CHAPTER 1. INTRODUCTION

1.1 NEED FOR GIS-T

Transportation agencies are currently faced with ever-increasing demands for information to support more effective decision making throughout their organizations, from engineering at the individual project level to statewide planning and management. Furthermore, the broad environmental and economic development problems that confront all of society today require data sharing and cooperation among multiple government agencies at all levels. These demands for improved information often manifest themselves as mandates such as the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 that requires systems for traffic monitoring and for management of pavement, bridges, safety, congestion, public transportation, and intermodal facilities and equipment.

ISTEA includes consideration for the ability of these mandated systems to integrate with one another. The recent Hazardous Waste Act will force the integration of transportation-specific data with externally managed data (such as demographic data) to produce routing and emergency response plans. Recent amendments to the Clean Air Act will entail the integration of diverse information on transportation, population, and land use, as well as the integration of independently developed and managed forecasting systems such as urban planning and air quality models.

All of the data required by the ISTEA management and monitoring systems, the Hazardous Waste Act, the Clear Air Act, and, in fact, nearly all of the data managed by transportation agencies in general, are or can be and should be, geographically referenced. Therein lies the key to integration. The concept of location as an integrator for transportation data was promoted by Briggs and Chatfield in 1987 (*1*). GIS now provides the means.

1.2 GIS-T IN TRANSPORTATION AGENCIES

The research included a survey and data-collection task consisting of the following five primary components: (1) interviews with each state's DOT, (2) site visits to selected state DOTs, (3) a meeting of the research team with a panel of experts to assure correct interpretation of preliminary findings, (4) interviews with selected Metropolitan Planning Organizations (MPOs), and (5) a survey of GIS software vendors covering product characteristics and plans for the future (especially as these characteristics and plans pertain to transportation applications).

Based on the results of the survey and data-collection effort, the technology and institutional contexts for GIS-T planning and implementation were characterized. Principal aspects of the technology context are as follows:

1. The moving target problem. GIS technology and, more generally, the information technology of which it is a part are changing rapidly, making them very difficult to plan for.
2. The multiple technology problem. There are several new and imminent information technologies, including GIS, for which plans must be developed in concert. For example, a GIS-T technology adoption plan cannot and should not be developed independently of a networking technology plan. Moreover, the integration of these technologies should be addressed in the planning process.
3. The data integration problem. Data integration across different application areas is an urgent, longstanding need of DOTs. Because of the cost of their acquisition and maintenance, GIS data must be shared and integrated across as many applications as possible. On the other hand, the concept of location, for which GIS technology provides an efficient means of representing and processing, can serve as an integrative concept across a wide variety of data, both geographic and other kinds.

Principal aspects of the institutional context for GIS adoption and application by DOTs include the following:

1. Determining the most critical applications that must carry the brunt of initial GIS spatial data acquisition costs.
2. Sharing costs across applications.
3. Gaining and retaining support of high-level management and of the public.

4. Coordinating with other state agencies and with external organizations.
5. Utilizing standards developments.
6. Integrating GIS introduction and development into an information systems plan that covers all aspects of information technology for the entire organization.

1.2.1 State DOTs

Details of the status of GIS-T within state DOTs have been previously published (*2*). The nine topic areas addressed by the interview questionnaire are summarized as follows:

1. Activities, Objectives, Status. Nearly all DOTs have some GIS-T activity. Some are just starting, some are evaluating systems, some are doing pilots, and a few are doing strategic planning. Very few have organization-wide commitment, and even fewer have organization-wide applications and support in place. Many DOTs recognize that there is great potential in GIS-T.
2. Applications. A number of DOTs are redesigning their highway inventory databases in order to begin GIS-T application development. Many functional applications are based on pilot projects. The applications mentioned most often as being in place, under development, or planned were pavement management, bridge management, safety analysis, and routing (typically for oversize or overweight vehicles).
3. State Government Computing Environment. The general trend in the administration of statewide computing appears to be toward more centralization. However, the technological trends are such that they no longer provide much of the justification for such centralization that used to exist. Most DOTs retain autonomy in the administration of engineering computing.
4. Departmental General Computing Environment. Nearly all DOTs have their corporate databases on large mainframes. There are often linkages to numbers of PC local area networks (LANs). Many DOTs are moving, or intend to move, their engineering computing to powerful workstations. The use of networks is growing, but most states are far from achieving seamless network integration among PCs, workstations, and mainframes.
5. Departmental GIS-T Computing Environment. DOTs have acquired software from three primary vendors—Intergraph, Environmental Systems Research Institute (ESRI), and McDonnell Douglas (their GIS software division was recently acquired by Electronic Data Systems). Some DOTs are using Caliper Corporation's software experimentally. A number of DOTs have invested previously in computer-aided design (CAD) systems and are now acquiring their CAD vendor's (Intergraph) GIS products. Most often, a DOT's GIS-T software is workstation-based. All of the primary vendors' products can be linked to external database management systems for the management of attribute data. The administration of GIS-T computing ranges from full-service GIS sections to loosely confederated end-user groups.
6. Data Environment and Issues. The GIS-T data environment is fraught with unanswered questions and unresolved issues. There is disagreement on the appropriate scale for the spatial database. (Actually, there is no single appropriate scale and DOTs should probably plan on managing three. See Section 3.4.1.) There is no accepted standard for spatial database maintenance. However, database maintenance from the standpoint of lineage tracking has been addressed by the Wisconsin DOT (*3*). Many states have found that the structures of their attribute databases are incompatible with GIS-T. They are also finding that there are inconsistencies in location-referencing methods used throughout their departments for different applications. It appears not only that future data collection will be affected by technology such as GPS, but also that the future administration of data will need to change to realize the full potential of GIS-T. (That is, data need to be viewed as a corporate resource.)
7. Statewide Efforts. Every state has some GIS coordination activity among state agencies (*4*). Some of these efforts are ad hoc, some are under executive order, and some are legislated. DOTs are often looked to for leadership and technical knowledge in these statewide efforts.
8. Management Issues. Knowledgeable support for GIS-T from top management is generally viewed as indispensable but difficult to obtain and sustain. The most effective efforts have a top manager (with budget authority) who sponsors a technical manager who in turn spearheads system

design and implementation. There is a danger in over-selling GIS-T. It is critically important that GIS-T be included in a formal strategic planning process. It is difficult to find personnel with the right background. Typically, staffing of successful GIS-T involves retraining; the skills and expertise required are not otherwise available.

9. Advances in Technology. More intervendor compatibility must be developed. Current data-exchange formats and procedures result in the loss of too much information. GIS-T data models need better representation of objects important for transportation like networks, routes, and linear segments. Computer-aided software engineering (CASE) capabilities that support GIS-T applications need to be developed. Networking technology needs to be improved. Work must be done to integrate advanced data-collection techniques with GIS-T.

1.2.2 Metropolitan Planning Organizations

Eleven MPOs were interviewed by telephone. A summary of the results has been previously published in (*2*). Nearly all of the MPOs contacted reported at least beginning to look at developing GIS-T capability, but not necessarily as a result of agency-wide commitment. Some efforts have been hampered by lack of funds and by staff limitations. Landsat and SPOT images are being used to develop land use databases. Some agencies have participated in development of parcel-level databases as part of an overall local government effort. One agency has established linkages between GIS-T and existing transportation models. One of the major barriers to integration of GIS-T and transportation planning activities is the lack of detailed documentation of the methodologies used by the leading MPOs.

CHAPTER 2. DEFINITION AND ROLE OF GIS-T

2.1 DEFINITION OF GIS AND GIS-T

There is considerable variation across different contexts and among different speakers in usage of the phrases "geographic information system" and "GIS." In its narrowest sense, "GIS" refers only to specialized software for the management and analysis of spatial data and their attributes. In other contexts, the term refers to both hardware and software. Still other usages comprehend hardware, software, and data.

Perhaps the nearest to a consensus definition is the one provided by Dueker and Kjerne (*5*, pg. 99). They used a Delphi process to generate the following definition:

Geographic Information System -- A system of hardware, software, data, people, organizations, and institutional arrangements for collecting, storing, analyzing, and disseminating information about areas of the earth.

According to this definition, as shown in Figure 1, a GIS includes not only computing capability and data, but also managers and users, the organizations within which they function, and the institutional relationships that govern their management and use of information. This broad view establishes a fundamental premise that the technology of GIS cannot usefully be evaluated, projected, and planned for in isolation from institutional setting, management framework, and staffing resources on which success or failure of the GIS will depend. GIS system design and implementation planning are not separable processes. They must occur in conjunction with one another.

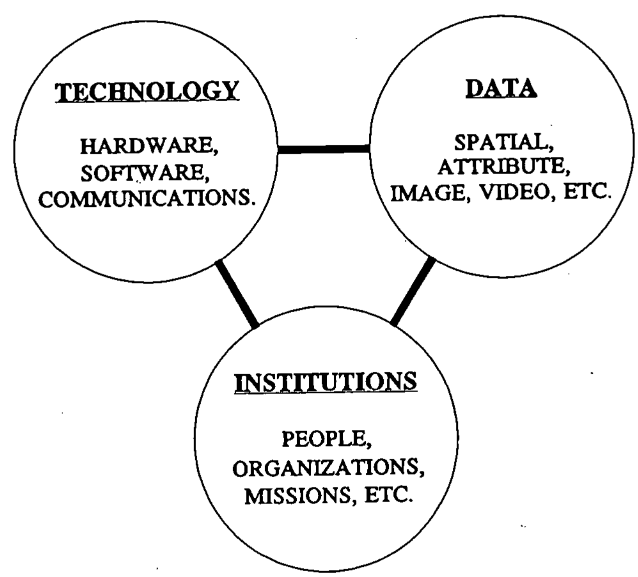

Figure 1. The Domain of GIS.

"GIS" also connotes a new paradigm for the organization of information and the design of information systems. The essential aspect of this paradigm is use of the concept of location as a basis for the restructuring of information systems and the development of new ones. The concept of location becomes the basis for implementing the long-sought goals of data and systems integration (*1*, *6*, pg. 1).

Figure 2 depicts GIS-T conceived from this point of view, that is, as the union of an enhanced Transportation Information System (TIS) and an enhanced GIS. The necessary enhancement to existing TISs is the structuring of the attribute databases to provide consistent location reference data in a form compatible with the GIS, which in turn has been enhanced to represent and process geographic data in the forms required for transportation applications.

This does not imply that databases must be redesigned according to constraints imposed by commercial software. In fact, one of the required enhancements to off-the-shelf GIS software is the ability to link with and utilize the linearly referenced highway data collected and maintained by transportation agencies.

What it does imply is that the attribute databases use a database schema for the concept of location that is translatable into the location schema used in the GIS spatial databases (the databases containing the digital base maps) so that the content of the former can be unambiguously correlated with the content of the latter. Queries can then span both kinds of databases, and separate attribute databases can be integrated through their use of a location schema translatable into the ones used by the GIS software.

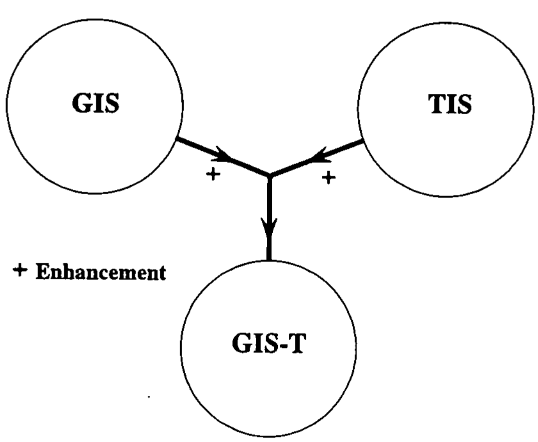

Figure 2. GIS-T as the Merger of an Enhanced GIS and Enhanced TIS.

In addition to improved management of linearly referenced data, necessary enhancements to GIS software include better modeling and analysis of transportation networks. These necessary enhancements are described in further detail in the following section.

2.2 FUNCTIONALITY OF GIS AND GIS-T SOFTWARE

Recently, a number of other authors have classified the extended functionality of GIS software according to various schemes [for example, see (*7*, pp. 7-10; *8*, pp. 29-38; *9*, pp. 42-43; *10*, pp. J.1.3-J.1.6; *11*, pp. 11-25; *12*, pp. 165-179; *13*, pp. 319-335; and *14*, insert)]. However, no single software product contains all possible GIS functionalities. Each product has its relative strengths and weaknesses. Many products have historical roots that underlie current strengths (e.g., image processing or polygon processing). Based approximately on the classification scheme provided in (*14*), Sections 2.2.1 - 2.2.9 describe a functional framework for GIS.

2.2.1 Supported Spatial Data Models

A GIS spatial database is a structured collection of digital graphic and nongraphic data that describe the locations and spatial relationships of geographic features. As shown in Figure 3, the data can be represented by various models, depending on types and characteristics of the data, requirements for efficient data storage and processing, and the varied applications that make use of GIS in particular situations: (1) raster, (2) two-dimensional topological vector, (3) surfaces, and (4) three and four dimensions. A raster data model consists of a matrix of grid cells (usually square in shape), each of which stores an identifier for the type, value, or index to the attribute being mapped within its area. A two-dimensional topological vector data model consists of points, lines, and areas that are encoded with topological relationships such as incidence, adjacency, and connectivity. Surface data models add the third dimension, as a function of the first two, in the form of raster-based digital elevation models (DEMs) or vector-based triangulated irregular networks (TINs). Three-dimensional data models describe solid features, while the time

dimension is added in four-dimensional models. Current GIS software does not fully support three- and four-dimensional data models.

Some current GIS products allow hybrid and flexible processing of two-dimensional raster and vector data. One example is performing interactive operations in vector space with a raster image as a backdrop, such as on-screen digitizing of a new highway alignment from the display of a digital orthophoto. A second example is automatic extraction of information from raster data to be used in vector-based analysis, such as extracting land-cover polygons from a satellite image with a classifier, to overlay them with a transportation network model.

2.2.2 Data Entry

Data entry is the process of encoding data from their existing forms into an automated database. Geo-referenced data exist in various formats such as hardcopy maps, tables of attributes, electronic files of map features, airphotos, satellite imagery, and documents of field observations. In addition to keyboard entry of attribute data and input from existing digital files via spatial data-exchange formats discussed below, GIS can support data entry through (1) manual digitizing, (2) scanning, (3) photogrammetric stations, (4) coordinate geometry (COGO) from field surveys, (5) global positioning system (GPS) receivers and (6) raster-based devices such as digital cameras and satellite, thermal infrared, and radar sensors. Additional processing in the GIS environment is often required to make the spatial data fully useful.

2.2.3 Spatial Data Exchange Formats

Spatial data exchange is important in GIS for the integration of disparate data sets from dissimilar computer systems. The two basic methods for data exchange between different GISs are: (1) direct conversion of data from one system to another using proprietary formats and (2) translation of data via a standardized neutral exchange file format. The use of neutral exchange file formats has the significant advantage that, in theory at least, only two software routines are required (i.e., one to import and one to export the neutral exchange format). Some of the most widely used exchange formats developed by either major data producers or national standards institutions are (1) GBF/DIME, the Census Bureau's geographic base files (GBFs) created for the 1970 and 1980 censuses using the dual independent map encoding (DIME) technique (*15*); (2) TIGER, the Topologically Integrated Geographic Encoding and Referencing system developed by the Census Bureau to support data collection and data tabulation for the 1990 decennial census (*15*); (3) DLG, the Digital Line Graph cartographic data standard established by the United States Geological Survey (USGS) (*16, 17, 18*); (4) IGES, the Initial Graphics Exchange Specification for typical geometric, graphical, and annotation entities in computer-aided design (CAD) and computer-aided manufacturing (CAM) systems (*19*); and (5) SDTS, the Spatial Data Transfer Standard approved by the National Institute of Standards and Technology as Federal Information Processing Standard (FIPS) 173 (*20, 21*).

2.2.4 Spatial & Nonspatial Data Management

With a few exceptions, a typical commercial GIS package manages spatial data with customized software that is linked to a database management system (DBMS) fc. handling attributes. In some cases the DBMS is internal, but in many others the spatial data management software can be linked to external, third-party DBMSs such as DB2, Dbase, Foxbase, INFO, Informix, Ingres, Oracle, Rbase, and others. This feature allows GIS spatial databases to be linked directly to existing attribute data. It also incorporates the functionality of the third-party DBMS in the overall system. This functionality can include various query methods; database operations such as file sorting, relational joins, and calculation of new values by arithmetic or logical expressions; report generation; statistical summaries; status and lineage tracking; system security measures; and computer network operations.

2.2.5 User Interfaces

GIS software usually provides one or more interactive interfaces so that users can initiate system operations using command languages, menus, or user-generated macros. In some cases, source and object code libraries are made available for application development. Many GIS packages run under windowing environments that allow concurrent running of separate GIS tasks and multiple views of

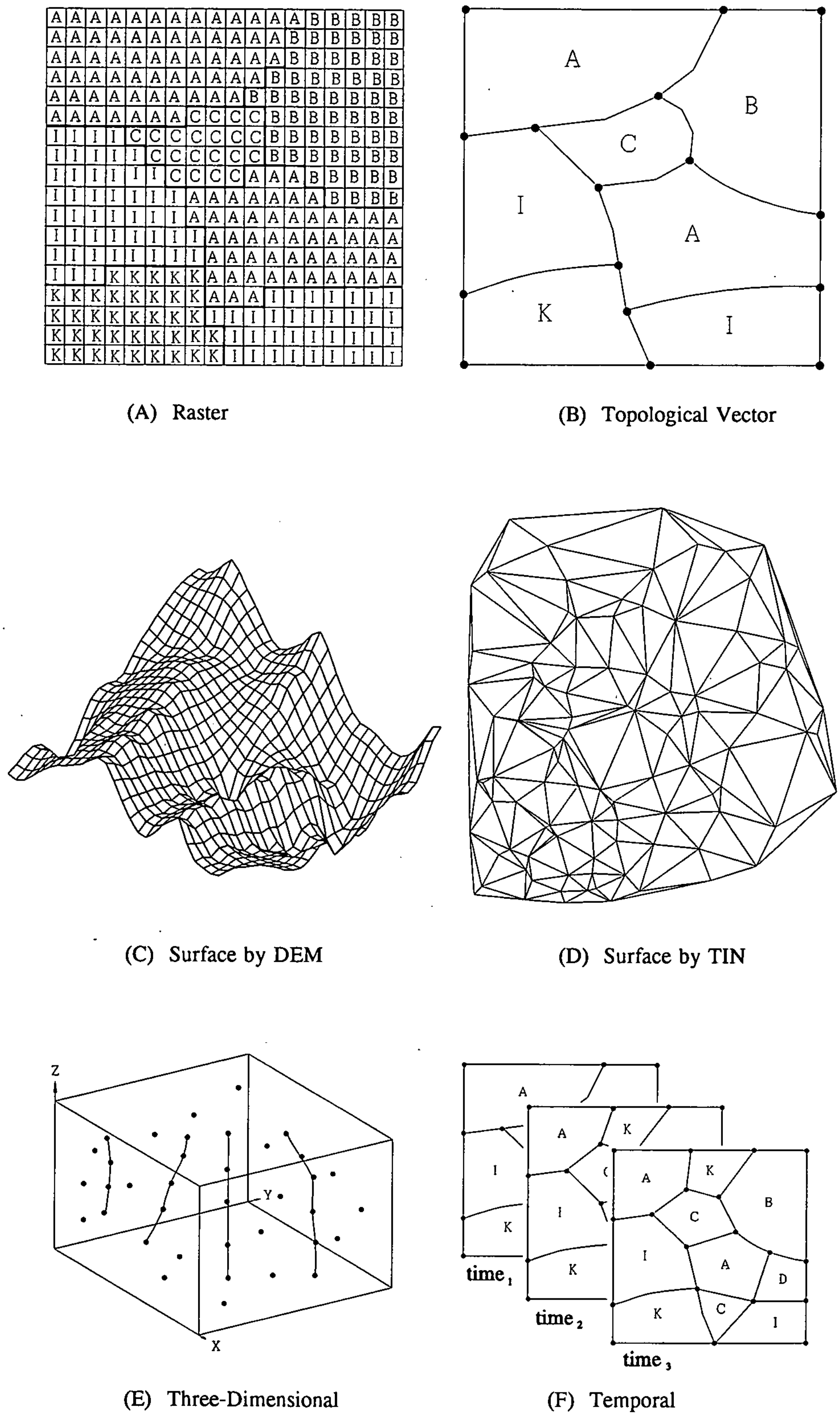

Figure 3. Spatial Data Models.

the database on split screens. Workstation-based packages use multiuser operating systems that allow several users to share software and data resources.

2.2.6 Spatial Data Processing and Editing

Typically, a number of functions will be provided for building and maintaining spatial databases including (1) editing; (2) topology building; and (3) edge matching, aggregation, and generalization. Editing encompasses a wide variety of interactive functions such as zooming and panning; adding, deleting, copying, moving, and transforming individual objects or collections of objects selected by pointing, by encompassing within an area, or by attribute values; associating identifiers with features (attribute tagging); and annotation editing. Many vector-based systems will automatically determine topologic relationships. Edge matching is used to create seamless spatial databases from individual, adjacent, digitized map sheets. Line generalization functions drop densely packed vertices according to user-controlled criteria.

2.2.7 Database Transformation

Transformations on entire databases are either between data models or between coordinate systems. Transformations between data models include raster-to-vector conversion and vector-to-raster conversion. These automated procedures often lead to interactive editing of the data after transformation. Coordinate system transformations can be (1) arbitrary-to-ground, (2) between geodetic datums, or (3) ground-to-ground.

2.2.8 Data Retrieval, Data Manipulation, and Spatial Analysis

Retrieval operations on both spatial and nonspatial data involve selective searches of databases and output of retrieved data in response to various queries. Queries can be made by location (through geographic features) or by characteristics (through attributes).

Spatial analysis functions distinguish GIS from other information systems and from computer-aided mapping systems. Six general categories of functions for data manipulation and spatial analysis are:

1. Measurement. Spatial measurements reveal metric properties of geographic features such as straight-line distances between points, lengths of lines and perimeters, areas, and centroids of polygons.
2. Proximity Analysis. Some proximity analysis functions, such as buffer generation and Thiessen tessellation, create zones of interest around selected geographic features that can then be used to retrieve attributes or generate new features. Other functions support queries concerning adjacency and spatial clustering of features.
3. Raster Processing. Raster data are processed using either map algebra (for map layers) or digital image analysis (for images). Map algebra integrates geographic features on different map layers to produce a new map layer according to a set of specific algebraic operations. Map layers of individual characteristics such as soil type, land use, or elevation are treated as variables that can be combined or transformed into new variables by numerical operations, size measurements, distance and direction calculations, zone reclassifications, and so on. Combinations of these algebraic operations can be used to model complex geographic phenomena (*13*, p. 365). Digital image analysis involves extraction of information from satellite images or scanned aerial photographs. Image enhancement can be used to derive spatial properties and spectral characteristics can be used to classify features.
4. Surface model generation and analysis. Surface model generation functions create TINs from DEMs or from randomly spaced points, or they create DEMs from TINs or from randomly spaced points. Surface analysis functions that calculate values, determine characteristics, and identify features on surfaces are used extensively in engineering planning and design.
5. Network analysis. Network analysis is obviously critical for transportation applications. Two vital analysis functions, dynamic segmentation and network overlay, were identified and found wanting when transportation professionals first attempted to apply existing GIS tools to major transportation problems (*6*, *22*, *23*, *24*):

   a) Dynamic segmentation. This function associates network attribute databases that are linearly referenced with topologically structured spatial databases (network models) whose reference frameworks are coordinate-based. To avoid the need for explicit representation of all point features and segment

boundaries within the spatial database, dynamic segmentation computes coordinates from linear references "on-the-fly." Some implementations provide an option for creating new spatial objects and topology with dynamic segmentation by inserting nodes at each pair of computed coordinates.

b) Network overlay. This function enables the integration of disparate, linearly referenced, highway attribute databases. It is in effect a spatial relation function that joins two or more sets of attributes by performing a combined sort of their linear references. Network overlay can be used to integrate points with segments (e.g., accidents with pavement conditions) and segments with segments (e.g., pavement types with shoulder widths).

Dynamic segmentation and network overlay enable spatial analysis and integration of highway inventory databases and any other databases that are linearly referenced. They open the door to a host of transportation applications in all functional areas.

Another class of functions addresses spatial or statistical analysis of topology, impedance, and flow within networks. Functions in this class fall into four groups: (1) shortest path analysis, (2) optimum tour routing, (3) location/allocation, and (4) transportation and transshipment problems (*25*, p. II-74; *26*).

6. Polygon overlay. Polygon overlay operations combine separate spatial databases and at the same time integrate their attributes. New spatial features with combined attributes often result. Polygons can be overlaid with other polygons, lines, or points to determine which geographic features and their attributes fall within the polygons of interest.

2.2.9 Data Output and Presentation

Numerous devices and functions exist for data output and presentation in the forms of maps, tables of values, text reports, graphics displays, or softcopy files. Supported hardcopy output devices can include pen plotters, electrostatic plotters, laser printers, line printers, optical film writers, and screen capture devices connected to graphics displays. GIS functions that support final output and presentation include vector-on-raster display, multiple maps on single plots, three-dimensional display, and animation. Specialized cartographic tools are used to produce maps. Capabilities for generating reports depend on the database management system that is linked to the GIS. Very often this will be a relational DBMS that supports structured query language (SQL).

2.2.10 Enhancements for GIS-T

Dynamic segmentation and network overlay have been described as critical for GIS-T. These are enhancements to the analytical functionality of GIS. There are also aspects of the GIS-T data model that are of vital importance:

1. The set of spatial primitives must include routes. Effective implementation of dynamic segmentation and network overlay depend on this. Multiple routes should be capable of sharing common links.
2. General attributes should be assignable to nodes. That is, in addition to turns through intersections, nodes should be able to have attributes such as signal timing or the number of turning lanes.
3. Network topology should not be dependent on a planar graphical representation. That is, there should be support for the absence of nodes at underpasses and overpasses.
4. It should be possible to associate multiple topologic representations with a single geometric representation, for example, in the case of a divided highway represented geometrically as a single chain due to a high level of abstraction. And, conversely, it should be possible to associate a single topologic representation with multiple geometric representations, such as those at different levels of abstraction.

2.2.11 Summary

Two-dimensional raster and vector data models dominate GIS. It is possible to represent surfaces with 2.5-dimensional DEMs and TINs. Three-dimensional models need further development and research is just beginning to establish some building blocks for four-dimensional models.

Technologies that capture spatial data include manual digitizing, automatic scanning, advanced

photogrammetric methods, coordinate geometry, GPS, electronic data collectors, digital cameras, multispectral scanners, radar, and thermal infrared imaging. Options for exchange of spatial data include direct conversion from one proprietary format to another and translation through a standardized neutral exchange format. The Spatial Data Transfer Standard (SDTS) became Federal Information Processing Standard 173 in 1992.

Spatial data in a GIS are usually managed by customized software while attribute data might be managed by a third-party DBMS. User interfaces include command languages, menus, and windowing environments. Development tools might include macro languages and object code libraries.

Both batch and interactive editing are usually supported. There might be functions for topology building, edge matching, aggregation, and generalization. Transformations of entire databases can be made between data models and among various coordinate referencing systems. Simple queries enable data to be retrieved by pointing with a cursor or by specifying attributes. A number of functions support map preparation and presentation of data for final output.

Spatial analysis functions distinguish GIS from other information technologies. These functions can be placed in six groups: (1) measurement, (2) proximity analysis, (3) raster processing, (4) surface model generation and analysis, (5) network analysis, and (6) polygon overlay. Of these, extended network analysis functions, including dynamic segmentation and network overlay, are critical for GIS-T. This is not intended to diminish the importance of all other GIS functions. Indeed, they are all important to transportation. As the number and complexity of GIS-T applications grow, the number and kinds of necessary functions will also grow.

In addition to specialized functionality, GIS-T requires certain characteristics of its data model. These include the recognition of routes as spatial primitives, a general treatment of node attributes, freeing the network model from that of a planar graph, and allowing multiple associations among geometric and topologic representations.

It is the overlay functions (i.e., network overlay and the variations of polygon overlay) that best exemplify the data integration power of GIS. Their very purpose is to combine existing databases in such ways that new information is created.

In summary, at a minimum GIS-T software will have the following:

1. A topological data structure that enables appropriate representation of highway networks.
2. Input and editing capabilities for geographically structured data.
3. The ability to link locational and attribute data (including dynamic segmentation).
4. The ability to perform spatial analysis, including map overlay extended to include network overlay.
5. The ability to display geographic information.

2.3 ROLE OF GIS-T IN TRANSPORTATION AGENCIES

The major significance of GIS-T for DOTs is in its paradigm as an integrator. GIS-T is clearly a data integrator. Stand-alone databases of the past can now be integrated as needed. This is true not only for data referenced to highway networks such as highway and bridge inventories; photologs; alignments and other design detail; signage, accident records, and other safety data; traffic volumes, flows, and other operational data; and right of way and other ownership data. It is also true for even more disparate data such as administrative, land use, demographic, environmental, resource, terrain, and subsurface data. GIS-T does not create a single integrated database, rather it creates a mechanism for integration at will to assist in solving whatever problem is at hand.

GIS-T also serves as a systems and process integrator. As depicted in Figure 4, the components of the infrastructure lifecycle management process (also the functional areas of a transportation agency) can be viewed as contributing to and extracting from a common spatial data store (*27*, pg. 18). Although the various components might require data at varying levels of abstraction and over varying geographic extents, GIS-T provides mechanisms for data conflation and data aggregation. In this view, the major functional areas of DOTs are more closely bound than in earlier views of infrastructure management as a series of linearly related processes.

Potential GIS-T applications span all functional areas and include the following:

1. At the planning stage—transportation planning, pavement management, bridge management, capacity management, air quality analysis, etc.

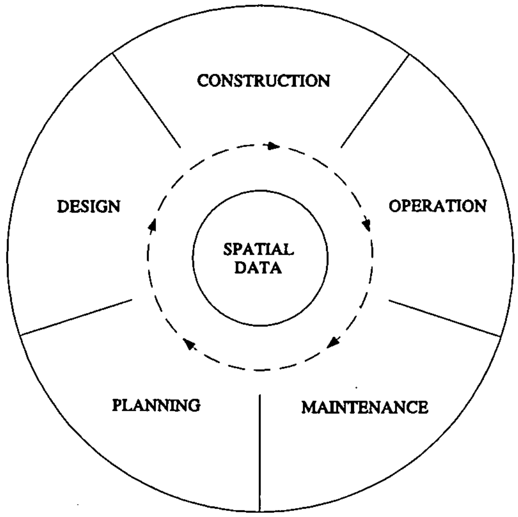

Figure 4. Spatial Data Are Central to Transportation Infrastructure Lifecycle Management. (Source: Adams et al., Ref. 27, p. 19)

2. At the preliminary design stage—corridor investigation, environmental investigation, right-of-way acquisition, etc.
3. At the construction stage—construction planning, detour routing, site management, etc.
4. At the operations and maintenance stages—highway inventory, accident analysis, winter storm management, traffic monitoring, hazardous waste routing, oversize and overweight permitting, etc.

Process integration is also apparent in Huxhold's holistic model of information needs and the business of government (*28*, pp. 12-24) (see Figure 5).

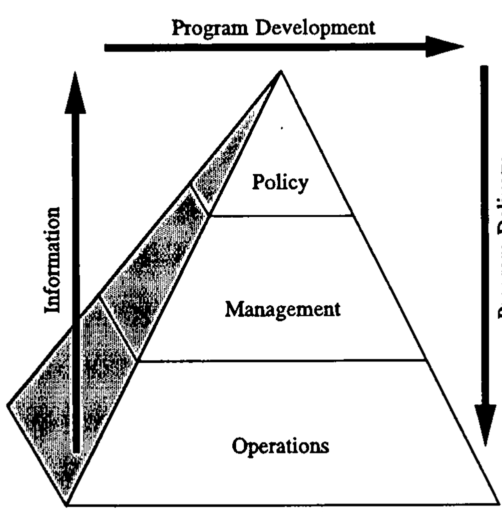

Figure 5. Transportation Business Pyramid. (Source: Huxhold, Ref. 28, p. 14)

Here, basic data are created at the operations level, are summarized for decision making at the management level, and are aggregated even further for policy making. In turn, top-level or policy decision making addresses organization-wide issues during extended time periods, management translates policy into actions, and services to the public are delivered at the operations level. Most of the data at all three levels are geographically referenced. This view of the relationship between information flow and program delivery leads to comprehensive information systems design that supports the organization as a whole.

GIS-T concepts are also at the heart of technology integration. The technologies depicted in Figure 6 are integratable, along the indicated linkages, at either (1) the visual level through display-time overlays or (2) the data model level through conversion mechanisms (*29*, pg. 24). All of the technologies in Figure 6 are used to capture, manipulate, analyze, or present spatial data and spatially referenced data.

The potential impact of GIS-T is profound. If this technology is exploited to its fullest, it will become ubiquitous throughout all transportation agencies and will become an integral part of their everyday information processing environments. It will become as typical and normal to use GIS as it was to depend on long printouts from the mainframe applications of the past and as it is to use general-purpose PC tools like spreadsheets and word-processors at the present time. GIS-T has the potential to become pervasive because it provides an effective means for transportation agencies to address many of the major information management problems that they face today.

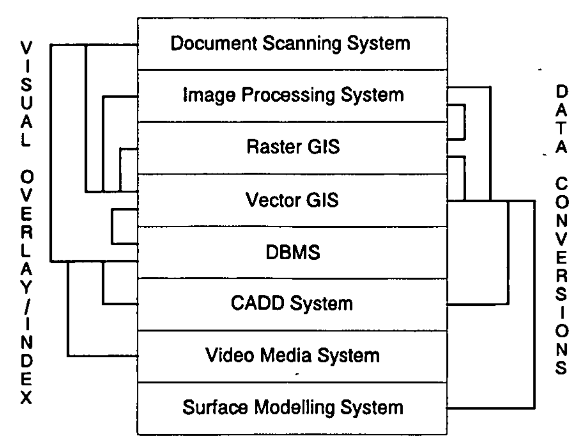

Figure 6. Technology Integration. (Source: ESRI, Ref. 29, pg. 24)

CHAPTER 3. CRITICAL SUCCESS FACTORS

3.1 INTEGRATED INFORMATION SYSTEMS STRATEGY

This chapter provides a critical success factor base that can be used to evaluate a particular organization's ability to successfully plan and implement GIS-T, as well as a base that can be used to monitor progress. To fully realize the potential of GIS-T, to have the widest possible base of users, and to have the technology instilled in an organization's information management environment, each of the factors discussed below is deemed critical.

3.1.1 Multiple Technologies

DOTs need to plan for and combine the simultaneous implementation of several promising technological developments. At the present time GIS is not the only emerging technology that should be incorporated in an information technology plan. There are a number of others all of which must be coherently integrated. Treating the different emerging technologies in isolation (i.e., developing a separate plan for each) is to miss their interdependencies and to fail to take advantage of the ways in which they complement each other. There will be significant benefits in merging them into a single, coherent plan.

Several of the technologies on the following list have been around for some time. They constitute new technologies in that they will be reaching practicality and affordability within the next 5 years; in every case, they will be extended beyond the isolated pilot implementations to become ubiquitously applied, generally accepted state of the art. The list includes the following:

1. Networking. Included among many noteworthy developments relevant to networking are developments in fiber optics, national planning for "data highways," ISDN implementation by telephone companies, and developments in data-compression techniques.
2. Low-cost, powerful computing engines, from parallel-processing supercomputers to $1000 1000-MIPS (Millions of Instructions per Second) personal computers before the year 2000. There is consensus agreement among experts concerning the 1000-MIPS prediction. What can so much cheap computing power possibly be used for? It is a prerequisite and an enabling technology underlying several of the other new technologies on this list. (The same is true of networking.) There is no longer an economy of scale that applies to computing engine size. And computational power is now so cheap that it is no longer necessary to design computing organizations in such a way that high priority is put on keeping computing engines constantly busy. Other considerations, in particular, user convenience and productivity, have become more important.
3. Distributed and cooperative computing based on decomposition of computing tasks and assignment of subtasks to separate but interconnected computing engines. Appropriate decompositions are determined on the basis of separability of functions, different mixes of the functions being needed for different applications, and the efficiency and possible standardization of communication among the functions.
4. Client-server network architectures. The essential idea here is division of labor among network nodes. Each node is specialized to provide a particular computing service to other nodes on a network. Each node functions as both a server to, and a client of, other nodes on the network. It is important to note that such an architecture begins as a logical rather than a physical structuring, with different "services" corresponding to the functions of different logical modules of a computing system (e.g., a GIS-T), even though the different modules are not necessarily located on different physical computing platforms. This distinction between logical and physical is important for two reasons: First, division of labor for client-server structuring does not require an exact fit between network node capacities and the volumes of computing that will be required for particular services. Second, it is possible to implement client-server structuring on older computing machines, in particular, mainframes and minicomputers, thus enabling their full

amortization, by delegating to them several services (in the case of mainframes, perhaps a large number).

5. Computer-based graphics (high resolution, true-color, dynamic, three-dimensional) and realistic, interactive visualization.
6. Geographic information systems. Many planners might omit this from the list because they would consider GIS technology an application rather than a new core technology. Given the potential role of the concept of location as the basis of data integration, GIS technology is not just an application but is a central part of the technology infrastructure.
7. Computer-aided design—for many different kinds of design, from design of highway intersections to design of buildings to design of VLSI circuits. Of particular importance for these purposes is computer-aided design of software systems, an area that has come to be referred to as computer-aided software engineering (CASE). Essential aspects of CASE technology are rapid and incremental prototyping capabilities.
8. New data storage and processing capabilities. These include object-oriented data structuring; storing, managing, and processing text in the form of document images; storing, managing, and processing images of other kinds; graphical querying; optical (laser-disk) storage; and laser-disk database publishing.
9. Data-collection technologies. These include GPS (both geodetic and navigation capabilities), video, weather radar, softcopy photogrammetry, total station data collectors, electronic notebooks, and telemetry systems such as those for pavement condition and traffic counts.

3.1.2 Data and Systems Integration

Throughout the history of data processing one can observe a natural tendency toward bottom-up application implementations, with different applications assuming responsibility for collecting and maintaining the data they require, resulting in wasteful data redundancy and duplication across the organization. The problem has been widely recognized and numerous attempts have been made to solve it, but without widespread success. DOT data processing has been no different.

The data integration problem is especially important for GIS technology adoption, because the costs of geographic data acquisition and maintenance are high and thus need to be shared across applications, and because GIS data provide the potential for integrating many other kinds of data.

Data that can be shared across applications need to be considered as a corporate resource, rather than "owned" by particular applications. This is not a property unique to geographic data but it is especially apropos for GIS spatial data because of their cost, because of their centrality to integration of data of many other kinds (that is, because of their usefulness to the organization as a whole), and because of their potential use in so many different applications.

Despite its general recognition as an important problem, data integration remains an elusive, largely unsolved problem in DOTs—and elsewhere. An apparent solution is to turn data-collection and maintenance responsibility over to a centralized group (e.g., the Management Information Systems (MIS) department), but such a top-down approach carries with it political and organizational dangers. Making a single group responsible for geographic data collection and maintenance gives that group a stranglehold over the successful introduction and use of GIS technology throughout the organization. Experience has shown that successful introduction of an information technology into an organization, GIS technology as well as other kinds, is likely to be stifled by excessive centralization, that is, by an organizational structure where a single department has complete responsibility for the introduction or has authority to delay or reject initiatives from other departments.

New technology introductions into an organization benefit from the empowerment of decentralized initiative. People down within the organization, close to the real problems for which a technology is being proposed as a solution, are the ones best able to evaluate and justify it, to work out precise requirement specifications, to plan the most cost-effective levels and locations of use, and to assure that effective use is actually made of the technology once it has been made available. There have been significant exceptions to this general pattern of centralized MIS departments being weak and slow innovators and new technology initiators, typically because of enlightened MIS management, some of which was discovered in the survey of DOTs. But such enlightenment is the exception rather than the rule.

So there clearly needs to be a middle position

that does not choose either extreme but combines the primary benefits, on the one hand, of a pure MIS-directed, centralized, top-down approach and, on the other hand, of a bottom-up, decentralized, application-by-application approach with applications largely unrelated and uncoordinated with each other. In the ideal framework a golden mean for effective GIS implementation is obtained: First top down, then bottom up.

3.1.3 Effective Planning

Information technology planning never ends; it should be considered a continuous, ongoing process attending to a regularly reviewed and updated product. At any given point in time, the product (i.e., the plan) in its current form must be recognized as rapidly becoming outdated. Only thus can an organization deal with the moving target of rapidly changing technology.

Any good information technology plan must address a range of time horizons, say 10 years, 5 years, and 1 year. The longer-term horizons are necessary to set context and to assure that the organization is not planning itself into dead ends. The shorter-term ones are necessary to assure relevance to current conditions and responsiveness to unpredicted constraints or opportunities (e.g., financial exigencies or appearance of new software).

Long-term planning needs to anticipate, lay a basis for, and initiate preparation for future technological developments. Short-term plans without the benefit of context set by long-term plans may well be surprised by technological developments, and become obsolete and irrelevant as a result of those developments.

Some might respond that this is well-intended advice but that it does not have any operational significance—because technological developments cannot be precisely enough predicted. Certainly there will be surprises and breakthroughs that cannot be predicted, nor can the precise time of availability nor the precise capabilities of new products be predicted. But the general shape of the technological future can be predicted and be prepared for. This applies to two important matters:

1. There is no question but that computing environments of the future will be network based and will utilize some form of the client-server model.
2. There is no question but that GIS will play an increasingly central role in the computing of DOTs, if not of all organizations, both because of the additional applications and capabilities they enable and because of their potential integrative function.

Thus, with respect to 1), DOTs need, within their long-term plans, to think in terms of networked, interacting computing services; and they need to put a conceptual server-net architecture in place as an organizing principle even before full physical realization is feasible. This will facilitate gradual, incremental physical realization of a server-net architecture as the requisite standards, networking technology, and appropriately designed and priced hardware and software products do become available.

Similarly, with respect to 2), use of the concept of location as data integrator should begin as a conceptual organizing principle, to the extent that GIS spatial databases cannot immediately be put to use (say because they are not yet completely enough populated) to link data from different databases for current applications. One important immediate operational impact of this approach will be on how those databases are schematized. Then, when the data they contain can actually be linked through location, they will not need to be reschematized.

3.2 STAFFING

It is important that GIS-T planners and implementers realize the special nature of the staffing problem. Merely turning evaluation and adoption of the new technology over to traditional data processing staff, on the belief that this is just one more technology included in that staff's repertoire, will not work. The knowledge and expertise required (e.g., concerning the potential use of the concept of location as a data integrator) is not a part of traditional data processing training and experience. Significant additional training is required, for example, in the areas of geographic reasoning and of cartographic design.

In many cases GIS-T staff are retrained from other positions. Some states have recently developed new job classifications for GIS managers and GIS specialists. In any case, it is critical that "core" GIS-T staff be devoted full time to GIS-T and not have their responsibilities split with GIS-T as "something on the side."

In an organization-wide implementation, there are likely to be three levels of GIS-T staff and users:

1. Core staff who are responsible for spatial database design and development, establishment of standards, training, low-level programming and application development. The core staff is often within the MIS division.
2. "Master" users who participate with the core staff in application design and who do high-level (macro language) application development. Master users are attached to user divisions.
3. Other users who are trained only in the use of fully developed applications. These are most of an organization's employees, from entry level planners and engineers to top management.

3.3 REQUIREMENTS DEFINITION

A requirements definition results from an internal study of the organization and its data. The study reveals how data are used, how they are stored, and how they flow through the organization (*12*, p. 216). The process involves a number of critical decisions concerning applications, data, software, and hardware. A requirements definition lays the technical groundwork for implementation planning and request for proposal (RFP) development (*30*, p. 43).

There appear to be generic requirements that may apply to nearly all transportation agencies, particularly with regard for software functionality and for priority applications (that might be mandated). Nevertheless, a requirements definition should be undertaken by all those implementing GIS-T. The reasons include the following:

1. Fine tuning of previously determined generic requirements to meet more specific needs of the agency.
2. Involvement of personnel throughout the organization in determining needs—and the potentially resulting widespread interest in the implementation effort.

The requirements definition must establish priorities for application development. These priorities, in turn, establish the initial data architecture and continuing strategy for spatial database development. Applications also establish the required software functionality in terms of the necessary spatial operators, location-referencing method support, data management characteristics, reporting and cartographic output capabilities, user interface, and so forth.

The requirements definition will lead to decisions concerning hardware platforms, mass storage, networks, compatibility with existing computing environments, and integration with other technologies (including those mentioned in Section 3.1.1). The requirements definition, effectively, provides the first detailed version of an implementation plan.

3.4 DATA ARCHITECTURE AND STRATEGY

A well thought out data architecture and strategy are vital to the success of GIS-T. The requirements definition will have established priorities for application development. The first few applications to be developed will drive the selection of the scale of the initial spatial database, but the implementation strategy should consider future applications and the availability of data. Further, strategies need to be established early for maintaining the quality of the information in the database.

3.4.1 Choice of Initial Spatial Database

Given the range of geographic extent and levels of abstraction that support decision making throughout the highway life cycle, no single spatial database at a fixed scale can be expected to support all applications (see Figure 7). Eventually, DOTs should probably plan on supporting at least three different scales:

1. 1:500,000 for statewide planning. This relatively high level of abstraction supports agency-wide budgetary planning and analysis, program development and evaluation, and policy making at the upper management level. These applications require summary statistics, aggregations of more-detailed, larger-scale data, and widearea, overview perspectives. Executive information systems are supported at this level. On hardcopy 1:500,000 USGS maps, the widths of highways are exaggerated by their line weights. No detail is present at major interchanges. Streets and local roads do not appear.

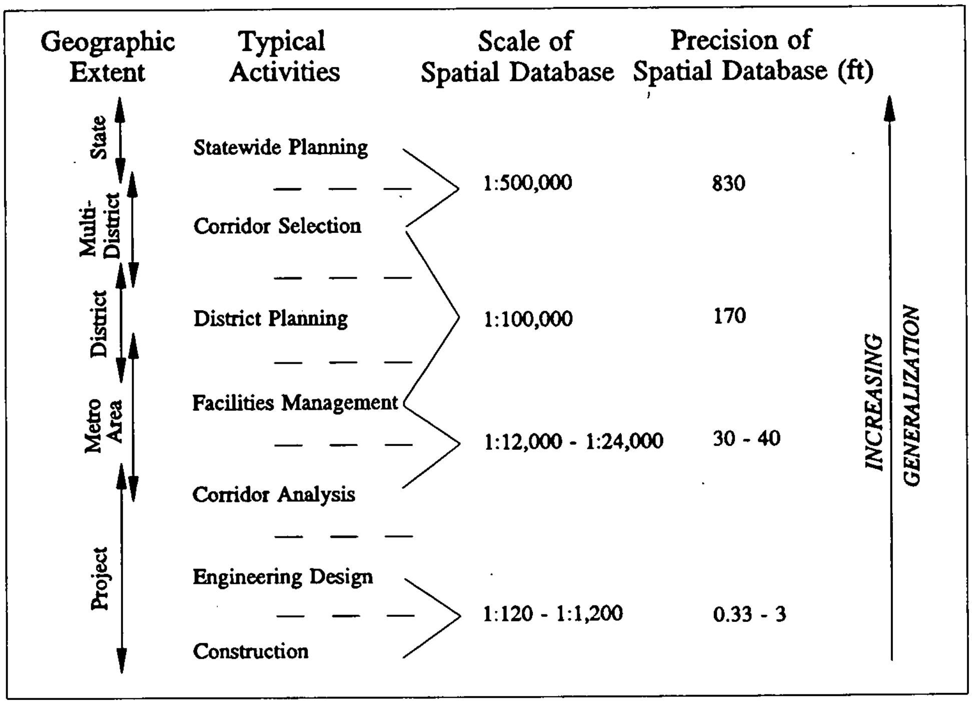

Figure 7. Relationship Among Geographic Extent, Typical Activities, and Scale and Precision of the Associated Spatial Data.

2. 1:100,000 for district-level planning and facilities management. This intermediate level of abstraction supports budget development, strategies for program delivery, and management of resources and facilities. These applications use data acquired at the operational level but presented on a more general or regional basis. Examples include pavement management and bridge management systems. On hardcopy USGS 1:100,000 maps, divided highways appear as solid lines. Ramps at major interchanges are generalized. Streets and local roads appear as medium-weight lines.
3. 1:12,000-1:24,000 for engineering. These relatively large scales support preliminary engineering for projects and other aspects of program delivery that require detailed information over considerable geographic extents. Examples include some aspects of congestion management and analysis of corridors for alternative alignments. This scale range is most likely to be compatible with those of spatial databases developed at the local government level. On hardcopy USGS 1:24,000 maps, the medians of divided highways appear. Ramps at interchanges are detailed. Widths and cul-de-sacs are plotted for streets and local roads.

The fourth level of scale shown in Figure 7 (1:120–1:1,200) is operational at the project level and is probably not amenable to widearea GIS coverages. It might be reasonable to track project-level data over time and assemble it as it becomes available. Also, engineering design data and as-built data developed at large scales can and should be used to update smaller-scale GIS spatial databases if the large-scale data can be appropriately generalized and other quality control measures (such as lineage tracking) can be implemented.

The choice of initial application is crucial. For example, if the initial application is at the statewide planning level, say using an executive information system, the small-scale spatial database can be brought up relatively quickly. However, the additional applications that it can support will be considerably limited. The database will probably not contain enough detail for district-level decision making. Preliminary design and corridor analysis will definitely not be supported.

On the other hand, if top priority applications require large-scale data, there will be considerable time and effort invested before they can be brought up on a statewide basis. Typically, the trade-off for

DOTs has been between the availability and lower cost of 1:100,000 data and the detail contained in 1:24,000 data (both data sets being derived from USGS maps).

It is wise to develop cost recovery mechanisms, perhaps in the form of charge-backs from future applications, so that the large investment in a multipurpose spatial database is spread over more than the initial applications. Managers of the first applications should not have to bear these costs alone. Also, there is a danger of associating the cost of database development with the cost of application development, with a resulting apparent high cost of applications, unless the distinction is made clear from the outset.

It is critical that long-term responsibility for maintenance of spatial databases be established early. This responsibility need not necessarily be with the group that develops the database to begin with. For example, database development may be performed by a technical implementation team and long-term maintenance may be assigned to the cartographic section or to the photogrammetric mapping section.

3.4.2 Sources of Digital Data

Edge-matched digital spatial data for transportation and hydrography at 1:100,000 scale are generally available from USGS in Digital Line Graph (DLG) format. (During 1991, there were parts of some midwestern states for which these data were not yet available). DLG data include topological relationships. 1:24,000 DLGs are much more sparsely available from USGS. However, a number of DOTs have entered into cooperative agreements with USGS to fund (on a matching basis) production of these larger-scale data or to help produce these data themselves. In November 1991, USGS estimated the average cost to a state agency of having USGS produce 1:24,000 transportation DLGs to be $650 per quadrangle.

Topologically Integrated Geographic Encoding and Referencing System (TIGER) data are available from the Bureau of the Census. A number of transportation agencies are working with TIGER data that include state and federal highways and local roads. TIGER data are derived from 1:100,000 USGS quads in rural areas and from GBF/DIME files in urban areas. Much has been written elsewhere about the purpose, extent, availability, and quality of TIGER data (see *15*, for example).

Digital transportation data are also available from private sector vendors. These data are typically derived from TIGER, GBF/DIME, and 1:100,000 scale quads. They usually have been enhanced (improved spatial accuracy, edge matching, address geo-coding, etc.) beyond what is available from government sources.

In any case, transportation agencies acquiring spatial data from outside sources will save scanning or digitizing costs, but should expect to invest in preparing the data to suit their own needs. For example, the data may need to be translated into the agency's format, edited (especially with TIGER) including updates and geometric changes, edge-matched, merged with other data (e.g., highways with local roads), and enhanced according to the agency's linear-referencing systems (e.g., insertion of reference points and topological linking). As an indicator of necessary level of investment, the Wisconsin DOT began with 1:100,000 DLGs statewide and invested 7.7 person-years (including training) in preparing and integrating the data before their spatial database was complete (State Trunk Highway Network only) (*3*).

3.4.3 Quality Control

A viable data strategy includes quality control methods during both database development and database maintenance (*3*, *31*). Otherwise the integrity of the spatial databases may be undermined, thus threatening the entire GIS-T enterprise.

The five steps in database quality assurance and quality control form a loop (*31* after *32*):

1. Define database properties.
2. Establish processes to create the database.
3. Define quality control measures.
4. Obtain quality control measurements.
5. Take corrective actions.

Database properties will have been defined by the requirements definition. Processes are established to create those properties. Quality control measures might follow the methods outlined in the data quality section of the Spatial Data Transfer Standard (*21*): (1) comparison to an independent source of higher accuracy, (2) comparison to original source, (3) internal evidence, and (4) deductive estimate. In addition to positional and attribute accuracy checks, quality control measures should also include checks

for logical consistency (do the data make sense internally and when related to other data) and completeness (geographic and taxonomic). Quality control measures, results, and corrective actions should be documented and combined with other historical metadata to produce a lineage of the database, resulting in a quality report.

3.5 EDUCATION AND TRAINING

Education and training are critical for the success of GIS-T. In organization-wide implementation, there will be a need for perhaps three levels of training, corresponding to the three levels of staff (see Section 3.2):

1. Core staff must be intensely trained to the point where they are adept at database and application design and at GIS-T programming.
2. "Master" users must be trained to the point where they are comfortable with the high-level programming or macro languages of the GIS.
3. Other users must be trained minimally—production staff to the point where they are comfortable with the applications and management to the point where they can make informed decisions about the technology.

An introductory short course in GIS-T has recently been developed for the Federal Highway Administration (FHWA) and is being offered on a regular basis through 1992 (*33*). Some universities offer introductory continuing education short courses on GIS-T. Training services (introductory through advanced) can be obtained from consultants and from software vendors. Such services can be provided either on-site (if demand is high enough) or at remote central locations of the provider's choosing.

For organization-wide implementation, there will be some need for training on a continuing basis when there is personnel turnover, when new applications are being introduced, and when new releases of the core GIS software become available. Large transportation agencies should consider developing their own internal training services, in which case there should be staff whose job it is to provide GIS-T training for other staff. Resources will also be needed to provide training facilities with space and workstations devoted to that purpose on at least a part-time basis.

3.6 SPONSOR AND CHAMPION

Examination of the most successful GIS-T operations reveals the presence of two key individuals. One shall be dubbed "the Sponsor" and the other "the Champion."

The Champion is a technical manager, often in a user division but sometimes in the MIS area. The Champion is a technical leader who has vision, devotion, and enthusiasm and works well with people. This person leads the technical implementation team described in Section 4.2 and is probably also the top candidate for Director of the "core" staff. The Champion seeks the approval of the Sponsor for initiatives and procurements. The Sponsor is a manager at the Bureau or Division Chief level. This person has budget authority and is a member of the management implementation team described in Section 4.2. The Sponsor must create the conditions for potential Champions to emerge, must be able to recognize them when they do, and then must be able to support them. The Sponsor also has vision, devotion, and enthusiasm—they manifest themselves in facilitation of the Champion's initiatives.

Without Champions, Sponsors must assign technical implementation tasks to staff without an enthusiastic leader and the effort might flounder. Without Sponsors, Champions confront negative institutional inertia and become frustrated in attempting to implement the vision beyond the bounds of their limited sphere of influence.

CHAPTER 4. PLANNING AND IMPLEMENTATION PROCESS

The focus of this chapter is on the process needed to select and implement a GIS-T agencywide. For the GIS-T pioneers this process required several years. Several DOTs that began the process have yet to complete it; but the factors that will lead to successful implementation are now quite clear. With the appropriate commitment of resources the process can be completed in months rather than in years.

4.1 OVERALL PLANNING PROCESS

The overall process for GIS-T implementation is shown in Figure 8. The process begins with an assessment of agency needs and resources. This is a feasibility study in which the agency decides whether or not to implement GIS-T. If the answer is affirmative, then the agency proceeds to develop goals and objectives, identify alternative GIS-T software, evaluate the software alternatives, select the best software and implement it. The focus here is on software, rather than hardware. Hardware costs have declined dramatically in recent years and will continue to decline. Thus, hardware should be selected to support the software and applications—not the reverse.

4.2 ORGANIZATIONAL RESPONSIBILITY

The key to successful implementation of GIS-T is the support of top management. As shown in Figure 9, the management team has overall responsibility for deciding the direction GIS-T will take in the agency. Because GIS-T will have agencywide impacts, the management team must include top managers from all agency divisions. If GIS-T is viewed as only an MIS activity, then the full power of GIS-T to integrate information across agency lines will be less likely to be achieved and the speed of implementation will be slowed. The management team must include a Sponsor—an individual who at least initially is committed to exploring the feasibility of GIS-T and ultimately will be committed to securing the resources required for successful GIS-T implementation.

The second and equally important organizational requirement is the technical team. The technical team is composed of technical managers who will be responsible for planning and implementing GIS-T. As with the management team, all agency divisions should be represented. The specific needs and capabilities of each division must be incorporated in the decision-making process so that GIS-T will have the widest possible potential for application and ultimately provide the greatest benefits. Just as GIS-T needs a Sponsor on the management team, it needs a Champion on the technical team. The Champion will provide the leadership needed to overcome institutional inertia and push the process forward to a successful conclusion. The Champion may be located anywhere in the agency, but most likely in one of the areas where the initial pay-offs from GIS-T are likely to be the highest. Multiple Champions may also emerge who strongly support GIS-T implementation within their own divisions as well as agencywide.

Consulting services may be used to augment staff resources at each step of the planning and implementation process and at both the management and technical team levels. A consultant could be hired to conduct the feasibility study, reporting directly to the management team. In this context the consultant could provide a temporary Champion who would be responsible for identifying and developing in-house technical resources until an in-house Champion emerges. Alternatively, a consultant could be primarily responsible to the technical team with the technical Champion providing direction to the consultant. The consultant would augment the initially limited GIS-T expertise of agency staff.

Use of consultants will speed the planning and implementation process and when used effectively enable agency staff to climb the learning curve more quickly. The level of involvement of consultants could range from a single personal services contract to a complete turnkey package including an agencywide application. Each agency will have different needs for a mix of management and technical level consulting services and for the level

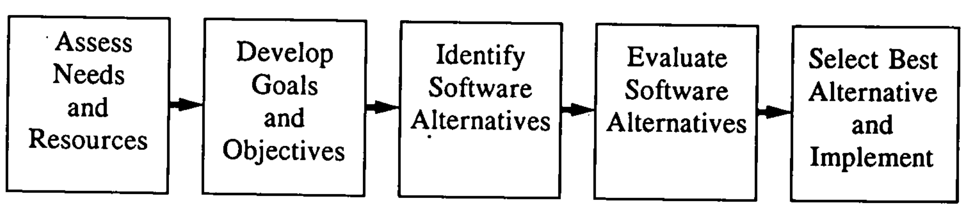

Figure 8. GIS-T Planning and Implementation Process.

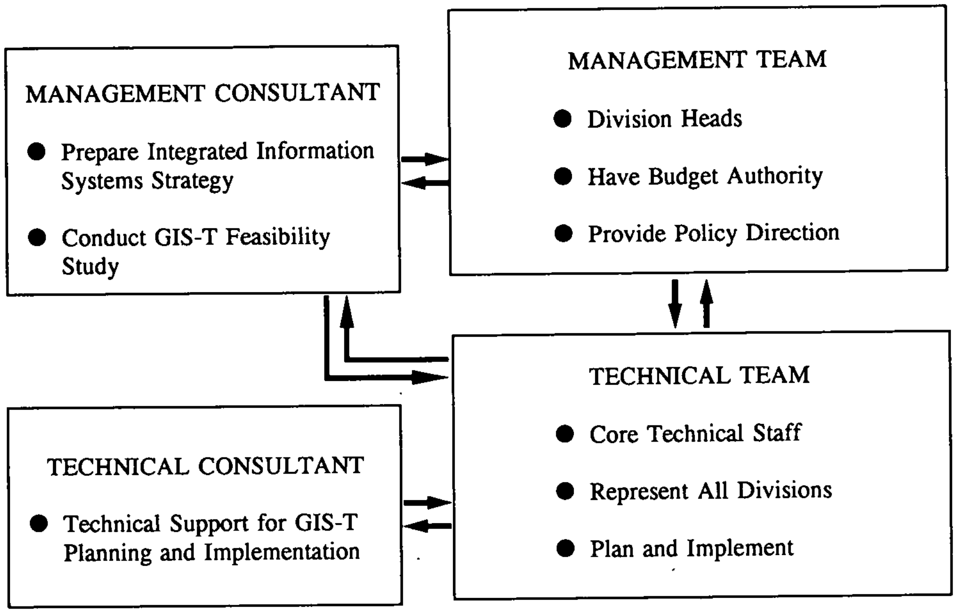

Figure 9. Organizational Responsibility for GIS-T Planning and Implementation.

of involvement of the consultant. Ultimately, some level of in-house expertise must be developed to support database maintenance, development of additional databases, and development of additional applications over time.

4.3 ASSESS NEEDS AND RESOURCES

The first step in the planning process is to assess agency needs and resources for GIS-T. Agency needs and resources in each of six critical success factors identified in Chapter 3 must be addressed. In most agencies, considerable work will be needed in order to develop an integrated information systems strategy, define GIS-T requirements, and define the overall GIS-T data architecture and strategy. Consultants can be particularly useful here to obtain state-of-the-art expertise and to build on work done by other agencies. Both management and technical staff should be heavily involved so that the technology fits agency needs rather than attempting to restructure the agency to fit an arbitrary view of the technology.

For GIS-T to be most effective, it must be fully integrated with the agency's overall information systems strategy. GIS-T can provide the conceptual basis for the overall information systems architecture with nearly all of the corporate data linked through location. Initially, of course, GIS-T can be implemented as merely another software system with links to the corporate databases. The real power of GIS-T, however, will only be realized through a central role in the corporate information systems architecture.

To define GIS-T requirements, potential GIS-T applications for both the short and long term must be identified and prioritized. Internal agency needs as well as the potential for interaction with other agencies, both public and private, must be considered. A broad view of potential applications will require a GIS-T with the full range of functionality. Direct involvement of agency staff here serves to educate them as to the potential for GIS-T and to generate interest in the overall process.

Given a list of potential GIS-T applications, it is now possible to identify both general and application-specific functional requirements for the GIS-T. These will include specification of the general functional requirements for user interfaces, spatial and attribute database management, database creation, data manipulation and analysis, and data display and map generation. Functionality that is specific to transportation applications, such as, dynamic segmentation and route (minimum time path) generation, must also be identified.

The overall GIS-T data architecture and strategy must be defined to the extent possible. This has important implications for the staff resources required as well as for the applications that are

feasible. Other agencies' experiences with implementation of different architectures and their relationships to feasible applications are invaluable here. The primary trade-off in the choice of an initial spatial database is between the lower cost of a smaller-scale database with fewer potential applications and the higher cost of a larger-scale, more detailed database with different and perhaps a larger set of potential applications. (See Section 3.4.1 for a more complete discussion.)

Finally, the availability of staff, education and training resources, and the current and future status of Sponsors and Champions must be addressed. Of these, the Sponsor might be the most critical. Staff can be hired or retrained, education and training resources can be initiated, and even Champions can be recruited. Without a Sponsor, however, GIS-T must be planned and implemented piecemeal without realizing its full potential. Over time, of course, a dedicated Champion may succeed in obtaining a Sponsor so that full-scale planning and implementation can be initiated.

4.4 DEVELOP GOALS AND OBJECTIVES

Development of goals and objectives for GIS-T planning and implementation follows directly from the assessment of agency needs and resources. The goals provide the broad policy framework within which GIS-T will be planned and implemented. The objectives are more specific statements of how each goal is to be achieved including guidance as to scope, timing, and duration. As the goals and objectives are developed and refined, more information on agency needs and resources may be required resulting in an iterative process. For each objective one or more measures of effectiveness (MOEs) should be developed. Ideally, the MOEs will provide a quantitative measure of how well a particular alternative meets the relevant objective. In some cases the MOEs will only permit a qualitative assessment of performance.

Goals and objectives should include the critical success factors discussed in Chapter 3. For example, the GIS-T should (1) maximize the level of integration with the corporate information systems strategy, (2) minimize the staff requirements, (3) facilitate education and training, (4) provide the widest range of functionality, and (5) provide the highest degree of flexibility in the data architecture. Cost-related goals and objectives should also be included. Because the primary focus here is on GIS-T software, particular attention should be given to the goal of maximizing functionality. The objectives for this goal will focus on specific categories of functionality with MOEs that identify the entire range of functionality needed in each category.

4.5 IDENTIFY SOFTWARE ALTERNATIVES

A number of vendors provide GIS-T software that is likely to meet many of a DOT's goals for implementing a wide variety of GIS-T applications. The capabilities of current GIS-T software are changing fairly rapidly. Thus, the best source of information on the potential functionality of each software product is the vendors themselves. This information should be supplemented where possible by independent validation by current GIS-T software users in the form of technical reports or even informal communication. The specific information that must be collected for each alternative depends on the objectives and MOEs that were developed in the prior step.

4.6 EVALUATE SOFTWARE ALTERNATIVES

Full evaluation of the GIS-T software alternatives requires in-house "hands-on" testing of the most promising alternatives. There simply is no other way to demonstrate that the software performs as claimed, is compatible with the agency operating environment, and meets the primary DOT functionality requirements.

Initial screening of the entire set of alternatives probably will be needed to reduce the alternatives selected for in-house testing to a manageable number. The "trade-off and balance sheet" evaluation methodology is appropriate for the initial screening where many qualitative assessments must be made based on limited information (*34*). The methodology involves display in matrix form of all relevant information about the extent to which each alternative satisfies each objective as illustrated in Figure 10. Simple descriptive information as well as quantitative and qualitative ratings may be included in the matrix. Decision makers use the information in the matrix to identify trade-offs in the performance of alternatives and then to select alternatives that "on balance" are the best.

GIS-T Software Alternatives	Maximize Integration with Info. Systems Strategy		Minimize Staff Requirements		Facilitate Education and Training		Maximize Data Architecture Flexibility		Maximize Functionality			
									User Interface	Database Creation	Database Management	Dynamic Segmentation
	MOE_1[a]	Etc	MOE_1	Etc	MOE_1	Etc	MOE_1	Etc	MOEs	MOEs	MOEs	MOEs
Alt. 1	I_1[b]											
Alt. 2	I_2											
Alt. 3	I_3											

Notes: [a] Measures of Effectiveness (MOEs)
[b] Impacts -- Quantitative or qualitative assessment of the extent to which the given alternative meets the goal/objective as measured by the Measure of Effectiveness (MOE)

Figure 10. Conceptual Illustration of "Trade-off and Balance Sheet" Evaluation Matrix.

The in-house testing of two or more promising software alternatives ideally would be conducted with current DOT hardware and operating systems and actual DOT databases. The testing should cover the full range of required GIS-T functionality. Evaluation criteria should be included for user interfaces, database creation, database management, data manipulation and analysis, data display and map generation as well as transportation-specific functions such as dynamic segmentation and route generation. One or more prototype applications should be demonstrated. The testing will provide DOT staff with a greater understanding of GIS-T software capabilities and the extent to which the software alternatives are likely to meet DOT application needs. The testing and subsequent performance evaluation should lead to further refinement of DOT needs, which should be reflected in a revised statement of goals and objectives.

The "trade-off and balance sheet" evaluation methodology used for initial screening of GIS-T software alternatives is also appropriate for the final evaluation of the most promising software alternatives. The in-house evaluation is likely to show that each alternative has strengths and weaknesses. It is important to identify as clearly as possible the trade-offs that are apparent and to reach a consensus among the technical team and the management team as to which alternative "on-balance" best meets both short- and long-range goals and objectives.

4.7 SELECT THE BEST ALTERNATIVE AND IMPLEMENT

Completion of GIS-T software evaluation leads logically to the development of the final system design and detailed specifications. The specifications form the basis for the Request for Proposal (RFP) and the competitive bid process. Procurement of GIS-T software is merely the beginning of a long implementation process. The procurement process itself should include a provision for operational testing of the software and formal acceptance based on clearly defined evaluation criteria. Further testing of the software with a pilot project is highly recommended. Only at this point should full agencywide applications be initiated. The final step in the implementation process is "application enabling." A systematic process for identifying and implementing promising applications across the agency should be institutionalized so that the full power of GIS-T is realized.

4.7.1 GIS-T System Procurement

This section focuses on alternative approaches to procurement, the content of RFPs, and evaluation of bids. In many cases full implementation of new GIS-T software will require additional computer hardware. Acquisition of hardware may be

incorporated with the software in a single RFP or, more likely, may be made separately.

The two primary alternatives for procurement are (1) the engineer (manager)/contractor (vendor) approach and (2) the systems manager approach. The first approach has traditionally been used by highway agencies in the construction of highway facilities. The second approach has been used in the building construction industry where the developer or ultimate building owner does not have the engineering staff required for procurement. The systems manager approach also has been used successfully for the procurement of systems involving advanced technology (*35*).

Both approaches require first that the procurement specifications be developed by an organization that does not have a vested interest in the primary product being acquired and second that competitive bidding be used for the primary product (*36*). Both approaches may also use a two-step procurement process in which the low-bid process is modified to include contractor (vendor) pre-qualification.

Engineer/Contractor Approach

The standard approach to procurement for highway facilities involves the preparation of design plans, specifications, and cost estimates (PS&E) either in-house or by a consultant. The resulting PS&E are then issued for bid to the eligible contractors. The quality of the contractor's work is monitored again either by in-house engineers or by a consultant. For the acquisition of advanced computer software systems such as GIS-T, the preparation of PS&E may be the primary responsibility of the information systems manager in consultation with engineering staff. A consultant may also be retained to provide the PS&E.

In the second step, rather than selecting a contractor who constructs a highway, a vendor is selected who provides an operational GIS-T software system including installation, testing, and initial training of agency staff. Any additional computer hardware required would also potentially be included in the contract. Agency staff may take responsibility for monitoring the quality of the vendor's product or an additional consultant may be given this responsibility. If a consultant provided the PS&E, then that organization may also be asked to monitor the vendor's activities and products.

Systems Manager Approach

The systems manager approach involves the selection of a single consultant to be responsible for the entire GIS-T acquisition process from PS&E preparation through system installation and testing. To avoid conflicts of interest, the systems manager cannot be a GIS-T vendor or a hardware supplier. The same procedures that are used to select an engineering consultant can be used to select the systems manager. The contract for system manager services is typically a negotiated cost-plus-fixed-fee contract.

While the systems manager has primary responsibility for PS&E preparation, agency staff should be heavily involved in identifying specific agency needs and constraints. The systems manager would use the agency's standard bidding procedures to acquire the appropriate GIS-T software, hardware, and possibly additional services such as installation, testing, and even staff training. The systems manager in effect becomes an extension of agency staff for the purpose of making GIS-T operational.

4.7.2 Selection of Procurement Approach

The engineer/contractor approach is most appropriate for an agency that has the staff expertise required to oversee the entire GIS-T acquisition process. There is a clear delineation between the PS&E preparation and the acquisition process. Full flexibility is maintained at each step for either using agency staff to manage the process or contracting with a consultant. Management has full control over when and even whether to proceed with acquisition.

The systems manager approach has the advantage of giving responsibility for producing an operational GIS-T to a single organization. Problems with inconsistencies between system design and implementation may be reduced and continuity between PS&E preparation and system acquisition is enhanced. The time required to obtain an operational system is likely to be minimized because procurement can proceed seamlessly from beginning to end without the time required to decide how and when to proceed with the next step. The systems manager, with an appropriate fee structure, should have an incentive to complete the process as expeditiously as possible.

The two approaches may produce somewhat different plans and specifications. Because the systems manager has responsibility for implementation, the manager may choose to develop more detailed specifications that focus on how specifically the GIS-T will be integrated with existing agency hardware and software. In contrast, the engineer/contractor may produce more generic specifications focusing on the overall functionality requirements rather than specifically on how the functionality is to be achieved.

4.7.3 Request for Proposal (RFP) Content

The RFP will include all of the information needed by a consultant, contractor, or vendor to submit a valid bid. The RFP will contain a description of the work to be performed or the product to be delivered in the form of system design and specifications as well as contract documents that identify the bid procedures and the contractual requirements. Contract documents will typically include the following seven items:

1. Invitation to bid—a summary of the project and bid procedures.
2. Instructions to bidders—a detailed description of how bids are to be prepared and the format for submission. Permitted exclusions and substitutions are identified.
3. Bid proposal—the actual response by the bidder in the format specified in the "instructions to bidders," includes a budget for completing the work and commitment to complete the work if selected.
4. Bonds—may include bid bond, performance bond, or labor and materials payment bond.
5. Agreement—legal document that identifies the parties, the work to be performed, the time allowed, the amount of the award, and signatures binding the parties.
6. Conditions—definition of general contractual relationships and procedures.
7. Contractor qualifications—identification of the minimum experience and qualifications necessary to submit a bid and instructions for submitting specific data on qualifications.

4.7.4 Evaluation of Bids

Experiences with acquisition of advanced technology for traffic control systems have shown that conventional "low-bid" procurement procedures used for major highway projects "result in mismatch of equipment, poor workmanship, and excessive contractual disputes." (*35*) While some components of a high-tech system may be obtained on a "low-bid" basis, others should be obtained through negotiation with the best qualified supplier. Where Federal funds are involved, flexibility in procurement exists in Federal-aid requirements. More restrictive provisions, however, may be imposed by state and local agencies (*36*).

If procurement is governed by "low-bid" requirements, then the specifications and qualifications of the supplier are critical to ensure that all agency requirements and constraints are met. At the same time, the specifications and qualifications should not be so restrictive that reasonable alternative solutions are rejected.

Where selection of a supplier on a "best value" or cost-effectiveness basis is permitted, a formal bid evaluation procedure is needed. A "utility-cost" analysis technique can aid decision makers in selecting the supplier who will best meet agency needs. Utility is determined using a variety of performance measures that are directly related to the specifications and contractor qualifications. Weights are assigned to performance measures based on their relative importance with the sum of the weights equal to 100. Bids are then evaluated by assigning a rating from zero to ten as to how well each supplier is expected to meet each performance measure. Ratings are then multiplied by performance measure weights and summed to give the overall utility of each bid.

Individuals involved in the bid evaluation process, in general, will assign a different set of ratings to each bid. The resulting utilities can be averaged and then compared graphically with bid prices. Bids that exceed a maximum cost threshold may be eliminated at this point, but if the utility/cost trade-off is favorable, negotiation on price may be possible.

4.7.5 Software Testing and Acceptance

The final step in the procurement process is to install the software and verify that it meets the functional requirements and specifications. The same evaluation procedure that was used for in-house testing of the software alternatives can be used here with appropriate modifications to reflect any changes in the requirements and specifications.

Vendor technical support staff may provide training in any new features of the software and provide guidance to DOT staff. To be successful, however, the evaluation procedure must be representative of actual work DOT staff will accomplish with GIS-T applications.

4.7.6 GIS-T Pilot Project

Development of successful GIS-T applications is a complex task. Staff must first be trained in how to use the new software. They will then begin to construct a new spatial database and link it to existing and new attribute databases. Specialized analytical models may be required to address specific problem areas. Since the staff will have had little or no practical experience with major GIS-T applications, a number of procedures will need to be developed and problems will need to be addressed. The problems of making GIS-T operational can most easily be addressed in a pilot project. A pilot project minimizes the risks inherent in implementing any new technology. The project should be large enough so that meaningful results are obtained, but small enough so that alternative approaches and solutions can be tested without excessive commitments of staff time and other resources.

The best candidates for pilot projects are high-priority applications that were identified in the initial needs assessment. These applications have the highest potential benefits compared with development and operational requirements. A successful pilot project should lead directly to agencywide application once the benefits and costs of implementation are demonstrated.

4.7.7 Application Enabling

Many early applications of GIS-T in state DOTs were examples of the bottom-up approach. These applications resulted from the efforts of individual departments, or even single individuals, who worked on their own without any formal links to other groups in the organization or any direction from top management. These efforts were highly problem-specific with a focus on the solution to an immediate pressing problem. Transportation network and database development were limited by the single problem focus of the efforts and the lack of organization-wide support or even knowledge of the activity. Nevertheless, useful products were often obtained and the ability of GIS to solve real problems was demonstrated.

An alternative to the bottom-up approach to GIS application development is the top-down then bottom-up approach. In this approach, an overall strategic plan for GIS-T in the agency is developed and approved by top management. Initial high-payoff GIS-T applications are identified and the required transportation network and database development are initiated. On completion of one or more of the initial GIS-T applications, a framework exists for individual applications throughout the organization. With the appropriate training and commitment to documentation of GIS-T activities, each later application can potentially use the corporate databases generated by the initial agencywide GIS-T applications.

Two key requirements for successful GIS-T implementation are construction of the appropriate databases and staff training. Limited agency resources require that choices be made concerning which databases are enhanced first and which staff are trained in the use of GIS-T. Consequently, the top-down then bottom-up approach to GIS-T application enabling can benefit from a phased approach. Initially, those individuals or groups who have the most interest in GIS-T and who can potentially generate the highest payoff applications are provided the opportunity for training and the additional resources needed for database development. As early GIS-T applications come on line and benefits are documented, additional staff are likely to request their turns for training and database development. Thus, GIS-T is implemented in phases, with the speed of implementation governed by the level of resources available and the interest and commitment from the "bottom-up."

CHAPTER 5. TECHNICAL AND ORGANIZATIONAL CONSIDERATIONS

5.1 DATABASE ALTERNATIVES

A number of alternatives are possible for the general nature of GIS-T databases and their administration. All databases (spatial and nonspatial) could be centralized. With this model the computing environment is certain to be in place and there is central control over database structure and content.

However, there might be significant delays in response time during heavy use and users have very little flexibility, with no control over data and very little control over their applications.

Alternatively, databases could be application-dependent—that is, generated and maintained by separate divisions. This is often the current situation. It is driven by distributed computing and results in a proliferation of independent, redundant databases that are impossible to hold together.

On the other hand, a confederation of GIS-T databases has users responsible for their own applications and to some extent their own attribute databases which they connect to centrally maintained, corporate, spatial databases. The spatial databases connect the applications and the attribute databases to one another. It is under this model that GIS-T serves best as a database integrator.

5.2 SYSTEM ARCHITECTURE ALTERNATIVES

As there are alternatives for the structuring of databases, there are alternatives for the structuring of the functional capabilities of the system.

5.2.1 Stand-alone and Mainframe/Workstation

Stand-alone systems are often the result of different application areas being responsible for their own computing. Stand-alone systems perhaps offer autonomy to individual users or small groups of users. But individual users in large organizations interact frequently. They share data and have common computing needs. Stand-alone systems not only lack the synergy of networks, but they also exacerbate the integrity and redundancy problems inherent in multiple copies (or versions) of the same data scattered throughout an organization.

Rapidly advancing technology might appear to make the stand-alone option viable by offering unlimited computing power on single platforms. However, computing needs seem to expand and overwhelm advances in technology as rapidly as they appear. Satellite images containing 250 megabytes of data need to be managed today. The latest release of GIS software from one vendor resides in 400 megabytes of storage.

Local-area networks, isolated in individual application areas, have similar disadvantages from the perspective of the organization. Without integrated networks, the concepts and full benefits of corporate databases cannot be realized.

The alternatives to immediately implementing a server net are (1) not networking computers together at all (clearly unreasonable); (2) assigning so many functions to single nodes (probably mainframes) in such an undifferentiated way that those nodes are indispensable to continued functioning of the network; and (3) incremental development of systems from the bottom up (which will lead to a server-net if that is a long-term goal). Even when there is loading of mainframe nodes (say to fully amortize an investment in a mainframe before it is replaced by a network cluster), it is possible to separate and modularize the functions in terms of a conceptual server-net architecture so that they can one by one be gradually moved to their own specialized platforms as the load on the mainframe requires or as the mainframe reaches retirement age. Thus the typical star networks of the present (a large number of star-vertex user-station nodes that provide user input and display, connected to the star-center mainframe that does everything else) can gradually be transformed into physical (as opposed to conceptual) server nets. Clearly, some of the nodes in those server nets will require substantial computing capacity, and nodes reminiscent of the mainframes of the present will be relegated to the role of database servers, maintaining and providing access to large, corporate databases.

5.2.2 Server-Net Model

The framework proposed here is intended as a goal for planning. Note well that it includes adopting and exploiting more technological developments than just GIS. Several new technologies of importance to DOTs complement each other and should not be planned for and introduced in isolation from each other (see Section 3.1.1). The following are characteristics of a server net:

1. Network nodes are specialized, with computing labor divided among them.
2. Each node operates both as a server of other nodes and as a client of other nodes.
3. Nodes may vary substantially not only with respect to specialty, but also with respect to capacity. That is, some nodes may be

supercomputers or mainframes and others much smaller (e.g., those providing single-user terminal services). However, the larger machines do not in general serve as network centers or controllers. No one node is indispensable to continued functioning of the network, only to whether its specialized service remains available.

4. A given network may be constituted of thousands of nodes.

In general, computing environments are now almost universally being moved toward realization of the server-net model. Figure 11 depicts a conceptual server-net model as a seamless stream of services with various specializations at individual nodes. Good technical overviews of the server-net concept are presented in references *37*, pp. 1-52; *38*; *39*, pp. 454-465; and *40*, and popular overviews are presented in *41* and *42*. Application of the concept specifically to GIS environments is discussed in *43*. The seminal ideas are introduced and defined, and the original, prototyping Xerox PARC research establishing the feasibility and practicality of the concept is discussed in references *44*, *45*, *46*, *47*, *48*, and *49*.

Server nets of the near future might have labor divided so that the following functions are delegated to specialized servers: (1) printing, (2) phototypesetting, (3) plotting, (4) input digitizing, (5) user file backup and archiving, (6) e-mail store and forward, (7) gateways to other networks, (8) databases (with different servers supporting different databases), (9) user stations (with different servers supporting different users), and (10) computation (with different servers supporting different software (e.g., statistical, finite element modeling, or linear programming). Advantages of the server-net model include evolutionary, incremental system change and growth. New capabilities can be added to a computing environment (e.g., image databases, additional kinds of hardcopy output, expert systems, or high-resolution supercomputer modeling) without disrupting capabilities already present and without requiring their conversion and upgrading to new, larger machine models. The division of labor among nodes can be changed to balance loads. Upgrading can be done node by node. System capacity can be increased relatively smoothly. A new technology (e.g., GIS-T) can be implemented in stages, with earlier, more visible payback from initial costs. (None of this is easy, of course. All that is being claimed is that it is easier and cheaper than adding new capabilities and new capacities to mainframe-centered architectures.)

Further, organizations are provided the opportunity to better stay abreast of rapid technology changes because introduction of a new technology does not require replacing the platforms supporting older technologies, only adding to them. Star networks can be gradually transformed into full-fledged client-server networks, enabling full depreciation of investments in mainframes, dumb terminals, and limited-capacity PCs.

There are other advantages of the server-net model. Important among them is the increased system reliability that results from different hardware platforms in a net being able to perform the same server functions and thus providing backup for each other. The division of labor among nodes can be made to reflect the existing organizational division of responsibility and labor, thus avoiding the dictation of unwanted organizational change as a result of technology adoption. Other organizational advantages include increased independence of particular vendors because, as open-system standards are realized, different servers can be based on products from different vendors.

5.2.3 GIS-T Server-Net Architecture

Design of a server net begins with determining feasible and appropriate division of labor among servers. Presented here is an ideal for the GIS-T functions performed within a DOT computing network, once again intending the ideal as a planning goal.

The goal can and should be implemented immediately as a conceptual architecture. The rate at which the conceptual architecture (as represented in software modularizing and database schematizing) can be transformed into a physical network architecture depends on many factors, especially on how soon networking technology is robust and cheap enough to support the connectivity and transfer rates required; how soon the required open-systems standards are in place; and how soon GIS software vendors make available products decomposable into the required modules and with the right kinds of coupling among the modules.

In the meantime, much of the coupling of servers will be quite loose, with transfer of significant amounts of data often being by physical transfer of

disks or tapes. Beginning with a conceptual client-server architecture, as a strategic principle underlying information-technology planning, facilitates timely adoption of the technology when it has matured. As indicated in earlier sections, a major justification for long-term planning is to prepare the way for predictable technological developments so that when they do become available their adoption and exploitation is not disruptive.

A natural division of labor for GIS-T appears to be among 15 kinds of servers:

1. Spatial data servers.
2. Attribute data servers.
3. Spatial image data servers.
4. Nonspatial image data servers.
5. Complex object data servers.
6. Overlay servers.
7. Analytical computation servers.
8. User interaction and display servers.
9. GIS application development servers.
10. Spatial data capture and transformation servers.
11. Cartographic data servers.
12. New technology servers.
13. General purpose servers.
14. History servers.
15. Specialized application servers.

Figure 12 depicts a GIS-T server net. There will be several, in some cases many, servers of each kind in a given network. These 15 different kinds of servers are discussed here in some detail. It should be understood that the particular division of labor suggested here among GIS-T servers is but a first-iteration design that will require much refinement as further design proceeds and as implementation is initiated. The task of modularizing computer systems into feasibly separable functions is a subtly difficult but essential part of computer system design. An historically influential article by Parnas (*50*) is very useful for understanding the criteria for distinguishing between good and bad modularization.

Spatial Data Servers

Servers of the first kind, spatial data servers, contain and provide their clients with access to vector-based spatial databases. (A terminological point: raster-based representation of geographic information is considered as the function of a different kind of server, viz., spatial image data servers.)

More specifically, spatial data servers provide information about points, lines, areas, and networks —plus topological relationships among entities of these types. Spatial data servers might also provide information (elevations, slopes, aspects, and volumes) about triangulated irregular networks and other surface models. Finally, spatial data may be time stamped, e.g., with time of acquisition or time of validity.

Much of this spatial data is explicitly stored; when it is not explicitly stored but is implicitly available, it must be efficiently computable by the server. Thus, for example, cartographic generalization and other kinds of scale-change computations (that is, computations to determine locations and spatial properties of aggregates at a smaller scale than stored explicitly) are considered to be a spatial data server function.

Associated with these spatial databases is control information of various kinds, including information about the coordinate system used, registration points, and precision tolerances—and other information indicative of lineage, e.g., information about source, history, and quality testing.

Within a GIS-T server net different spatial data servers will be available for different resolutions, different data sources (e.g., manual digitizing of maps, vector scanning of maps, vectorization of raster data, and surveying measurements, including GPS data), different methods for location referencing, and different geographic extents. Within a server net there may well be servers covering the same geographic extents with data from alternative maps (originally made for different purposes or made at different times) or from other sources (e.g., construction plans).

Attribute Data Servers

Servers of the second, third, fourth, and fifth kinds contain and provide their clients with access to layer data to be combined with each other and with spatial data for GIS-T modeling or output, e.g., thematic maps or overlays of maps on images.

Attribute data servers contain data in relational tables (or perhaps in nonrelationally structured forms of the kinds used in older database models). In general, these servers are nodes using the standard database management systems of the present time, although the data schema used must in many cases be extended to include location fields that enable linking of the attribute data to spatial-data references.

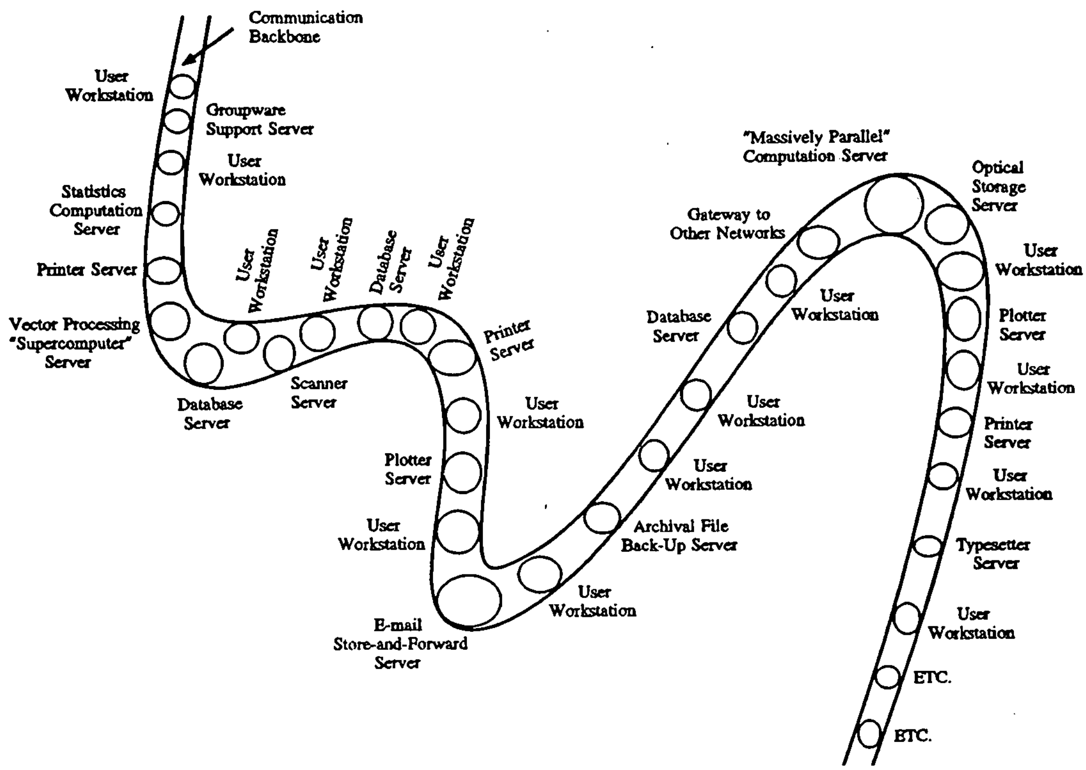

Figure 11. A Full-Fledged Client-Server Network.

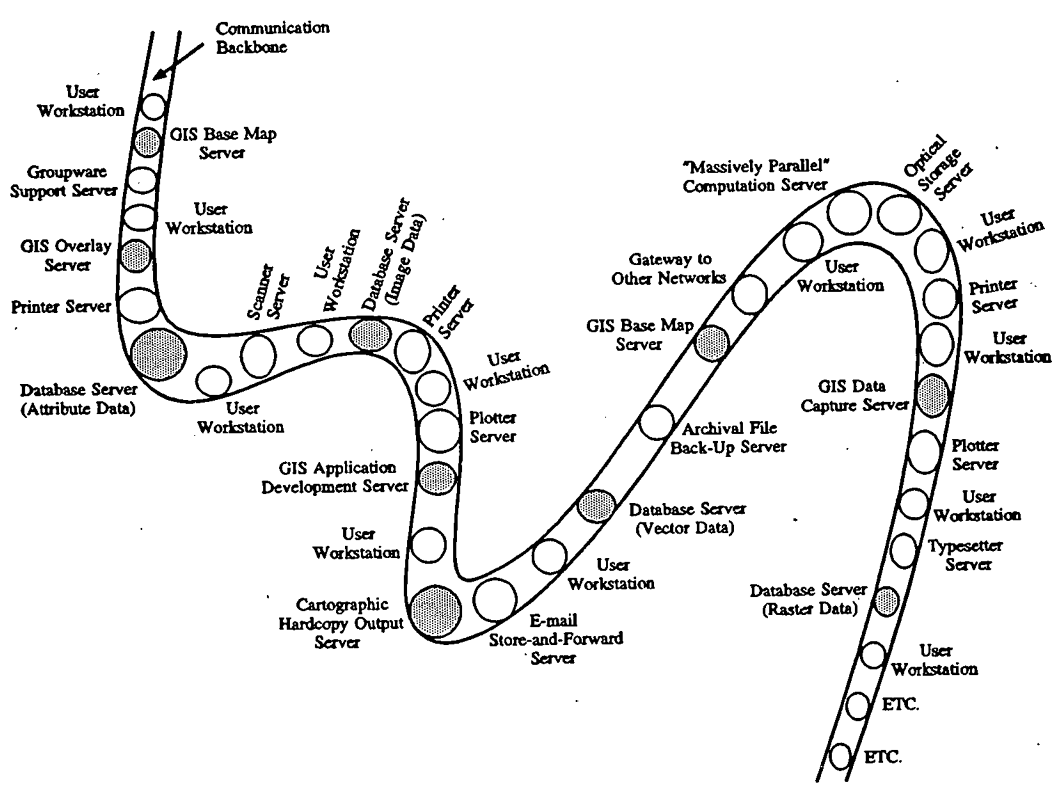

Figure 12. A GIS-T Client-Server Network (As for Figure 11 but with Various GIS-T Specific Servers Added).

Spatial Image Data Servers

Spatial image data servers contain geographic data organized by raster, e.g., satellite images, scanned aerial photographs, and digital orthophotographs. These images will be indexed so that they can be spatially retrieved and processed, for example, as required to register them against a map for purposes of displaying or printing a map laid over an image.

Nonspatial Image Data Servers

Nonspatial image data servers contain scanned documents (e.g., accident reports and sketches, or construction sketches), scanned photographs (e.g., of bridges or of pavement segments), and eventually (as digital audio and video media storage devices become efficiently integratable into computer systems) digital audio and video images. These images will be locationally indexed so that they can be retrieved and presented in terms of spatial data references.

Complex Object Data Servers

Complex object data servers contain complex data structures such as those used within CAD systems to represent, for example, highway construction designs. Once again, these structures will be locationally indexed so that they can be retrieved and presented in terms of spatial data references.

As the technologies of object-oriented programming and object-oriented databases mature, it is possible that all the data server kinds distinguished here may best be implemented as object oriented. Object-oriented database systems would obviously be well suited for the complex object data servers addressed here, but the point here is not to opt for a particular kind of database technology. Rather it is to identify a kind of data that must sometimes be available to users of GIS-T systems, and thus a kind of data server that must sometimes exist within a GIS-T server net.

Overlay Servers

Servers of the sixth kind, overlay servers, aggregate and integrate data from various kinds of data servers as required for construction of thematic maps, overlays of images and maps, spatially specified data retrieval, analytical modeling, and other GIS activities. Complex overlay operations can require combining information from several sources, including one or more spatial databases and one or more data sets from other kinds of data servers.

For transportation applications, overlay operations often involve network overlay rather than, or in combination with, the polygon overlay capabilities familiar from other kinds of GIS applications. Further, network overlays frequently require dynamic segmentation capabilities. Cartographic generalization and other kinds of scale-change computations on derived spatial databases generated by an overlay server are services to be provided by the overlay server.

Specific and different overlay programs are required for each coupling of two different data types used by different data servers. Programs for widely used overlay combinations come with GIS products, although at present they are not isolatable so that they could be assigned to specialized overlay servers. A needed extension of such products is a program development environment that facilitates user development of overlay programs for data type combinations not handled by programs in the libraries included with the products.

Analytical Computation Servers

Servers of the seventh kind, analytical computation servers, vary widely in function and complexity. They realize the models that users need to run against geographic data, such as network analysis models or travel demand models. They also do the many other kinds of computation required for transportation applications, e.g., image processing, proximity analysis, cluster analysis, flow analysis, aggregation and other kinds of statistical processing, resource allocation, path finding, pattern finding and matching, best-fit computations, surface-area and volume computations, and engineering design computations.

This long list cannot possibly be complete but should serve to make a central point: the GIS-T server net characterized here is not something separate from the general computing environment of a DOT. In the ideal, it is integral to that general environment. Thus the database servers that serve applications not typically considered GIS-T applications, e.g., personnel applications or financial management applications, might well be the same attribute data servers needed for various GIS-T applications, e.g., an application that associates

addresses with locations. And the servers characterized as analytical computation servers devoted to engineering design computations are not something separate from traditional CAD workstations. They are those workstations connected into a server net that contains, among other things, spatial data servers and servers performing other GIS-T functions. Once a GIS-T client-server architecture is specified, transportation computing is decomposed into separable kinds of services and activities (that both provide and use GIS-T capabilities), and these services and activities are in turn allocated out to separate server and client nodes as appropriate.

As with several other of the server kinds being discussed, whether a particular computation actually gets performed by an analytical computation server, or the program required for it is moved down to a user workstation where the actual computation is performed, will vary from case to case depending, for example, on resolution and extent of the model being computed. In any case, it is on analytical computation servers where analytical program libraries will be maintained and where computations beyond the capacity of individual workstations will be performed.

User Interaction and Display Servers

Servers of the eighth kind, user interaction and display servers, are the workstations that support individual users. They support map-oriented query directed against spatial data and the other kinds of data servers, and they support displays of the results — results whose generation may of course require calls on overlay servers and analytical computation servers. In the long-term ideal this all occurs interactively with the responses being generated quickly and displayed on high-resolution, large screens. Before technology developments make available the computational capacities and electronic display screens required for such real-time interaction, these user-station servers will be used to request and control map generation and analytic computations, results of which may not be immediately available. In the map generation case, for example, the results will sometimes be generated and stored by cartographic data servers to be accessed later by user-station servers.

These user-station servers are exactly the same ones that support word processing, desktop publishing, electronic mail, electronic collaboration support and other kinds of "groupware," accessing databases for all kinds of non-GIS-T uses, computer-aided design, decision support, financial modeling, project scheduling, and the hundreds of other now common, as well as yet to be imagined, uses to which networked workstations and PCs will be put. Clearly, it is important for DOTs to be planning the installation of GIS-T user support on general workstations available to all their managers, engineers, and other employees, and integrated into the general DOT computing network. The goal should be to use GIS-T technology as a general database integrator and to make it available to everybody, not just to certain specialists.

There are a number of capabilities required of a user station, for displaying geographic data and for interactive control of the processing of geographic data, that go beyond the capabilities of contemporary workstations. For example, cartographic snapping, partitioning, panning, and zooming are likely to require software (or special purpose circuitry) not only in the overlay server but also in the user-station server. Similarly, overlay editing or data input editing is likely to require software (or hardware) not only in the overlay server or the data capture server, respectively, but also in the user-station server.

All this might suggest that a geographic user station should be specified as a special kind of server, rather than expecting general user stations to perform geographic display and editing functions. Indeed, the GIS-T server nets of the near term may properly contain GIS-specialized user stations. But there will be no justification for such specialized stations given the workstation computing power (and the software that it will be capable of supporting) to be available in the slightly longer term, in particular, within the next 5 to 10 years.

Application Development Servers

Similarly, there is an apparent need for special user stations for GIS-T application developers as opposed to the stations required for general GIS-T users, but for the same reasons there will be no justification for such user-station specialization except possibly in the very near term. On the other hand, specified as servers of a ninth kind, are GIS application development servers, intended not as separate servers for each individual programmer, but as servers that provide source code databases (with capabilities required for version control),

coordination support for programmer teams, documentation databases, linkers, optimizing compilers (it is expected that most other language tools, in particular, macro interpreters, incremental compilers, and language-specific editors, will be assigned to user stations), and other CASE tools.

These application development servers need to be something more than database and CASE systems for supporting programming in general, although, indeed, they must be that as well. They need, for example, capabilities supporting fast prototyping and interface prototyping that involve structuring, use, and display of spatial and nonspatial data from the data servers in a GIS-T server net.

Spatial Data Capture and Transformation Servers

Servers of the tenth kind, spatial data capture and transformation servers, translate data from digitizers and scanners into the formats required for input into, and updating of, the spatial databases maintained by spatial data and image servers, and do various kinds of data interpreting (e.g., of photogrammetric measurements) and data converting (e.g., between raster and vector formats, between spatial data structured according to different reference systems, between different map projections, or between standardized exchange formats and internal storage formats).

Cartographic Data Servers

Servers of the eleventh kind, cartographic data servers, construct and store symbolic structures that drive electronic map displays and hardcopy map printing and publishing devices. Once again, there is a question of the appropriate division of labor between individual-user workstations and multiuser servers. For users involved with map construction, many of the design, "what if" map display, map editing, contour generation, third dimension generation, and similar tools that they need will be supported directly by their individual workstations. The multiuser cartographic-data server maintains symbol libraries, map templates, finished maps (in appropriately differing versions), and other cartographic tools and products of general use to map-making and map-applying user groups.

New Technology Servers

This twelfth kind, new technology servers, is a place holder. It is meant to include any number of additional server types, different ones for different technologies. The point is that computing environments structured in terms of server nets can easily, nondisruptively be extended to exploit new technologies simply by incorporating new kinds of servers.

An example of such a new technology server type might be expert system servers, servers containing and applying knowledge bases and inference engines that enable computer-based spatial reasoning at a more aggregative, more general, and more abstract level than possible when working only with spatial data not supplemented by general knowledge.

Another example might be animation generator servers that would enable flybys, view manipulation, and other kinds of spatial data utilizing animation to be produced and stored as video. Other media would likely also be involved, voice for sure.

There will be many other new technologies that eventually may be incorporated into servers within GIS-T server nets. Many of these will become possible because the cost of computing power continues to decline so sharply. (That is, implementation is currently possible, however, the computing power required is not affordable.) Others will result from artificial intelligence and other kinds of computer science research. Many simply cannot be imagined at the present time; they have yet to be invented. Such servers might include collaboration servers, virtual reality servers, neural-net-based image recognizers and map readers, and "knobots" that constantly monitor external networks and databases for data of interest.

General Purpose Servers

Any given server net will have several other kinds of servers, e.g., internet gateways, plotter drivers, printer drivers, film recorder drivers, and typesetter drivers. These will be indispensable for GIS-T applications, for example, for map publishing, but they are not discussed further here where the intent has been to specify server kinds that are GIS specific in some sense. However, one such kind that will be available in every server net of the future is worth mentioning. Directory servers will catalog and describe the resources in a net, and from them users will be able to discover what resources are available and how to access them.

History Servers

Archival servers will be needed in at least some GIS-T server nets to store historical data no longer of current interest but possibly required for legal purposes, to perform historical analyses, and to create databases that contain event histories and temporal trajectories. These servers will be supported by mass storage devices (e.g., optical storage devices or tape devices) capable of economically storing massive amounts of data (many trillions of bytes). The data involved will be "dumps" or extracts or update logs from the several other kinds of data servers in the net, e.g., vector data, image data, attribute data, and complex object data. There are difficult issues involved in establishing archiving policies (e.g., what is important enough to be archived and how can the archives be indexed to enable relatively efficient historical analyses to be performed), but the point to be made here is simply to take note of the need for one or more servers that perform the archiving function.

Specialized Application Servers

In many cases particular applications, e.g., pavement management or bridge management, can feasibly be realized as special purpose servers. Such applications will make use of many of the servers in the net (e.g., the attribute data servers to store maintenance records, the image data servers to store photo-based images, and the overlay servers to integrate data of different kinds), but this is standard operating procedure for client-server networks. Servers, qua clients, make use of whatever other servers on a network can contribute to their function.

5.3 SERVICE AND SUPPORT ALTERNATIVES

There are a number of alternatives for GIS-T service and support that account for training, consulting, advice, application development, and production. Centralized service and support is provided by a single administrative unit that houses most GIS-T staff and expertise. A centralized GIS-T service and support unit can even be responsible for production, providing analyses and products that are requested by users. Such a centralized service and support unit can soon be overwhelmed with work and find that it cannot meet the urgent needs of a significant number of users.

Alternatively, a user-driven GIS-T service and support model has each administrative unit responsible for its own activities. Expertise is distributed and there are redundancies in staffing across the organization. Consistency in training and direction can become problematic.

On the other hand, service and support can be decentralized. With this model, there are "core" staff that are responsible for maintenance of corporate spatial databases, development of training programs, provision of advice and consulting services to users, and low-level system and application development. "Master" users in application areas provide local GIS-T support and services, including high-level application development. This model provides control over corporate data, minimizes staffing redundancies, and facilitates diffusion of the technology throughout the organization.

CHAPTER 6. SYSTEM JUSTIFICATION AND EVALUATION

6.1 SYSTEM JUSTIFICATION

GIS-T implementation must be justified to fiscal decision makers. Convincing arguments must be made that significant expenditures for GIS-T will ultimately provide a pay-off. The benefits of GIS-T must outweigh the costs or the required investments should not be made.

A number of studies have shown that the return on investment for GIS is substantial given that a critical level of investment is reached (*51*, pg. 181). For example, Gillespie (*52*) reported that, as a result of 40 case studies at the federal level, efficiency benefits alone justified the cost of GIS and that effectiveness benefits were many times larger. Efficiency benefits are those that result from

completion of the same tasks at reduced costs. Effectiveness benefits are those that result from completion of tasks that could not or would not be done otherwise.

Justification arguments for GIS-T are similar to those used initially for automation in general and later for CAD. GIS concepts are at the heart of new strategies for comprehensive information systems design and planning. As a result, the potential benefits of GIS-T are both organization-wide and profound.

A well-developed justification strategy can do more than provide arguments for GIS-T. It can force decision makers to consider all factors, including those that are quantifiable, those that are nonquantifiable, and those that are intangible (*53*). It can also provide a basis for future system evaluation.

6.1.1 Benefits

The concept of information as a resource leads to recognition of the most significant benefits from improved information management—improved efficiency in operations and effectiveness in program delivery (*28*, pg. 3). These are among the perceived host of benefits resulting from the shared integratable databases that have long been sought by transportation agencies.

Antenucci et al. (*12*, pp. 65-82) identify five types of benefits resulting from GIS:

Type 1. Benefits that reflect improvements to existing practices. These benefits are the reduced costs of doing business that result from enhanced productivity. GIS-T reduces or eliminates redundant data and associated activities such as assuring that updates are applied to multiple databases managed by different units. Single-purpose data collection, preparation, and analysis are avoided. Improved response time and efficiencies in cartographic production and updates result in lower labor costs and other direct costs.

Production of thematic maps such as traffic count maps is enhanced because there is now intelligence associated with the maps. Any attribute that is stored in a highway network database can easily be displayed. With time series data on traffic in the database, year-to-year changes in traffic, as well as average growth rates, can be computed and displayed.

In the planning area, the benefits of GIS-T can be estimated from the reduction in time needed to create new traffic analysis zones (TAZs) or to revise existing TAZs. With GIS-T, existing geography such as census tracts and minor civil divisions can form the template on which smaller or larger TAZs can be constructed with simple editing commands. Population, households, labor force, and many other attributes can be generated for new TAZs by overlaying TAZ and census spatial databases. Many Metropolitan Planning Organizations are still creating and modifying their TAZs manually in a process that is time consuming and error prone. The maps that are generated are not in digital form and thus are difficult to use for analysis and links to other databases.

An estimate of the monetary benefits of applying GIS-T to what has been essentially a manual process is provided by right-of-way litigation support in Maricopa County, Phoenix, Arizona (*54*). Without GIS-T, estimation of land value using overlays of zoning and current land use is a tedious manual process that can only realistically include a very limited set of attributes. In contrast, with GIS-T analysis of land value can encompass the entire study area and consider all attributes in zoning and land use databases. GIS-T generated estimates of development potential in an urban freeway corridor provided strong support for Arizona DOT's initial valuation of property that was subject to litigation. In at least one case the potential savings to ADOT was $40 million (the difference between the property owner's asking price and ADOT's offer when litigation began). Manual analysis probably would not have produced the same result and would have taken much longer and cost much more.

Type 2. Benefits arising from expanded capabilities. A multipurpose GIS-T facilitates completion of tasks formerly left undone. These benefits are the equivalent of additional staff and can be measured in labor equivalences and non-labor costs that would be incurred without GIS-T. They result from readily integratable databases, new analytical capabilities, and more flexible output (*8*, pg. 21). An example is avoiding the labor costs associated with the otherwise nearly insurmountable task of linking highway data and other attributes to maps and then performing spatial analysis.

Type 2 benefits escalate with the complexity of the data and analysis. For example, GIS-T is well-suited for the linking of land use, transportation, and

air quality data and models required by recent amendments to the Clean Air Act (*55*). The required analysis will be greatly inhibited without GIS-T.

GIS-T has enhanced the ability of transportation agencies to estimate the risks of hazardous material transportation. Without GIS-T, detailed evaluation of a large number of alternative routes was not economically feasible. Now lower-risk routes can be easily identified using GIS-T spatial analysis capabilities.

Type 3. Benefits that result from unpredictable events. Unanticipated applications can arise after a GIS-T is put in place. For example, a GIS-T might be used to help manage an unexpected emergency evacuation even though it was not initially planned as a disaster management system. Other, more routine, yet unanticipated applications can also arise—particularly if those conducting initial studies had little experience in GIS-T resulting in a tendency to underestimate its potential.

Type 4. Intangible benefits, or benefits that produce intangible advantages. These vary widely in type and significance. They can play a crucial role in system justification.

Elimination of redundant data and improvements in the quality of data reduce mistrust and lower the risk in decision making. Using GIS-T, data collected in the field can readily be displayed with thematic maps. These maps permit easy identification of many omissions or obvious errors in field data. Field data become readily accessible to operations staff in the field who can then make better decisions. As a result, field staff are more likely to do a better job collecting field data and to suggest new ways of collecting data that will make it even more useful. Enhanced confidence in data and decision making can lead to increased use of GIS-T.

GIS-T can make jobs less tedious, more interesting, and more rewarding, resulting in higher morale and self esteem for employees. There might be an associated reduction in staff turnover. Better working relationships might be possible, resulting in increased cooperation and organizational integration. "Turf battles" might be reduced.

The enhanced planning associated with GIS-T can lead to avoiding future pitfalls such as planning failures and design failures (*55*).

Visualization provides benefits in effectively communicating results of GIS-T analysis. A thematic map presents a comprehensive geographic view that is much more easily interpreted than a textual report, especially for large volumes of data with many comparisons.

Type 5. Benefits that arise from sale or sharing of information and services, or sharing of costs for information and services. Benefits can be derived by entering into cost-sharing agreements for data and services. Production of digital line graphs by USGS under cost-sharing agreements with state agencies is an example. Interagency data-sharing agreements can provide access to data that would otherwise require significant expenditures. Internal charge-back mechanisms for access to data, training, and services can be used to spread GIS-T costs throughout an organization. However, external charges for products and services of government organizations raise critical legal issues.

All benefits are either direct or indirect. Direct benefits are those that accrue to the organization or unit sponsoring the GIS-T (e.g., productivity improvements and reduction of workload). Indirect benefits are those that accrue to organizations or individuals who are not the sponsors of the GIS-T (e.g., improved program delivery and service to the public). Many indirect benefits can result in later direct benefits such as increased public support for an agency's program and improved credibility with the legislature.

Better program delivery and service to the public result from many factors associated with GIS-T, the most significant of which is enhanced decision making. For example, an executive information system (EIS) based on GIS-T provides a high-level decision maker with the ability to analyze the status of projects on a statewide basis in ways that were not possible before. Better budgetary planning and allocation of resources can result. This enhanced decision making derives from integration, aggregation, and visualization of data with GIS-T. Other GIS-T applications lead to improved safety, better scheduling, less congestion, and so forth.

The benefits of GIS-T are maximized by careful and effective system design and implementation planning. A casual approach can lead to decreased benefits, and possibly, to disaster, with large investments and restricted numbers of users and applications.

6.1.2 Costs

The costs of GIS-T vary considerably with the size, configuration, and level of sophistication of the system and with the scales of the spatial databases. According to Gillespie (*56*, pg. A-86), there are three primary types of costs associated with GIS implementation:

Type 1. Computing environment costs. These include costs for hardware, software, and networking infrastructure. Hardware and software costs rarely exceed 20 percent of overall system costs. Lifecycle costs of hardware and software (maintenance and replacement, including software upgrades) should be considered. Software maintenance (e.g., technical support and documentation) and upgrade fees can soon exceed initial costs (*12*, pg. 72). Some software is licensed according to the number of simultaneous users. In these cases, the cost of the license might increase with time as the number of users grows. Some states have statewide agency licenses covering acquisition and maintenance of software.

Networking infrastructure includes cabling, gateways, hardware interfaces, communications software, and so forth. Other general computing environment costs include supplies and overhead that covers space, power, heating, ventilation, and air conditioning. Computing environment costs that would be incurred in any case should be distinguished from new costs incurred only as a result of GIS-T.

Type 2. Data costs. The largest cost component of GIS (up to 80 percent) is typically associated with data. These include costs for database design, data acquisition, database development, and database maintenance—all of which might have internal or external cost components or both. Data and services can be purchased or the cost of data can be reflected in internal personnel costs.

Database design begins with the user requirements study, includes conceptual-level data architecture development, and continues until final entity relationships have been derived. Data acquisition costs include those arising from planning and management of acquisition, outright purchase of data, contributions to data-sharing programs, and labor devoted to spatial data conversion (e.g., digitizing, scanning, quality control). Database development costs arise from labor associated with planning and management, editing, edge matching, transformation, insertion of reference points, construction of topology, identification of routes, creation of libraries, treatment of attribute databases, quality control, and so forth. Database maintenance costs must be considered. If databases are not maintained over time, substantial reinvestments in data will be required in the future.

If consultant services are used, internal costs are incurred from developing specifications, selecting the contractor, and managing the contract.

Type 3. Additional personnel costs. These include costs associated with overall system planning, design, and implementation, direct costs of training plus lost production time while staff is in training, time devoted to application development and user support, and so forth. Both salary and fringe benefits should be considered. As a result of substantial demand for GIS personnel, salary premiums might be required to retain highly trained staff (*55*).

Some costs of overall system planning, design, and implementation might be reflected in consulting contracts. Once again, there are additional internal personnel costs associated with contracts.

A fourth type of cost might also be considered:

Type 4. Intangible costs (*12*, pg. 78). These can include costs arising from modification of existing practices, diversion of attention to the new program, resistance to change (*57*), and concerns about liability associated with data sharing (particularly if data is to be shared externally).

6.1.3 Justification Strategy

Successful justifications for GIS-T have included thorough identification of the breadth and depth of applications on an agencywide basis, a sound implementation plan, and quantification of costs for preliminary budgetary purposes during a 4-5 year period (*58*).

It might be possible to quantify some Type 1 benefits by determining the cost associated with a current task and projecting the cost of that task when using GIS-T. However, if quantification becomes a matter of conjecture, other arguments for GIS can be undermined (*51*, pg. 173). Quantification of benefits is most meaningful after-the-fact. It can be used for future system evaluation and continuing justification (see Section 6.2).

Benefit-Cost Relationships

Figure 13 is a general depiction of the relationship between benefits and costs of GIS-T over time. It compares cumulative costs of doing business, with and without GIS-T, beyond the point where the curves intersect and benefits begin to outweigh costs. Benefits can be thought of as future costs that have been avoided.

The GIS-T cumulative cost curve is steeper in the short term as start-up costs are incurred. It begins to flatten out as required new investments diminish and benefits begin to be realized. Earliest benefits accrue with a well-designed pilot project that contributes to the agency's mission. Additional benefits are realized when redundant data and associated redundant effort begin to diminish as GIS-T databases are developed. However, these early benefits are overwhelmed by costs for system design and development. Much more significant benefits begin to accrue in say 3-5 years as GIS-T goes organization wide and applications become effective.

The "without GIS-T" curve is more gentle initially but grows steeper with time as problems and tasks become more complex and existing approaches begin to bog down. New demands and mandates force applications that cannot be effectively supported by the existing system. The costs of "business-as-usual" eventually escalate well beyond those of implementing GIS-T.

The "pay-off" point is reached when the cumulative cost curves intersect. The initial heavy investment in GIS-T is thus more than recovered in the future. Ultimately, GIS-T provides a higher level of service at less cost and results in more effective use of limited resources.

Additional Arguments for GIS-T

Convincing arguments can be made by describing current constraints on required tasks and how they will be relieved by GIS-T. Without GIS-T, data and systems integration have many inherent problems that make accomplishment of some tasks nearly impossible. ISTEA mandates will be terribly difficult to meet without GIS-T.

GIS-T is here to stay. Its true benefits have been proven by Arizona DOT's right-of-way litigation avoidance (*54*), Wisconsin DOT's pavement management decision support system (*59*), North Carolina DOT's environmental analysis of corridors, and others. It is not a matter of whether DOTs will adopt GIS-T—it is a matter of how and when they will do it.

GIS-T is the latest step in the evolution of technology. It represents a technological breakthrough, as did CAD and database management systems (DBMS). Its value is in information delivery. GIS-T provides at least as favorable an advantage over current practices as DBMS provided over management of flat files.

A phased strategic plan for adoption of GIS-T, beginning now, will be far less costly than trying to catch up all at once sometime in the future. Staying at the forefront of technology is in any agency's best interest.

6.2 SYSTEM EVALUATION

Periodic evaluation of a GIS-T implementation is necessary to ensure efficiency and effectiveness in meeting goals under changing circumstances such as new demands for applications; turnover, increases, or reductions in personnel; and changes in funding and organizational structure. Monitoring the performance of GIS-T might be necessary to sustain funding and institutional support. Possible evaluation methods include the following:

1. Comparison to plan. The following questions should be addressed: a) Is implementation on schedule—have planned milestones been met? b) Have planned goals and objectives been met? c) Have there been unexpected benefits? d) Have there been unexpected costs?

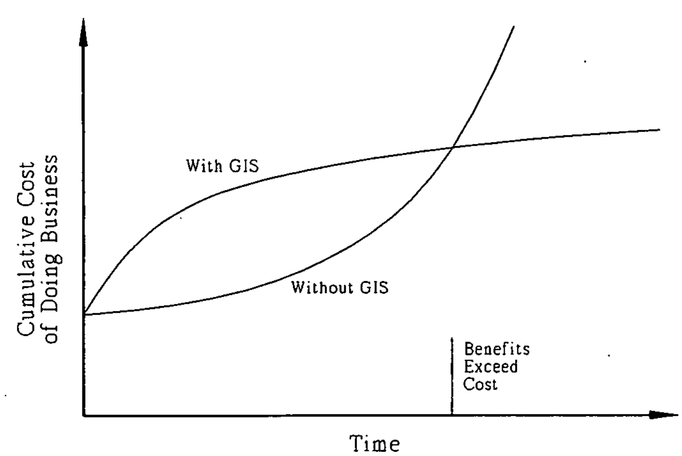

Figure 13. Cumulative Future Costs of Doing Business with and Without GIS. (Source: Antenucci et al., Ref. 12, pg. 79)

The GIS-T implementation plan should be updated following each evaluation.

2. Determination of user satisfaction. The following questions should be addressed: a) How many active users are there of GIS-T in the organization? How does this compare to the number that have been trained? b) What is the extent of the organization's application portfolio? c) Has the users' confidence in data and decision making increased? d) Is there a higher morale?
3. Quantitative benefit-cost analysis. System evaluation can have a larger comparative economic component than did initial justification. Empirical determination of required resources is now possible. For example, the effort required for completion of a specific task with GIS-T can now be measured. Types 1 and 2 benefits can be quantified.

Recent research has shown that many of the benefits of GIS are quantifiable (*52*, *56*, *60*, *61*, *62*, *63*). For example, Gillespie described the procedure used to determine the value of risk avoided from the Oak Ridge National Lab's use of GIS to examine population density when routing nuclear waste shipments (*56*, pp. A-90-91). In fact, Gillespie developed and tested methods and analytical models for quantifying the benefits of improved decision making with GIS in general.

Under certain circumstances, some apparently intangible benefits might be quantifiable. For example, improved morale might result in reduced absenteeism that can be readily measured. Improvements in data quality might eliminate the need for ad hoc data verification, resulting in reduced labor costs. When performing economic analysis, as many benefits as defensibly possible should be quantified.

CHAPTER 7. STATEWIDE COOPERATIVE EFFORTS

7.1 APPROACHES

An integral part of a DOT's information technology and GIS plans must be coordination with other state agencies. There is significant potential for sharing of at least some spatial database construction and maintenance costs. Recognizing this, every state has some GIS coordination activity among state agencies (some extend the activity to include local governments and the Federal Government, and even the private sector) (*4*). In some cases coordination is ad hoc and informal with periodic or irregular meetings among interested individuals. In other cases coordination takes place under executive order, with agency designees having memberships on committees or commissions.

In yet other cases coordination has been legislated and there may be an office or board responsible for statewide GIS coordination. For example, Vermont has a State Office of Geographic Information Systems, North Carolina has a State Center for Geographic Information and Analysis, and Wisconsin has a State Land Information Board.

Compatible or confederated systems development to facilitate data sharing is the primary objective of many of these efforts. Some have taken a decentralized approach and concentrated on standards and mechanisms for data sharing. Typically, each state agency agrees to be the responsible "custodian" of the spatial data that is primary to its mission, to maintain that data according to agreed on standards, and to make it available to other participants. In this way, DOTs become the custodians of transportation data, Departments of Natural Resources become the custodians of hydrography and wetlands data, and so forth.

The Growth Management Data Network Coordinating Council in Florida facilitates data sharing among eight state agencies and offices. North Carolina is operating under a statewide GIS library network concept. Some states have developed GIS data clearinghouses (the Arizona Land Resources Information System, the Teale Data Center in California, and the Resource Geographic Information System at the University of New Mexico are examples). A data clearinghouse can be either a source of data (the actual data is on hand) or a source of information on how to obtain data (users are directed to appropriate agency contacts).

Some states have used a top-down approach, at least to the extent that a single base map scale has been established for state agencies (e.g., Vermont and New Hampshire). Some statewide efforts slowed GIS development within individual agencies until conclusive statewide directions had been

established (e.g., Kentucky and Kansas). Some states have or are developing blanket-order mechanisms with preferred GIS software vendors. And some states have used consultants to develop statewide GIS strategic plans (e.g., Minnesota).

7.2 STANDARDS

In many cases, the agreed on quality and maintenance standards for data sharing are those that are or would be used internally by the agencies anyway, so that the requirement to conform to standards imposes no additional burden on internal GIS efforts. However, concern over liability appears to be hindering some data-sharing efforts. The concepts of "truth in labeling" on the part of data providers, and the corresponding judgment of "fitness for use" on the part of data users, that stand behind the quality section of the Spatial Data Transfer Standard (*21*, Part 1, pp. 21-24), represent current thinking concerning the risks of data sharing.

Typically, state agencies do not have common GIS hardware and software. A number of data exchange format standards have been used—all with their limitations. Problems arise from the incompatibilities of proprietary data models. Typically, either information is lost or spurious information appears when translating among various vendors' exchange formats. Implementation of neutral, robust standards, such as the Spatial Data Transfer Standard (SDTS) is vital to efficient data sharing efforts.

7.3 DOTS' ROLE

DOTs often have primary roles in statewide GIS efforts. There appear to be at least three reasons for this:

1. DOTs have a tradition of map making and geographic data management.
2. Many other agencies need transportation data. Among other things, highway and road networks are often used as reference systems by others.
3. DOTs have always worked closely with local governments (e.g., with MPOs in transportation planning and with engineering offices in geodetic control, aerial photography, and large-scale mapping).

DOT roles seem to revolve around these concepts. DOTs are often looked to for leadership and technical knowledge. (The Pennsylvania statewide group waited for PennDOT's GIS strategic plan to be developed before moving forward with a broader one.) DOTs are the custodians of transportation information. And they are often important players in local government land information system (LIS) development efforts, particularly with regard to geodetic control. The local need for geodetic control is great and de facto responsibility at the state level is usually with the DOT.

The New Hampshire, Minnesota, and Colorado DOTs have derived considerable benefits from their active involvement in local government LIS efforts. New Hampshire is using locally developed 1:600 scale mapping in its spatial database. Minnesota uses local control and mapping for engineering planning and design. Colorado loans GIS equipment to local governments and participates in pilot projects that have mutual benefit.

CHAPTER 8. FUTURE DIRECTIONS

8.1 INFORMATION TECHNOLOGY TRENDS

This is an age of major and rapid technological changes—changes that will affect the use, scope, and methods of transportation in society, as well as how DOTs and other organizations responsible for transportation infrastructure plan, design, construct, and manage that infrastructure. A number of experts have recently made projections concerning imminent technological changes that will be realized and that can be exploited in the decade of the 90s. The projections are not wild guesses but predictions about which there is general agreement. And the predictions are of changes near enough in time that they must be factored into current planning efforts of organizations like DOTs.

The list of imminent major technological changes compiled by the science and technology writers of the *New York Times*, April 26, 1991, is a distillation of lists constructed by such groups as the

Department of Defense, the Commerce Department, and the White House Office of Science and Technology. Items on the list most relevant for DOT planning during the next decade include the following:

1. New computer architectures exploiting parallelism.
2. Superconducting materials used for electric power transmission and for computer circuits.
3. Very high definition, true-color electronic display used in TV and in computer display screens (that will not continue to be two separate things but will merge into a single multimedia technology).
4. An increase in the number of transistors on silicon chips from about a million to about a hundred million, enabling the placement of entire computer systems (e.g., GISs) on single (or a very small number of) chips—among other things, thus bringing the cost of such systems down by orders of magnitude.
5. Fiber-optic gigabit-per-second networks interconnecting computers and computer databases, both local- and wide-area networks.
6. Computer-aided software engineering (CASE) that utilizes low-cost computing power to support software development environments that in turn enable faster, cheaper, more rapidly developed, and more reliable computer applications, for example, GIS applications and multimedia applications.

Not on the *New York Times* list but of comparable importance for DOT planning:

1. Rapid improvement and lower cost of data storage techniques, both optical and magnetic, enabling the cost-effective production and distribution of very large geographic databases.
2. Rapid improvement and lower cost of various geographic measurement and data-collection technologies, for example, GPS (Global Positioning System) technology.

In general, information technology is moving in the direction of very large amounts of computation power being available at very low cost and thus affordable for many functions and activities not previously supported by computing because of its relatively high cost. Computing power will no longer be a limiting factor in information system strategies appropriate for organizations like DOTs. The emphasis of those strategies can and should be on productivity of human beings served by computing, on networking infrastructure that enables convenient communication among many different kinds of computational devices distributed throughout the organization, and on development and maintenance of data considered as a primary corporate resource and integrated across departments and their specialized applications.

GIS technology plays a central role in several of these areas. It enables map-oriented information display of a form conducive to increased productivity for users of all kinds, from highly technical professionals to high-level managers. It provides a natural basis for formulating questions of databases and applying models against them. And it provides the means for managing locational data around which most other kinds of data can be effectively integrated. A major reason why GIS technology has not previously been given these central roles in data processing and use is that it requires a lot of computation power. But computation is rapidly becoming an abundant resource, and this will enable widespread use of GIS technology wherever it can be made to serve a good purpose.

An example that illustrates this rapid decline in cost of GIS technology: The cost per GIS user station has decreased from about $30,000 in 1988 to less than $5,000 in 1992, and there is no change in the slope of the decline.

8.2 GIS SOFTWARE TRENDS

Cheaper computation power will make affordable and widely available not only basic GIS display and integration capabilities (e.g., the computational overlaying of thematic layers), but also an increasing number of very powerful and sophisticated GIS functions. GIS products possessing the special functionality needed for transportation applications can be expected to become generally and economically available, with the computation power needed to support them easily affordable. This functionality will include network description, display, and overlay capabilities; linear referencing and linear reference transformation capabilities; dynamic segmentation capabilities; and transportation analysis and modeling capabilities. (For a full list of the functionality to be expected in GIS products of the near future, see Section 2.2.)

Other capabilities to be expected in GIS software products of the near future include fast prototyping capabilities that will make it possible for managers and users to directly experience and evaluate the "look and feel" of proposed applications before major amounts of programming labor have had to be expended on them, and computer-aided application development environments that significantly reduce the amount of programming labor required to implement GIS applications. At the same time GIS products will be more compatible with open systems, that is, systems that use industry-wide standards independent of the products of particular hardware vendors. The open systems movement is now so strong that in a few years products not compatible with its standards will simply not be able to survive in the marketplace.

As the functionality of GIS software increases, however, it is not necessarily the case that the full gamut of functions will be provided in a single, indivisible software package. As spatial data storage and spatial data transfer standards become firmed up and more widely adopted, GIS software will become increasingly modularized with different modules being available separately, in some cases even from different vendors, but nevertheless sufficiently compatible with each other that efficient communication among them will be possible. This will enable mounting of the different modules on different nodes of a client-server network, as appropriate for the best service and the most cost-effective division of labor among different nodes in the network. Just as with open systems, client-server network architectures are becoming so widely realized that, if they are to survive, software products will have to be designed for and usable within such client-server environments.

8.3 FUTURE TRANSPORTATION APPLICATIONS OF GIS

Since almost all information used by DOTs can be linked to location, a wide variety of applications of GIS-T is possible. Applications will cover the entire range of modal responsibility of DOTs from air, rail, and highways to ports and waterways. Using location as the key, multimodal applications will become feasible. Joint consideration of rail and highway networks will include locations of railroad-highway grade crossings and facilitate analysis of safety and other impacts. Similarly, in urban areas simultaneous consideration of rail, bus, and highway systems will facilitate multimodal planning and system design and even provide a basis for real-time multimodal system operation.

Future GIS-T applications will cover a wide range of spatial and temporal dimensions. Applications will be needed at the statewide, district/region, corridor/project and engineering design levels. Typically, statewide applications will focus on long-range, multimodal planning issues as well as management issues relating to the current and projected status of the transportation system. District/region level applications will focus on mid-range planning and management issues while corridor/project applications will focus on short-term facility planning, design, operations, and maintenance problems.

GIS-T applications will cover the full range of DOT functional areas—planning, design, construction, operations, and maintenance. Because of the ability of GIS-T to integrate information across functional areas, management applications are likely to provide the highest short-run payoffs, but planning and engineering applications will quickly follow once the appropriate spatial databases are in place. GIS-T will also enhance DOT research capabilities. GIS-T will provide much greater access to corporate databases thus providing the information base needed to address a wide variety of research questions.

GIS-T will generate a broad array of new uses for transportation system attribute data including physical (pavement, base, geometrics, etc.), traffic, travel, freight, operational, and financial data. The new uses will create a demand for more complete and higher quality data which will provide incentives for automating more of the field data-collection process. GIS-T can also provide the links to related databases providing access to demographic, land use, environmental, hazardous material, utilities and management, accounting, and budgetary data.

At the urban area and statewide levels, a wide variety of future GIS-T applications are possible to support the comprehensive planning process. GIS-Ts will be used to inventory vacant land, to analyze development patterns and to help forecast land use. GIS-Ts can also be incorporated in the air quality, noise, stormwater runoff, soil, wetlands, and vegetation models needed for effective planning.

Future DOT GIS-T use will involve a large number of management applications. Thematic mapping applications will be extended to real-time

data display and analysis such as freeway incident detection and management. This is just one of a number of applications that are potential intelligent vehicle highway systems (IVHS) applications.

The freeway incident application involves a broad range of transportation system attributes including travel and operations attributes. With the appropriate travel database, possible alternative routes for traffic diversion can be displayed for evaluation and implementation. Arterial street system operations can be evaluated in real time and included in the decision making process.

Other IVHS applications that are similar to freeway incident detection include more comprehensive freeway and corridor congestion management applications as well as driver information systems. GIS-Ts will provide the data retrieval, integration, and display capability for evaluation of current transportation system operation including freeway ramp metering and traffic signal control.

For bus systems with automatic vehicle location systems, GIS-Ts can manage vehicle location in real time. GIS-T can then support performance monitoring, dispatching, and customer information service functions.

Air quality management is another example of an important future GIS-T management application. Air quality impacts need to be quantified in terms of land use and demographics of the affected zones. Environmental attributes such as prevailing winds will be incorporated directly into air quality models. The GIS-T overlay function will be used to map plumes and pollutant loads onto population and land use databases. The GIS-Ts involved will have to include surface modeling capabilities in order to correctly represent and predict the impact of terrain on wind flows and plume formation.

Other GIS-T management applications that will be much more widespread in the future than at present are right-of-way (ROW) studies, maintenance management, environmental impact studies, and construction management. For example, ROW studies and maintenance management will require spatial data on vegetation as well as on gas, power, and water utilities. Monitoring of environmental impacts of noise and air pollution will require data on surrounding land use and population and possibly on topography. Construction management will potentially require an even broader range of data including surrounding land use, demographics, and environmental features as well as utilities.

Integration of GIS-T into engineering functions will permit the consideration of a much broader range of factors in design, construction, operations, and maintenance. With GIS-T, integration of corridor planning and design is possible. Engineering applications can also use many of the corporate database display and analysis tools developed for management applications. Simultaneous consideration of multiple attributes through dynamic segmentation and overlays will be particularly important.

Construction impact mitigation is a logical extension of existing urban corridor design applications. Construction impacts on available traffic routes will be evaluated more easily for both local and through traffic. Similarly, utility system overlays and surrounding land use will be integrated to evaluate the impacts of utility cut-offs. In effect, the list of possible GIS-T transportation applications in the future—the near future—is limited only by the imagination. Their actual implementation will of course also be limited by data-collection costs, by software development and adaptation costs, and by staff training costs. But, and recognizing this is essential for effective GIS-T planning, they will not be limited by the costs of the large amounts of computation required. Computation is rapidly becoming an abundant resource.

GLOSSARY & REFERENCES

AASHTO - American Association of State Highway and Transportation Officials.

AI - Artificial Intelligence; the capability of a computer to simulate inductive reasoning based on a set of logic rules.

BLM - Bureau of Land Management.

Centroid - Representation of a geographical area (zone or polygon) with the single point (node) within the area, which is the least distance from all points on the area periphery.

Client-server network - Network of computers (nodes) among which computing labor is divided, with each node (qua server) providing certain specialized services to others and each node (qua client) requesting from others services that it cannot itself compute.

DBMS - Database Management System; a set of computer programs for organizing and using the information in a database.

DLG - Digital Line Graph; a standard file structure for digital cartographic data in vector form established and used by the United States Geological Survey (USGS) that includes information on planimetric base categories, such as transportation, boundaries, hydrography, hypsography, Public Land Survey System (PLSS), and other significant cultural features.

DNR - Department of Natural Resources.

DOD - Department of Defense.

Dynamic segmentation - An automatic procedure for dividing a geometric representation of a network into homogeneous sections based on a particular linearly referenced attribute (or combination of attributes) with the segmentation varying from one attribute to another.

EIS - Executive Information System.

EPA - Environmental Protection Agency.

Expert system - A computer system that works out problem solutions by drawing inferences from a large base of knowledge, usually derived from human experts and represented symbolically within the system in the same terms and at the same level of abstraction used by the experts in their discourse with each other.

4GL - Fourth generation "programming" language; a language using data types and control constructs that facilitate development of data intensive computer applications operating on databases.

GBF/DIME - Geographic Base File/Dual Independent Map Encoding; a geographic file based on line segments produced by the United States Bureau of Census for each Standard Metropolitan Statistical Area in the United States.

GPS - Global Positioning System; a constellation of satellites and a tracking and control network developed by the US Department of Defense to support military navigation and timing needs that recently have become available to the public. The satellites transmit signals that can be decoded by specially designed receivers to determine positions precisely (within centimeters).

GUI - Graphic User Interface; an interface that uses pictographic resources, such as menus, windows, mouse buttons, dialog boxes, and icons for real-time communications between users and a computer system.

IGES - Initial Graphics Exchange Specifications; a data exchange format for product data of typical geometric, graphical, and annotation entities in CAD systems.

Linear referencing - Means of identifying location on a transportation network by specifying a starting point and a directed distance along a particular route.

MIPS - Millions of Instructions Per Second; a unit used for comparing computational capacities of different computer models.

MIS - Management Information System.

Motif - One of the competing proposed standards for GUIs (see above) developed in X-windows (see below), the one developed and adopted by the Open System Foundation (see below).

mutatis mutandis - with the necessary changes having been made or the respective differences having been considered.

Network overlay - A spatial relation function that joins two or more sets of attributes by performing a combined sort of their segment boundaries to produce a new set of segment boundaries.

NGS - National Geodetic Survey.

Object-oriented programming - A popular computer programming style that builds programs as complexes of modules ("objects"), which communicate with each other in terms of precisely defined input-output behavior, which are not allowed to access or modify each other internally, and each of which is intended to be used and re-used many times over in different programs.

Open Systems - Computing systems using nonproprietary formats and conventions that are developed by standards-setting bodies (rather than particular vendors) and that are used by hardware and software products from many different vendors.

OSF - Open Systems Foundation; a consortium of several main computing system vendors established to develop and dictate Open Systems standards (see above) -- unfortunately only one of several such organizations that are competing with each other.

Raster display - Method for display of graphical images (e.g., maps) where the images are represented as rasters or matrices of explicit values (pixels) (contrast with vector display, where images are represented as vector-defining formulas from which such pixel values can be computed when needed).

Relational database - A database that appears to programs accessing it as a collection of relations, each of which in turn appears as a tabular structure of rows and columns (the number of rows may vary, for example, with new input to the database, but for a given relation the number of columns and the type of value allowed in each column is fixed).

Server-net model - The organization of a computing system as a set of possibly many separate computers organized as a client-server network (see above) (contrast with mainframe model or star-net model where most, if not all, computation is performed by a single, large computer at the center of a network of terminals and other input-output devices).

SNA - Systems Network Architecture; a proprietary computer network communication architecture developed by IBM for data communications between mainframe computers and locally or remotely attached microcomputers and data terminals.

SPOT - System Pour l'Observation de la Terre; an earth resource satellite with high resolution sensors launched by France in early 1986 (SPOT-1).

SQL - Structured Query Language; an Open Systems (see above) query language for use with relational databases (see above).

SDTS - Spatial Data Transfer Standards; a national spatial data transfer mechanism recently approved by the National Institute of Standards and Technology (NIST) as Federal Information Processing Standard (FIPS) 173. SDTS provides specifications for organizing and structuring transfer of digital spatial data, defining spatial features and attributes, and encoding data transfer between dissimilar computer systems. SDTS became effective February 15, 1993.

TCP/IP - Transmission Control Protocol/Internet Protocol; a preliminary Open Systems (see above) network communication protocol family.

Thematic map - A map displaying selected information relating to a

specific theme, such as soil, land use, population density, etc.

Thiessen tessellation - The process of splitting up a study area such that all points are grouped into tiles according to the minimum distance between them and a previously sampled point. Also known as Voronoi or Dirichlet tessellations.

TIGER - Topologically Integrated Geographic Encoding and Referencing system; a digital data base developed by the Census Bureau to support the data-collection and data-tabulation operations of the 1990 decennial census.

TIN - Triangulated Irregular Network; a topological data model that represents terrain features as a continuous network of non-overlapping triangular facets derived from a set of randomly spaced points.

TIS - Transportation Information System.

Token Ring - A ring network topology developed by IBM to link personal computer and other devices on a local area network (LAN).

Topological Data Structure - Description of spatial objects that records the relationships of incidence and connectivity among the objects.

UNIX - A computer operating system that is widely used on professional workstations (high-powered personal computers -- see above) and that has become the basis for development of an Open Systems operating system (even though it was originally developed by a particular vendor, viz., AT&T).

URISA - Urban and Regional Information Systems Association.

USDA - United States Department of Agriculture.

USGS - United States Geological Survey.

UWS - User WorkStation; a node in a client-server network (see above) whose primary function is collection of input from and presentation of output to a human user of the network.

VLSI - Very Large Scale Integration; as used, for example, in the fabrication of microelectronic processor or memory chips each containing hundreds of thousands to tens of millions of components.

WIM - Weigh-In Motion.

WYSIWYG - What You See Is What You Get; computer screen presentation of documents and graphic images very close in format and quality to what gets printed by hard-copy output devices (thus enabling users to get a precise idea of the results of computer processing without having to go to the trouble and expense of hard-copy printing).

X-windows - an Open Systems (see above) specification and programming language for developing GUIs (see above).

REFERENCES

1. Briggs, D.W. and Chatfield, B.V., "Integrated Highway Information Systems." *NCHRP Report 133*, Transportation Research Board, National Research Council, Washington, DC (1987), 31 pp.

2. Vonderohe, A.P., Travis, L.E. and Smith, R.L., "Implementation of Geographic Information Systems (GISs) in State DOTs." *NCHRP Research Results Digest*, No. 180 (1991), 31 pp.

3. Ries, T.G. and Fletcher, D.R., "A Network Data Base Model for GIS Applications: Implementation at the Wisconsin Department of Transportation." ACSM-SPRS Annual Convention, Denver, CO, *Proc.*, Vol. 3 (1990), pp. 237-248.

4. Warnecke, L., Johnson, J.M., Marshall, K. and Brown, R.S., *State Geographic Information Activities Compendium*. Council of State Governments, Lexington, KY (1992), 603 pp.

5. Dueker, K.J. and Kjerne, D., "Multipurpose Cadastre: Terms and Definitions." Annual Convention of ACSM-ASPRS, *Proc.*, Vol. 5 (1989), pp. 94-103.

6. Nyerges, T.L. and Dueker, K.J., "Geographic Information Systems in Transportation." *Office of Planning HPN-22*, Federal Highway Administration, U.S. Department of Transportation, Washington, DC (1988), 51 pp.

7. Burrough, P.A., *Principles of Geographical Information Systems for Land Resources Assessment*. Monographs on Soil and Resources Survey, No. 12. Clarendon Press, Oxford (1986), 193 pp.

8. Guptill, S.C., ed., "A Process for Evaluating Geographic Information Systems." *U.S. Geological Survey Open-File Report 88-105* (1988), 57 pp.

9. Aronoff, S., *Geographic Information Systems: A Management Perspective*. WDL Publications, Ottawa, Canada (1989), 294 pp.

10. Transportation Systems Center, "Solicitation, Offer and Award." Solicitation No. DTRS-57-90-R-00026, Cambridge, MA (1990), 81 pp.

11. Wisconsin Department of Administration, "Request for Proposals for Geographic and Land Information Systems Software." Madison, WI (1990), 40 pp.

12. Antenucci, J.C., Brown, K., Croswell, P.L., Kevany, M.J. and Archer, H., *Geographic Information Systems - A Guide to the Technology*. Van Nostrand Reinhold, New York (1991), 301 pp.

13. Maguire, D.J., Goodchild, M.F., and Rhind, D.W., *Geographical Information Systems: Principles and Applications. Volume 1: Principles.* Longman Scientific & Technical, Essex, England (1991), 649 pp.

14. Parker, H.D., Stutheit, J., Dobson, J.E., Hughes, J.R. and Cartwright, J.C., eds., *1991-92 International GIS Sourcebook*. GIS World, Inc., Fort Collins, CO (1991), 597 pp.

15. American Congress on Surveying and Mapping (ACSM), *The Census Bureau's TIGER System*, Cartography and Geographic Information Systems, Vol. 17, No. 1 (January 1990), pp. 7-113.

16. United States Geological Survey (USGS), *Digital Line Graphs from 1:24000-Scale Maps, Data Users Guide*, Reston, VA (1986), 109 pp.

17. United States Geological Survey (USGS), *Digital Line Graphs from 1:100,000-Scale Maps, Data Users Guide 2*, Reston, VA (1989), 88 pp.

18. United States Geological Survey (USGS), *An Enhanced Digital Line Graph Design, USGS Circular 1048*, Guptill S. C. (ed.), Reston, VA (1990).

19. American National Standards Institute (ANSI), *Initial Graphics Exchange Specification (IGES), Version 3.0, ANSI Standard Y14.26M*, New York (1987).

20. American Congress on Surveying and Mapping, "Implementing the Spatial Data Transfer Standard." *Cartography and Geographic Information Systems*, Vol. 19, No. 5 (December 1992), pp. 277-334.

21. National Institute of Standards and Technology, *Federal Information Processing Standard Publication 173: Spatial Data Transfer Standard*. U.S. Department of Commerce (1992).

22. Fletcher, D.R., "Modelling GIS Transportation Networks." Urban and Regional Information Systems Association, 25th Annual Conference, Fort Lauderdale, FL, *Proc.*, Vol. II (1987), pp. 84-92.

23. Dueker, K.J., "Geographic Information Systems and Computer-Aided Mapping." *Journal of the American Planning Association*, Vol. 53, No. 3 (Summer 1987), pp. 383-390.

24. Nyerges, T.L., "Locational Referencing and Highway Segmentation in a Geographic Information System." *ITE Journal* (March 1990), pp. 27-31.

25. Goodchild, M.F., "Towards an Enumeration and Classification of GIS Functions." International Geographic Information Systems (IGIS) Symposium: The Research Agenda, Arlington, VA, *Proc.*, Vol. II (1987), pp. II-67 - II-77.

26. Haggett, P. and Chorley, R.J., *Network Analysis in Geography*. St. Martin's Press, New York (1969), 348 pp.

27. Adams, T.M., Vonderohe, A.P., Russell, J.S. and Clapp, J.L., "Integrating Facility Delivery Through Spatial Information." ASCE *Journal of Urban Planning and Development*, Vol. 118, No. 1 (March 1992), pp. 13-23.

28. Huxhold, W.E., *An Introduction to Urban Geographic Information Systems*. Oxford University Press, New York (1991), 337 pp.

29. Environmental Systems Research Institute Inc. (ESRI), "Integration of Geographic Information Technologies." ARC News, Vol. 11, No. 1 (Winter 1989), p. 24-25.

30. Ventura, S.J., *Implementation of Land Information Systems in Local Government -Steps Toward Land Records Modernization in Wisconsin*. Wisconsin State Cartographer's Office, Madison, WI (April 1991), 83 pp.

31. Ries, T., "Data Quality in the Geographic Data Base Creation Process: Guidelines and Recommendations." Geographic Information Systems (GIS) for Transportation Symposium, Orlando, FL, *Proc.* (March 1991), pp. 59-76.

32. Bissex, D.A., Franks, C.J., and Heitkamp, A., "Quality Assurance for Geographic Information Systems." Urban and Regional Information Systems Association Annual Conference, *Proc.*, Vol. II (August 1990), pp. 106-118.

33. National Highway Institute, *Geographic Information Systems for Transportation Participant Notebook*. NHI Course No. 15129, Federal Highway Administration (October 1991), 477 pp.

34. Lockwood, S. C. and Wagner, F. A., "Methodological Framework for the TSM Planning Process." In *Transportation System Management, Special Report 172*, Transportation Research Board, Washington, D.C. (1977).

35. Rowe, E., "IVHS—Making it Work, Pulling it All Together." *ITE Journal*, Vol. 63, No. 2 (February 1993), pp. 45-48.

36. Wilshire, R., Black, R., Grochoske, R., and Higinbotham, J., *Traffic Control Systems Handbook*. Office of Implementation, Federal Highway Administration, U.S. DOT, Washington, DC (April 1985).

37. Coulouris, G.F. and Dollimore, J., *Distributed Systems: Concepts and Design*. Addison-Wesley (1988), 366 pp.

38. Svoboda, L., "File Servers for Network-Based Distributed Systems." *Computing Surveys*, Vol. 16, No. 4 (1984), pp. 353-398.

39. Tanenbaum, A.S., *Computer Networks, 2nd Edition*. Prentice-Hall (1988), 517 pp.

40. Tanenbaum, A.S. and van Renesse, R., "Distributed Operating Systems." *Computing Surveys*, Vol. 17, No. 4 (1985), pp. 419-470.

41. Francis, R., "Client/Server: The Model for the 90's." *Datamation*, Vol. 36, No. 4 (Feb. 15, 1990), pp. 34-40.

42. Sinha, A., "Client-Server Computing." *Communications of the ACM*, Vol. 35, No. 7 (1992), pp. 77- 98.

43. Ferreira, J. and Menendez, A., "Distributing Spatial Analysis Tools Among Networked Workstations." Annual Conference of the Urban and Regional Information Systems Association, Los Angeles, CA, *Proc.* (1988).

44. Lampson, B.W., Paul, M. and Siegert, H.J., eds., *Distributed Systems - Architecture and Implementation*. Springer-Verlag (1981).

45. Lampson, B.W. and Sproull, R.F., "An Open Operating System for a Single-User Machine." *ACM Operating Systems Review*, Vol 13, No. 4 (1979), pp. 98-106.

46. Mitchell, J.G., "File Servers." *Local Area Networks: An Advanced Course, Lecture Notes in Computer Science*, No. 184, Springer-Verlag (1985), pp. 221-259.

47. Mitchell, J.G. and Dion, J., "A Comparison of Two Network-Based File Servers." *Communications of the ACM*, Vol. 25, No. 4, (1982), pp. 233-245.

48. Sturgis, H.E., Mitchell, J.G. and Israel J., "Issues in the Design and Use of a Distributed File System." *ACM Operating Systems Review*, Vol 14, No. 3 (1980), pp. 55-69.

49. Swinehart, D., McDaniel, G. and Boggs, D.R., "WFS: A Simple Shared File System for a Distributed Environment." *ACM Operating Systems Review*, Vol 13, No. 4 (1979), pp. 9-17.

50. Parnas, D.L., "On the Criteria To Be Used in Decomposing Systems into Modules." *Communications of the ACM*, Vol. 15, No. 12 (1972), pp. 1053-1058.

51. Dale, P.F. and McLaughlin, J.D., *Land Information Management*. Oxford University Press, New York (1988), 266 pp.

52. Gillespie, S.R., "The Value of GIS to The Federal Government." GIS/LIS '92, San Jose, CA, *Proc.* (1992), Vol. 1, pp. 256-264.

53. Epstein, E. and Duchesneau, T., "The Use and Value of A Geodetic Reference System." Report prepared for the Federal Geodetic Control Committee, Rockville, MD (April 1984).

54. Hutchinson, S., "GIS Pilot Project for Right-of-Way Litigation Support." Geographic Information Systems (GIS) for Transportation Symposium, Orlando, FL, *Proc.* (1991), pp. 201-203.

55. Fletcher, D., Lewis, S. and Petzold, R., "GIS-T: Implementation/ Building The Road Center Line Data Base." Third Annual TRB Workshop on Application of Geographic Information Systems (GIS) to Transportation, Washington, D.C. (1993), 173 pp.

56. Gillespie, S.R., "Measuring The Benefits of GIS Use." ACSM/ASPRS Fall Convention, Atlanta, GA, *Proc.* (1991), p. A84-A94.

57. Dueker, K.J. and Vrana, R., "Systems Integration: A Reason and A Means for Data Sharing." National Center for Geographic Information and Analysis, Initiative 9 (1991), 27 pp.

58. Pennsylvania Department of Transportation, "GIS Strategic Plan Executive Report." Geographic Information Systems (GIS) for Transportation Symposium, Portland, OR, *Proc.* (March 1992), pp. 45-61.

59. Wisconsin Department of Transportation Geographic Information Services Section, "Pavement Management Decision Support Using a Geographic Information System." *FHWA Report No. FHWA-DP-90-085-006* (1990), 76 pp.

60. Joint Nordic Project, *Digital Map Data Bases: Economic and User Experiences in North America*. National Board of Survey, Finland (March 1987), 219 pp.

61. Dickinson, H.J. and Calkins, H.W., "The Economic Evaluation of Implementing a GIS." *International Journal of Geographical Information Systems*, Vol. 2, No. 4 (1988), pp. 307-327.

62. Wilcox, D.L., "Concerning 'The Economic Evaluation of Implementing a GIS'." *International Journal of Geographical Information Systems*, Vol. 4, No. 2 (1990), pp. 203-210.

63. Smith, D.A. and Tomlinson, R.F., "Assessing Costs and Benefits of Geographical Information Systems: Methodological and Implementation Issues." *International Journal of Geographical Information Systems*, Vol. 6, No. 3 (1992), pp. 247-256.

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