NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 359

Adaptation of Geographic Information Systems for Transportation

Transportation Research Board
National Research Council

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Adaptation of Geographic Information Systems for Transportation

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation Research Board

This report is recommended to administrators and managers of transportation agencies as well as other agency personnel having responsibility for gathering, processing, and maintaining the information used by the agency. Geographic Information Systems (GIS) represent a powerful new means to efficiently manage and integrate the myriad types of information necessary for the planning, design, construction, analysis, operation, maintenance, and administration of transportation systems and facilities. This report provides an overview of adaptation of the concept for transportation (GIS-T). GIS systems have proved to be powerful tools for the compilation, management, and display of data associated with geographic space. For example, many state departments of natural resources have applied GIS to define the location of resources and the threats to these resources, to monitor changes over time, and to generate a variety of reports and displays useful to making decisions related to environmental impact. However, application of GIS to transportation has required the extension of basic functionality to include network overlays and the linking of linearly referenced information to the network. This functionality has been developed in various generic forms by firms commercially developing GIS software and hardware platforms. Thus, these GIS-T platforms now represent a highly viable alternative for information processing in transportation agencies.

NCHRP Project 20-27 was initiated in response to the need to define the basic structure of GIS-T based on current and anticipated needs and characteristics of transportation agencies. In 1991, the researchers contacted all State DOTs and a selected group of regional and municipal agencies with transportation responsibilities to assess the implementation status of GIS-T. At that time, most agencies expressed an interest in employing GIS technology (many agencies had pilot projects underway), but only one state agency had a comprehensive, agency-wide application in place. The agency contacts were useful in identifying the types of applications envisioned for GIS as well as the perceived constraints in leadership, knowledge, capital resources, and staffing that were impeding the implementation of GIS-T. *NCHRP Research Results Digest 180*, "Implementation of Geographic Information Systems in Transportation Agencies," published in August 1991, provides a detailed summary of the potentials and problems that were identified in the first phase of this research. Rapid evolution of the technology has led to the implementation of these systems in other agencies and the development of new applications, but transportation agencies have only minimally exploited the capabilities of GIS technology.

The researchers investigated the potentials for GIS-T and concluded that data, technology, and institutions represented the three primary considerations that had to be addressed to promote the implementation of GIS-T. It was found that transportation agencies own numerous datasets. Often, these datasets have diverse origins in individual divisions, lack common location reference schemes, and suffer from poor data definition and lineage tracking making their integration difficult. This study concluded that a geographic referencing scheme was a highly viable means to organize these data, and that full benefits could be realized only if data were viewed as a "corporate" resource. Hence, the uses and costs of GIS should be shared throughout an agency. The study also discovered that concerns over technological obsolescence, the lack of trained staff, high capital costs, and frequent changes to software made agency management reluctant to commit to GIS-T implementation. To address these concerns, the researchers investigated various designs for information systems. A client-server network was shown to offer an effective alternative that would allow incremental implementation, full capitalization of existing equipment, efficient distribution of system functions, and integration of new capabilities or applications over time. The report describes a client-server system and its functionality for GIS-T. Institutional factors are important in the implementation of GIS-T, because GIS-T has the potential for profound changes in the structure and operation of transportation agencies. For example, the sharing of data necessitates greater coordination among divisions within the agency. The integration of data also offers opportunities for an unprecedented number of new forms of analysis resulting in improvements in the decision-making capabilities of the agency.

It was recognized that the findings of this effort need to reach managers of transportation agencies. A separate report was prepared as *NCHRP Research Results Digest 191*, titled "Management Guide for the Implementation of Geographic Information Systems in Transportation." The digest describes the features and applications of GIS-T technology and outlines the complexities associated with its implementation. It also offers guidance for assessing the costs and benefits to an agency resulting from the implementation of GIS-T.

The sponsors of the NCHRP have recognized that this study represents only the beginning of research and development that will be necessary to fully exploit the capabilities of GIS. Consequently, they have authorized a follow-up NCHRP study to 1) develop fundamental models that will represent the basis for understanding the processing of transportation information by GIS systems, 2) define the role of GIS in integrating the management systems mandated under the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), and 3) develop innovative applications for transportation planning, design, construction, operation, maintenance, and administration of transportation systems and facilities. This study is expected to begin in late 1993 and be completed in 18 months. Readers may contact the NCHRP for additional information.

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The research reported herein was performed under NCHRP Project 20-27 by the Department of Civil and Environmental Engineering and the Department of Computer Sciences at the University of Wisconsin-Madison. Alan Vonderohe, Professor of Civil and Environmental Engineering, was the principal investigator. The other members of the research team were Larry Travis, Professor of Computer Sciences; Robert Smith, Professor of Civil and Environmental Engineering; Myron (Mike) Bacon, Wisconsin Department of Transportation (retired); Raad Saleh and Victor Tsai, Research Assistants in Civil and Environmental Engineering; and William Berg, Professor of Civil and Environmental Engineering.

The research team consulted with a panel of experts chosen for their relevant knowledge and experience: Ralph Basile, Pennsylvania Department of Transportation; Joe Ferreira, Massachusetts Institute of Technology; Dan Gayk, Virginia Department of Transportation; Charles Groves, Ohio Department of Transportation (retired); Scott Hutchinson, Arizona Department of Transportation; Simon Lewis, GIS/Trans, Ltd.; David Loukes, GeoPlan, Inc.; and Bruce Spear, Transportation Systems Center.

ADAPTATION OF GEOGRAPHIC INFORMATION SYSTEMS FOR TRANSPORTATION

SUMMARY

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. Further, 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 management often manifest themselves as Federal mandates such as those arising from the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. The ISTEA requires traffic monitoring systems and management systems for pavement, bridge, safety, congestion, public transportation facilities and equipment, and intermodal facilities and equipment, and it includes consideration for the ability of these 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. The recent Clean Air Act will bring about not only the integration of diverse information on transportation, population, and land use, but also the integration of independently developed and managed forecasting systems such as urban planning models and air quality models. And intelligent vehicle highway systems (IVHSs) will impose new demands for large amounts of real-time data that are not currently collected.

All of the data required by these mandated systems and by IVHS and, in fact, nearly all of the data managed by transportation agencies in general, are or can be geographically referenced. Geographic information systems (GISs), which have been successfully applied in many fields outside of the transportation industry, offer the potential to assemble and process these data from a diversity of sources and to display them in a perspicuous, map-based graphical format.

GIS software is designed to store, retrieve, and analyze data that are referenced to geographic location. The technology was first applied to resource management problems that require data distributed over geographic areas. More recently, software vendors have extended the functionality of their products to include the management and analysis of the networks and linearly referenced data of the transportation industry.

The application of GIS to transportation problems is relatively new. Very few large-scale implementation efforts have been undertaken. However, a number of successful pilot projects and a few broadly introduced applications have effectively

demonstrated many potential benefits of GIS for transportation (GIS-T). Main inhibitors of large-scale implementation include a lack of awareness of the revolutionary nature of this technology, institutional barriers, and the significant costs of implementation.

GIS is much more than a tool to be applied case by case to a narrow set of specialized problems. Because of the inherent geographic nature of almost all transportation data, GIS concepts can and should serve as bases for the coherent organization of information structures and systems across the entire range of transportation applications. GIS provides a framework for moving from stand-alone, isolated databases and applications to truly integrated information systems. The capabilities of GIS in the transportation field will permit the assimilation, integration, and coherent display of data collected and stored by the separate divisions within a highway agency. There is potential for GIS technology to become as ubiquitous and useful throughout DOTs as word processors and spreadsheets have become.

An effective design and implementation plan for GIS-T must have both a technological and an institutional context. Information technology in general is changing rapidly and will continue to do so. GIS is one of a number of information technologies (e.g., the technologies of networking, of powerful workstations not only for engineers but for professionals of all kinds, and of computer-aided design) that must be planned for in concert. Principal aspects of the institutional context include determining the most critical initial applications, sharing costs of developing and maintaining the required spatial databases across applications, gaining and retaining support of high-level management, coordinating with external organizations, and utilizing standards developments.

DOTs should institute (or revitalize from the GIS-T perspective) a strategic planning process for information systems that is *needs driven* rather than *technology driven*. This process should provide both *short-term* and *long-term* plans that address GIS-T in conjunction with the complementary technologies mentioned above and others such as distributed and cooperative computing, client-server architectures, computer-based graphics, and new database system capabilities.

The plans should address a range of application scales from the individual project level to statewide planning. Methods should be developed for spreading the cost of geographic database development and maintenance across all applications. Initial applications should be prioritized. The researchers recommend a *top-down* approach to system design, then a *bottom-up* approach to application development. Successful implementation plans must also address staffing and training issues.

It is also recommended that DOTs begin moving toward the adoption of a server-net architecture for GIS-T. This is the inevitable direction of technology. GIS functionality is quite amenable to the partitioning of computational and database management labor inherent in server nets. However, the technology (e.g., cooperative computing, networking, efficient server coupling, and GIS software modularization) and the necessary standards for full-scale implementation of a GIS-T server net are not yet mature.

Therefore, long-term plans should put a *conceptual* server-net architecture in place even before physical realization is feasible. This approach will facilitate incremental physical implementation as the requisite standards, networking technology, and hardware and software products become available. Similarly, it is recommended that the GIS-enabled and managed concept of *location* be used as *conceptual* data schema integrator before the GIS-enabled and managed spatial databases required for actual integration are fully available and as they are being incrementally constructed. An immediate operational impact of this approach will be on how transportation databases, in general and of all kinds, are henceforward schematized.

An essential component of the recommended strategy is the adoption by DOTs of the view of data as a corporate resource, rather than as something that is "owned" by a particular division or application area. Such a view is especially important for GIS spatial databases, but by no means should it be limited to databases of this particular kind.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

1.1 THE NEED FOR GEOGRAPHIC INFORMATION SYSTEMS IN TRANSPORTATION

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 management 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, bridge, safety, congestion, public transportation facilities and equipment, and intermodal facilities and equipment.

Moreover, 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. The recent 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.

In the past, information systems and database development within most transportation agencies, and most other government agencies, has often been application-specific or even project-specific. This causes problems with integration at the functional-area level, let alone the agency level or interagency level. The need for more integrated systems was recognized before they became required. In 1987, the National Cooperative Highway Research Program (NCHRP) reported on the need for integrated highway information systems and on obstacles to their development (*1*). Because the ability to share data and logically integrate systems has become seriously constrained, current NCHRP research [Project 20-24 (6)B] is developing a business systems plan for highway engineering information using a top-down approach to account for the broad needs of highway engineering as a whole. Also, the American Association of State Highway and Transportation Officials (AASHTO) is currently sponsoring research on a comprehensive transportation information planning system that uses a high-level view of agency-wide information and activities.

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*). Geographic Information Systems (GISs) now provide the means.

Integrating data by location has been inhibited by the wide variety of location-referencing methods. During 1984, 38 different location-referencing systems were being used by the Michigan DOT (*2*). The very nature of GIS is to manage location-referenced data. A well-designed GIS can serve as a translator among referencing systems and thereby bring about integration without forcing complete reorganization of data collection and referencing methods.

At the same time that new demands for integrated information systems are being made, new technologies are being introduced that greatly impact the collection and management of data. In addition to GIS, these include satellite positioning and imaging systems, electronic data collectors and notebooks, advanced photogrammetric systems, data sensing and telemetry systems, communication networks, low-cost computing engines, distributed and cooperative computing, client-server network architectures, and others. To take the greatest advantage of these technologies, they must be viewed as part of a larger whole. Strategies must be developed for orchestrating comprehensive integrated systems design. Not until then will the full potential of technology be brought to bear against the very complex and difficult problems of today.

1.2 RESEARCH OBJECTIVE

GIS has been successfully applied in many fields outside of the transportation industry. However, the full capabilities of GIS for transportation (GIS-T) have yet to be realized. To move forward, there is a need to identify current applications of GIS concepts and technologies in the transportation field, to identify transportation problems that cannot be addressed by current GIS concepts and technologies, to design a GIS-T that will provide comprehensive and timely information for management decision support, and to assess the impacts of implementing a GIS-T on transportation agencies.

The primary objective of this research has been 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. In fulfilling the primary objective, the additional needs identified above, and those deriving from new demands, mandates, and opportunities, have been addressed. Research tasks included survey and data collection; development of an idealized GIS-T framework, forecasts of potential GIS-T applications, and development of a final top-level design and implementation plan.

1.3 SCOPE OF THE STUDY

A primary product of this research is a top-level, or conceptual, system design and implementation plan for GIS-T. Although detail on the functionality and interrelationships of the recommended system components and on the recommended approach to GIS-T implementation planning are provided, the results are general in nature and should be considered as guidelines rather than as specifications. There has been neither opportunity nor intention to undertake a complete systems analysis of any particular organization.

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:

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

1.4 RESEARCH APPROACH

The survey and data-collection research task was undertaken to provide an information base for development of the top-level GIS-T design and implementation plan. The data-collection task continued throughout the project, toward an understanding of current status and future plans for GIS-T. The task included identifying and understanding the following:

1. Technical and institutional problems and methods of addressing them,
2. Successful and unsuccessful applications and implementation strategies,
3. Additional design and implementation constraints (both internal and external),
4. Agency needs and priorities for applications,
5. The perceived role and organizational fit of GIS-T,
6. Limitations of currently available GIS-T technology,
7. GIS-T computing and data environments, and
8. The relationships among GIS-T and other emerging technologies.

The survey and data-collection task consisted of 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).

1.4.1 State DOT Interviews

During the first half of 1990, the American Association of State Highway and Transportation Officials (AASHTO) conducted a survey of the status of GIS-T at the state or provincial level in the United States and Canada. The questionnaire used for the survey addressed system status, goals, hardware, software, data, interagency and intraagency coordination, projects, application priorities, standards, technology transfer, research, and impediments. Copies of the raw responses were available. AASHTO also requested that each state designate a contact person for GIS-T. The resulting list was available (*3*).

During 1989, the Nebraska and Virginia DOTs conducted their own surveys concerning state-level GIS-T within the United States. In addition, the Virginia DOT did an internal survey to compile an inventory of geographic data throughout the Department. Copies of all responses were available.

The existing surveys provided considerable, but general, background information that was used as the basis for obtaining more detailed, individualized information from each state DOT. The list of AASHTO contact persons provided starting contact points for most of the DOTs.

To collect in-depth information from the 50 states, tailored questionnaires were prepared for each state based on responses to the AASHTO survey. This permitted a detailed follow-up to the AASHTO responses and a probing of new areas not addressed in the AASHTO survey. A reduced form was used for states that had not yet acquired any GIS-T hardware and software.

The questionnaires covered nine topic areas deemed critical for GIS-T design and implementation planning:

1. Activities, objectives, and status (brief history, management involvement, GIS-T strategic planning);
2. Applications (past, current, and planned; methods for setting priorities; system characteristics required for application development);
3. State government computing environment (administration, procurement approvals, trends);
4. Departmental general computing environment [administration, hardware and data management software, networking, degree of computer usage throughout department, strategic planning (fit of GIS-T)];
5. Departmental GIS-T computing environment (administration, present and planned hardware and software, expectations for diffusion throughout department);
6. Data environment and issues [spatial database scale and content, spatial database acquisition and quality control, linkage procedures, methods for updating, anticipated database redesign, location referencing methods, horizontal datum, planned modifications to data collection, role of Global Positioning System (GPS)];
7. GIS in other agencies and interagency data sharing (administration, other agencies and their activities, cooperative projects, data-exchange standards);
8. Management issues (top-level involvement, training, staffing, organizational structure, costs and benefits, data responsibility, standards and definitions); and
9. Advances in technology (data models, analytical capability, multimedia, networking, intersystem linkages, very large databases, real-time data acquisition, others).

The resulting questionnaire was 18 pages long (see Appendix A). The response rate to such a long mail-back questionnaire would have been low without extensive follow-up. Also, considerable state DOT staff time would have been required to prepare answers. Consequently, it was decided to conduct the survey as a telephone interview with a copy of the questionnaire sent to the AASHTO GIS-T contact person in each state prior to the interview.

AASHTO responses were not available for Alabama, Hawaii, Massachusetts, Mississippi, Nebraska, Nevada, New Jersey, Tennessee, and Utah. In these cases, more general questions in each subject area were asked. These questions were tailored according to responses to the Nebraska and Virginia GIS-T surveys, when available. In only the two cases of Hawaii and New Jersey was no prior information available.

1.4.2 State DOT Site Visits

The first use of information obtained from the interviews was selection of state DOTs for site visits. The purpose of the site visits was to pursue more fully issues raised during the interviews by discussing them at length with key personnel, and to observe firsthand operational GIS-T applications as well as ones under development. Criteria for site visit selection included experience with GIS-T application development and use, diversity in implementation strategies among the candidates, breadth in the functional areas being addressed, and representation of each of the major GIS-T software vendors with installations in state DOTs.

1.4.3 Expert Panel

Upon completion of state DOT telephone interviews and site visits, a panel of experts was convened for 2 days of discussion with the research team. The experts were asked to help by evaluating the initial stages of the research, by suggesting possible interpretations of the data obtained, and by providing early criticism of the idealized framework for GIS-T system design and implementation being worked out by the research team.

1.4.4 Metropolitan Planning Organization Interviews

A number of MPOs in both large and small urban areas were contacted to determine the extent of MPO use of GIS technology as well as to determine the degree to which GIS use is integrated into and extends throughout MPO transportation activities. In general, contact with MPOs was made on the basis of a staff member's being a member of the Urban and Regional Information Systems Association (URISA). Membership in URISA is a good indicator of interest and activity in GIS.

1.4.5 Software Vendor Survey

A number of GIS software vendors were surveyed to determine trends and plans, and to determine adequacy of commercially available products for use of GIS technology by DOTs in the ways recommended. The questionnaire used for the survey (Appendix B) was sent to the 127 vendors identified as providers of GIS software in the *1990–91 GIS Sourcebook* (published by *GIS World*). The questionnaire addressed the following issues:

1. Vendor definitions of GIS,
2. Form and availability of source code,
3. Software functionality (with specifics concerning transportation),
4. Operating system and hardware platform environments,
5. GIS sales levels,
6. Modularization of GIS products,
7. History of involvement with GIS,
8. Open systems plans,
9. Plans for client-server networks,
10. Focus on transportation,
11. System extendability and customizability,
12. Linkages with external databases,
13. Use of object-oriented structuring,
14. Coupling with external programs, and
15. Overcoming GIS product deficiencies (in particular, those that have to do with using the GIS representation of location as a basis for integrating data across different applications).

1.5 ORGANIZATION OF REPORT

Research findings are contained in Chapter 2, and Chapter 3 addresses the development and implementation of an integrated information strategy. The conclusions and suggestions for further research are presented in Chapter 4. Details of the research effort are found in the report appendixes (Appendixes C.3, F, and G are published herein; A, B, C.1, C.2, D, and E are available for loan).

CHAPTER 2

FINDINGS

2.1 SUMMARY OF STATE OF THE ART

The survey and data-collection effort revealed uniformity in some areas and diversity in others (*3*). Support and involvement of top-level management are universally viewed as critical for the long-term viability of GIS-T. Also, nearly all state DOTs with enough experience have confronted the problem of linking GIS-T to large corporate databases. Fundamental differences arise in the comprehension of what constitutes GIS-T and in the perception of the role of GIS-T within the organization.

Based on the results of the survey and data-collection effort, the technology and institutional contexts for GIS planning and implementation by DOTs were characterized. Principal aspects of the *technology context* are

- *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.
- *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 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.
- *The data integration problem.* Data integration across different application areas is an urgent, longstanding need of DOTs. GIS technology plays a dual role with respect to this problem: it both exacerbates the problem and offers a solution. 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 of other kinds.

Principal aspects of the *institutional context* for GIS adoption and application by DOTs include issues of (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, and (6) integrating GIS introduction and development into an information systems plan that covers all aspects of information technology for the entire organization.

2.1.1 State DOTs

A detailed narrative [much of which has been published in (*3*)] covering the results of the telephone interviews and site visits appears in Appendix C.1 (not published herein). This section, however, presents a brief summary of the nine topic areas addressed by the interview questionnaire:

1. Activities, Objectives, Status. Nearly all DOTs have some GIS activity. Some are just starting, some are evaluating systems, some are doing pilots, 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.

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 upon 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, while the technological trends are such that they no longer provide much of the justification for such centralization that used to exist. It is just the opposite. 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 (whose 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 2.4.2.4.) 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 (*4*). As mentioned previously, many states have found that the structures of their attribute databases are incompatible with GIS-T. They are also finding that there is inconsistency in the location-referencing methods used throughout the departments and 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 (*5*). 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, successful GIS-T staffing 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.

2.1.2 Metropolitan Planning Organizations

Eleven Metropolitan Planning Organizations (MPOs) were interviewed by telephone. A narrative summary [much of which has also been published in (*1*)] of the results appears in Appendix C.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.

2.1.3 Expert Panel

The expert panel that met for two days with the research team consisted of a group of eight professionals selected for their breadth and depth of GIS-T experience and knowledge. Thirty major points raised during the meeting are summarized in Appendix D [much of which has also been published in (*3*)].

The major points can be grouped into seven topic areas that parallel those addressed during the state DOT and MPO interviews: (1) definition and role of GIS-T, (2) data collection and presentation, (3) data environment, (4) implementation, (5) institutional and management issues, (6) interagency role, and (7) the appropriate context for the research at hand. These major points then provided input to the preliminary framework for system design and implementation planning.

2.1.4 Software Products

Although we are confident that we have correctly characterized technology trends in general and GIS technology potential in particular, there remains the question of whether GIS product trends are such as to support relatively near-term realization of this potential. Many of the companies surveyed are in agreement with our emphasis on the growing importance of client-server networks and of open systems. Far fewer understand the integrative potential of GIS. Appendix C.3 provides a discussion of the responses question by question and in some detail. The following are the 10 highlights of the responses.

Because of the requirement that this report remain vendor-neutral, the material received from vendors in response to the questions asked (see Appendix C.3) is presented even in the appendix in summary form (albeit in more detail), with none of the particular vendors identified by name. Readers interested in determining the capabilities and limitations of particular products should contact vendors directly. Representatives through whom they can be contacted are presented in the *GIS Sourcebook*, a GIS products and services compendium published annually by *GIS World*. The compendium contains not only addresses of the representatives, but also very useful product descriptions.

1. Question 3 and Question 10 attempted to discover the range of GIS functions offered, in particular, functions known to be required for transportation applications. Different GIS systems vary widely with respect to the functions of which they are capable. There is a common core, but it is surprisingly small. Many of the systems, including all the better known ones, include a relatively full suite of functions, but many others contain only a small part of that full suite.

Only a few vendors offer as part of their GIS any significant number of transportation analysis and modeling capabilities. Several more claim that they will be including more such capabilities in future releases.

There is a comparably wide variation in what vendors mean when they say that their products contain certain functions. This variation is especially noteworthy with respect to *linear referencing* and *dynamic segmentation*.

It is important to note that use of GIS technology for transportation applications has developed later than its use for other applications, and as a result some of the early GISs lacked features specially needed for transportation. However, at least for the vendors that attempt to include within their products a full suite of GIS functions, this deficiency has now been remedied with the additions to the systems of network representations that correctly symbolize transportation networks (for example, as graphs they have to be nonplanar), efficient route representations and computations, dynamic segmentation, and other capabilities useful for transportation applications.

One vendor designed its GIS system from the ground up to have spatial data structuring and other resources especially optimized for efficient support of transportation modeling. That vendor's GIS should indeed be included in the mix of GISs considered for acquisition by any transportation agency, but its development history no longer suffices as a reason for making it the only GIS to be so considered, given the capabilities that have now been added or that will likely soon be added to several other systems with different development histories.

2. Question 4 inquired about the operating system environment required for a vendor's product. Far and away the most popular operating system environment is Unix, which bodes well for open system planning, although it should be noted that there were many different varieties of Unix reported.

The second most popular operating system is MS-DOS, with several vendors having already modified or promising soon to modify their DOS implementations so that they run under Windows 3.x. Several of the vendors of DOS-based products claim that they will have Unix-based implementations available in the near future.

3. Question 6 attempted to discern whether there is any noticeable trend toward the prospect—once GISs are implemented in server-net environments—of being able to place on different specialized servers modules from different vendors (e.g., servers that divide up labor such that one supports overlay, another supports analytical modeling, and another suports cartographic publishing).

Although several of the vendors offer systems that are indeed sufficiently modular that a tailored subsystem containing only specifically required functions can be configured for particular customers, there is clearly no movement whatsoever toward the standardization that would enable a customer easily to use in combination different modules from different vendors.

The primary source of the lack of standardization is the use of incompatible spatial data structures by the different vendors. There do exist in many cases conversion routines for converting from the spatial data structures of one vendor to those of another, but needing to attach such routines to the links among servers in a server net would be clumsy and inefficient.

4. Question 7 asked for the history of a company's involvement with GIS products. One important fact that emerged from the responses was that the vendors that showed the most awareness of the potential of GISs for integrating data—across an entire organization and across applications not directly geographical—were those vendors with company experience in system integration.

5. Question 8 asked about open system plans. The widespread use by GIS vendors of Unix workstations as their primary hardware platform has already been noted. There was almost universal use of X-windows as the graphic user interface (GUI) base, and frequent reports either of an implementation's already using the GUI Motif (the Open Systems Foundation standard) or of plans for it to do so in the near future. The GUI Open Look is used apparently only for implementations that use Sun hardware platforms.

With respect to database standards, all vendors can now link to attribute databases by programs developed in structured query language (SQL). However, there was surprising lack of awareness of the deficiencies of SQL for GIS database purposes, in particular, of the need to extend it significantly if it is to be used for efficient spatial data structuring and querying. Only one vendor reported active participation in the standards working group investigating spatial extensions of SQL.

Conformance with open system standards for networks appears even further along, with all vendors making use of Systems Network Architecture (SNA) or DecNet protocols saying that they can also handle Transmission Control Protocol/Internet Protocol (TCP/IP) protocols and that they have plans for moving to full International Standards Organization (ISO) networking standards as those standards become more fully developed.

With respect to data transfer, several vendors reported interest or participation in the United States Geological Survey (USGS) guided development of a standard for spatial data transfer, but the current state of the art is largely one of including in GIS products data translators for converting among formats. One vendor claims the inclusion in its product of 22 such translators!

6. Question 9 asked about plans for client-server networks. In general, there was manifested in the vendor responses appreciation of the general trend in computing away from mainframe-dominated, star networks to networks consisting of many different kinds of specialized nodes each performing both as a client of other specialized nodes on the net and as a server of yet others.

However, the bad news is that with only two exceptions the vendors look on GIS processing, including management of the spatial databases, as one undifferentiated "specialty" to be allocated to the "GIS server." What they propose to allocate to other servers is only such functions as management of attribute databases and hardcopy output (plotting and printing). This is indeed a client-server division of labor but at very low resolution.

Usually the server node on which the vendors see the GIS processing being done is a Unix workstation or a relatively powerful DOS PC, which is at the same time serving as a user display station. A few of the vendors at least see the point of putting users in front of display stations specialized for display (both X-Windows terminals and MacIntoshes were mentioned for this purpose) and letting these be separate from the GIS server whereon the GIS processing per se is done. At least one vendor has developed browse-and-query software that is independent of its analytical GIS product and can be used to interrogate spatial and attribute databases.

7. Question 12 asked about linking to external databases. This question turned out to be relatively useless as a discriminator. The problem that it was getting at, namely that GIS applications should be able to use data from external databases originally populated for other reasons and not a subordinate part of the GIS, is a problem that has been almost universally recognized by the vendors. In response, again almost universally, they have provided their systems with the capability to generate embedded (i.e., non-interactive) SQL retrieval expressions, execute them against external relational databases, and correctly interpret the answers that are returned.

For the DOS-based systems, rather than accessing SQL databases, access of several different kinds of PC databases is possible. Almost all such systems can access DBase III databases, and some can access FoxBase, Paradox, and DBase IV databases as well.

It should be noted that, although GISs can now in general access attribute data stored in external, relationally structured databases, no mention was made by any vendor of a GIS ability to access databases with other kinds of structure (e.g., hierarachical or network), nor was any mention made of plans to provide a GIS with such an ability, although these older forms of database structure are still in wide use by many organizations, including many DOTs.

8. Question 13 asked about the use of object-oriented structuring. Given the variability and the complexity of the objects dealt with in geographic reasoning and computing, object-oriented databases would appear to be well suited for GISs and GIS applications. This is especially so because few if any developers have figured out how to use relationally structured databases for the efficient storage and retrieval of spatially described objects, the very essence of GISs. However, the general response by the vendors was that they are waiting and watching. There appears to be a general awareness that no vendor has yet been successful in using an object-oriented database for storing and retrieving spatial data, although several have tried.

Object-oriented programming is another matter. Several of the vendors are using it for their product development; several have used its principles as a basis for their software engineering practices—even though they did not use an object-oriented language for their development programming; and some support object-oriented approaches for user GIS extension and application development. However, there is a long way to go before object-oriented programming becomes the primary vehicle used and made available by GIS vendors for these purposes.

9. Question 15 asked, among other things, about the prospects of including within GISs capabilities for rapid prototyping of application programs. The answers received manifest surprising ignorance on the part of vendors concerning just how hard it is with their current products to generate an exploratory application program for purposes of trying out ideas—before a commitment is made to a particular way of building a production-strength version of the program.

It would appear that GIS product designers and vendors need to have their imaginations stretched by getting some firsthand experience with how programming productivity is increased in other areas (e.g., artificial intelligence research) with fast interface mock-up techniques, techniques for simulating behavior of subroutines without actually having to write them, and other techniques aimed at getting a good idea of how a program will look and feel before actually programming it.

10. Question 15 also asked about prospects of effecting better coupling between GISs and CASE systems, in order to improve the efficiency with which the concept of location can be used as an integrating concept in the database schemas specified with CASE systems. Only two vendors clearly indicated in their responses that they see the potential of using the concept of location as a basis for integrating databases across all applications of an "enterprise," e.g., a DOT. The others didn't understand the point of this question.

It should be noted that the problem raised can be considered a problem for CASE technology just as much as a problem for GIS technology. What is needed is an accommodation of each to the other, and this accommodation must incorporate an efficient way of storing locational, geometric, and connectivity information in the same kinds of databases used for storing attribute data. The two vendors who understood the question claimed progress in this direction.

2.2 DEFINITION AND ROLE OF GIS AND GIS-T

There is considerable variation across different contexts and across 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 (*6*, pp. 6–7). 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 for our research, the premise that the technology of GIS cannot usefully be evaluated, projected, and planned for in isolation from institutional setting, management framework, and staffing resources upon 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.

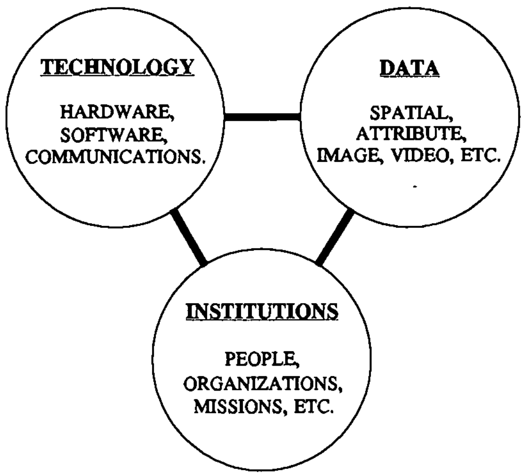


Figure 1. The domain of GIS.

There has been yet another significant usage underlying our research. In this usage, "GIS" refers to 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 existing information systems and the development of new ones. The concept of location becomes the basis for effecting the long-sought goals of data and systems integration (*1*, *7*, 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 the 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 all or nearly all of the linearly referenced highway data collected and maintained by transportation agencies.

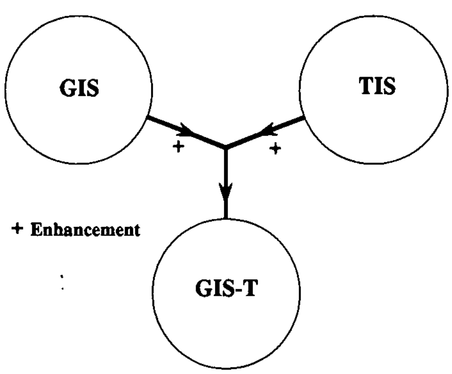


Figure 2. GIS-T as the merger of an enhanced GIS and an enhanced transportation information system (TIS).

What it *does imply* is that the attribute databases use a database schema for the concept of location translatable into the location schemas 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 latter, so that queries can span both kinds of databases, and so that separate attribute databases can be integrated through their use of location schemas translatable into the ones used by the GIS software.

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.

2.3 FUNCTIONAL FRAMEWORK FOR 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 References *8*, pp. 7–10; *9*, pp. 29–38; *10*, pp. 42–43; *11*, pp. J.1.3–J.1.6; *12*, pp. 11–25; *13*, pp. 165–179; *14*, pp. 319–335; and *15*, insert). However, no single software product contains all possible GIS functionality. Each product has its relative strengths and weaknesses. Many products have historical roots that underly current strengths (e.g., image processing or polygon processing). Based approximately on the classification scheme provided in (*15*), Sections 2.3.1–2.3.10 describe a functional framework for GIS.

2.3.1 Supported Spatial Data Models

A GIS spatial database is a structured collection of digital graphic and nongraphic data that describes the locations and spatial relationships of geographic features. 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*. A raster data model consists of a matrix of homogeneous grid cells (usually square in shape), referenced by numbers of row and column. The area within a grid cell defines the spatial resolution of the raster. Each grid cell stores an associated number or identifier for the type, value, or index to the attribute being mapped within its area. Individual grid cells in raster images are referred to as "picture elements" or "pixels."

2. *Topological vector*. A topological vector data model encodes the location and extent of spatial features as well as the relationships of incidence and connectivity among the features. A topological vector data model is well suited for connectivity analysis and spatial adjacency analysis. Transportation networks are usually represented with topological vector models.

3. *Surfaces*. Data in the third dimension (elevations) are necessary for the description of surface characteristics (i.e., relief). GIS surface data models generally take one of two forms: a) *Digital elevation models (DEMs)*. A DEM is a raster

in which the stored values are elevations. b) *Triangulated irregular networks (TINs)*. A TIN is a topological vector data model that partitions a plane into a continuous network of non-overlapping triangular facets from a set of randomly spaced points. Data points at triangle vertices have known elevations. Both DEMs and TINs can be used to represent any variable across two-dimensional space. In addition to elevation, examples of such variables are rainfall, temperature, and population density. Because DEMs and TINs model surfaces and not solids, they are sometimes referred to as being "2.5-dimensional."

4. *Three and four dimensions*. Some of the theoretical foundation for three-dimensional GIS has been established, and attention is just now beginning to focus on a range of geoscientific applications (*14*, p. 299). GIS software that supports three-dimensional applications is in its infancy. Moreover, theoretical work is just beginning and much lies ahead for development of a data model that incorporates time as a metric at the same time level as x, y, and z (*16*). Since transportation facilities and phenomena exist in three and four dimensions, the restriction of current data models to two-dimensional and 2.5-dimensional space limits the ability of GIS to effectively model the real world.

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, in order to overlay them with a transportation network model.

2.3.2 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, the following data entry systems can be supported in a GIS:

1. *Manual digitizing* is a widely used method for entering locational data from hardcopy maps. Typically, the map is fixed to a table digitizer and a pointing device, or cursor, is used to trace features.

2. *Scanning* provides a more automated method for entering map data. Hardcopy maps are scanned into digital raster images after which additional computer processing might be done to improve the quality of the image. After a *raster-to-vector conversion* is performed, the resulting vector lines are usually edited and checked by an operator with computer assistance. In lieu of running a raster-to-vector conversion program, images of scanned maps can be vector digitized from a computer display by an operator using a mouse. Scanning can also be used to capture images of design drawings, sketches, text, photographs, and other documents that might be managed in a GIS.

3. *Photogrammetric stations* are used to extract three-dimensional information on a terrain surface directly from stereo pairs of airphotos. A photogrammatic station might be an *analytical stereoplotter* or an *optical-mechanical stereoplotter* fitted with three-dimensional digital encoders. Alternatively, a photogrammetric station might be an engineering workstation, or even a personal computer, fitted with appropriate optical equipment and software to support *softcopy* photogrammetry.

4. *Coordinate geometry (COGO)* is a procedure for creating vector linework and related cartographic entities directly from field survey measurements.

5. *Global Positioning System (GPS) receivers* and other electronic data collectors provide spatial information directly in electronic format.

6. *Digital cameras, satellite sensors, radar sensors, and thermal infrared imaging devices* capture digital images directly in raster form.

2.3.3 Spatial Data Exchange Formats

Spatial data exchange is important in GIS for the integration of disparate data sets from dissimilar computer systems. There are two basic methods for data exchange between different GISs: 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). Of course, all three data models (sender, receiver, and neutral) must be compatible at the level of the data to be exchanged in order to prevent the loss of information, the introduction of spurious information, or the need for processing and editing of the data after it is exchanged. The following are some of the most widely used neutral exchange formats developed by either major data producers or national standards institutions:

- *GBF/DIME*. The Census Bureau's name for the geographic base files (GBFs) it created for the 1970 and 1980 censuses, using the dual independent map encoding (DIME) technique was GBF/DIME (*17*). Each GBF/DIME file contains information describing street networks and other map features in records representing segments of features.
- *TIGER*. The Topologically Integrated Geographic Encoding and Referencing (TIGER) system was developed by the Census Bureau to support data collection and data tabulation for the 1990 decennial census (*17*). The TIGER database is an integrated collection of files, including county partitions, geographic catalogs (GEO-CAT) of political and statistical areas, national partitions, and temporary work files. The design and implementation of the TIGER database strongly reflects the Census Bureau's needs for automated mapping and geo-coding addresses.
- *DLG*. Digital Line Graph (DLG) is a standard file structure for digital cartographic data in vector form established by the United States Geological Survey (USGS) (*18*, *19*, *20*). DLG files include information on planimetric base categories,

such as transportation, boundaries, hydrography, hypsography, Public Land Survey System (PLSS), and other significant culture features.

• *IGES*. Initial Graphics Exchange Specification (IGES) is a data exchange format for typical geometric, graphical, and annotation entities in computer-aided design (CAD) and computer-aided manufacturing (CAM) systems. IGES was first published in 1981 and was then extended and released as the American National Standards Institute (ANSI) standard Y14.26M on Computer-Aided Preparation of Product Definition Data (*21*).

• *SDTS*. Spatial Data Transfer Standard (SDTS) is a national spatial data transfer mechanism approved in July, 1992, by the National Institute of Standards and Technology (NIST) as Federal Information Processing Standard (FIPS) 173 (*22*, *23*). SDTS provides specifications for organizing and structuring the transfer of digital spatial data, defining spatial features and attributes, and encoding data transfer between dissimilar computer systems.

2.3.4 Spatial and 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) for 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 databases. 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 including statistical summaries; status and lineage tracking; system security measures; and computer network operations.

2.3.5 User Interfaces

GIS software usually provides one or more interactive user interfaces so that users can initiate a system operations:

1. *Command languages*. Command languages employ structured text dialogues that allow users to communicate with a system by interactive keyboard entry. Basically, a command language interpreter (CLI) translates typed commands into instructions according to a set of rules for grammar and syntax.
2. *Menus*. The menu-driven approach provides an easy way for users to issue commands. A menu is a list of possible commands or operations on an area of a screen or digitizing tablet. By entering a number or letter corresponding to the desired action, or by using various pointing mechanisms to place a cursor on menu items, the user selects and initiates desired commands and operations.
3. *Windowing environment*. Many current GIS packages run under windowing environments that allow concurrent running of separate tasks and simultaneous multiple views of the database.
4. *Multiuser capacity*. GIS software running under a multiuser operating system allows several users to share software and data resources.
5. *User-generated macros*. A macro program consists of a sequence of commands that, taken together, perform a more complex operation. Macros are typically developed for frequently-used higher level operations in specific applications. Some GIS packages have separate command languages for development of macros.
6. *Additional application development aids*. Source code and object code libraries are sometimes made available for user program development.

2.3.6 Spatial Data Processing and Editing

Typically, a number of tools will be provided for building and maintaining spatial databases:

1. *Editing*. Interactive functions include 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. Interactive editing is often assisted by invoking a "snap tolerance" that brings the user's cursor into coincidence with the nearest object within a specified distance. Spatial objects can often also be inserted or deleted in batch mode from an update file. The system might be able to automatically check for undershoots and overshoots resulting from small digitizing errors. Functions might be available for checking attributes for appropriate ranges or values.
2. *Topology building*. Many vector-based systems will automatically determine topologic relationships. Functions might be present for identifying errors such as misclosed polygons and missing attribute tags.
3. *Edge matching, aggregation, and generalization*. Edge matching is used to create a seamless spatial database from individual, adjacent, digitized map sheets. It includes joining of continuous lines across sheet boundaries and removal of slivers along sheet boundaries. Where digitized sheet boundaries overlap, slivers might be removed by an otherwise-available aggregation function referred to as "dissolve by attribute." This function drops boundaries between adjacent polygons that have the same specified attribute. Line generalization functions that drop certain densely packed vertices might also be available. In transportation, line generalization would be used when a smaller-scale spatial database is updated with new alignment information from a larger-scale design file.

2.3.7 Database Transformation

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

1. *Between data models*. These transformations do raster-to-vector conversion and vector-to-raster conversion. These

automated procedures often lead to interactive editing of the data after transformation.

2. *Between coordinate systems*. Coordinate system transformations take three specific forms:

- *Arbitrary-to-ground*. Newly captured spatial data, from scanners and digitizers, are in the arbitrary coordinate systems of their data-capture devices. These coordinates are transformed by least-squares fits to ground coordinates of known control points (usually on a map projection). Two-dimensional conformal or affine transformations are typically used. Projective and higher-order functions might be available.
- *Between geodetic datums*. Many newly produced maps will be on the North American Datum of 1983 (NAD83). Most existing maps are on the North American Datum of 1927 (NAD27). GIS spatial databases must be on a single geodetic datum.
- *Ground-to-ground*. Supported map projections could include all Universal Transverse Mercator (UTM) zones, all State Plane Coordinate System (SPCS) zones, and user-defined Lambert or Transverse Mercator projections. Transformation between map projections is usually a two-step process (map projection #1-to-geographic (latitude/longitude), followed by geographic-to-map projection #2). For statewide spatial databases, it might be appropriate to design a map projection that minimizes distortion for the state. However, in many cases, use of one of the state's existing UTM zones or SPCS zones for the entire state will cause no significant errors during analysis because of the scale of the database.

NOTE: Dynamic segmentation, described as follows, involves conversion between linear reference systems and two-dimensional coordinate systems. It does not necessarily operate on an entire spatial database. It is unique to networks.

2.3.8 Data Retrieval

Retrieval operations on spatial and nonspatial data involve selective searches of the databases and output of the retrieved data in response to various queries. Spatial and nonspatial data can be retrieved in several ways: a) *By cursor input*. Data can be selected by pointing at individual features, by specifying radii around individual cursor locations, or by constructing rectangular windows with a cursor. These methods are used to interrogate attribute databases about geographic features. For example, a pointing of the cursor can be used to ask the question "What is the name of this street?" b) *By attributes*. Geographic features can be retrieved by their identifiers or by specifying their attributes or Boolean combinations of their attributes. These methods are used to interrogate spatial databases according to their nonspatial characteristics. For example, all segments of Highway 12 that have concrete pavement between 7 and 12 years of age can be colored blue.

2.3.9 Data Manipulation and Spatial Analysis

Analytical spatial analysis functions distinguish GIS from other information systems and from computer-aided mapping systems. Some functions for data manipulation and spatial analysis integrate geo-referenced data, both spatial and attribute, to create new information in response to various queries. Listed below are some commonly stressed functions for data manipulation and spatial analysis. There are six general categories of functions for data manipulation and spatial analysis:

1. *Measurement*. Spatial measurements reveal metric properties of geographic features such as a) straight-line distances between points; b) lengths of lines; and c) perimeters, areas, and centroids of polygons.

2. *Proximity Analysis*. Some proximity analysis functions 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 clustering of features. a) *Buffer generation*. This function generates new polygons, i.e., buffer zones, of a specified size around one or more geographic features. Buffer generation is useful in a number of applications such as corridor analysis, noise propagation modeling, and right-of-way acquisition. b) *Thiessen tessellation*. This function divides a study area into adjacent polygons of influence around each of a set of data points such that polygon boundaries are equidistant from their neighboring points. All locations within a given polygon are nearer to that polygon's interior data point than to any other data point in the set. c) *Adjacency*. These functions retrieve information concerning features that are adjacent to other selected features. For example, an adjacency function could be used to retrieve the names and addresses of all owners of frontage along a strip of right-of-way that is about to be vacated. d) *Spatial clustering*. These functions identify regions containing groups of selected features. For example, spatial clustering can be used to find all segments of a highway, less than 0.2 miles in length, where more than five accidents have occurred in the past year.

3. *Raster Processing*. At least two general categories of functions apply to the processing of raster data: a) *Map algebra*. 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 (*14*, p. 365). b) *Digital image analysis*. Digital imagery, either obtained from satellites or scanned from aerial photographs, is being used increasingly in GIS. These images usually record spectral characteristics of features on the earth's surface. Various techniques can be used to extract information concerning these features:

- *Preprocessing*. Various types of error and distortion can creep into images during their acquisition. Of these, radiometric and geometric error are the most common. Image preprocessing removes some of these errors and produces a radiometrically corrected and geometrically rectified image that is registered to a ground control system.
- *Enhancement*. Image enhancement techniques are used to improve the appearance of an image for visual inter-

pretation or for subsequent machine analysis and information extraction. There are two kinds of operations: 1) point operations, that modify the brightness value of each pixel independently and 2) local operations, that modify the brightness value of each pixel in the context of the brightness values surrounding it. Image reduction and magnification, contrast enhancement, and ratioing involve point operations, while spatial filtering and edge enhancement involve local operations.

- *Extraction of thematic information.* For multispectral images, most information extraction techniques rely on spectral analysis. For example, both supervised and unsupervised classification methods analyze spectral response characteristics of pixels to extract land cover information.

Remotely sensed images can be used to develop land use information for transportation planning and to provide small-scale information on transportation networks over large areas.

4. *Surface model generation and analysis.* Surface model generation functions create TINS from DEMs or randomly spaced points or they create DEMs from TINS or randomly spaced points. Surface analysis functions calculate values, determine characteristics, and identify features on surfaces. They are used extensively in engineering design: a) *Elevation interpolation.* These functions predict elevations at unobserved points using known elevations at neighboring locations. A number of interpolation methods are used including linear functions, polynomial regression, splines, moving averages, and kriging. If the surface model is a TIN, elevation can be computed at any location on each triangular facet. In any case, the quality of interpolation depends upon the number, distribution, and accuracy of the known points as well as the mathematical model that approximates the terrain surface. b) *Contour generation.* Contours are generated by connecting points of equal elevation that have been interpolated along grid cell boundaries in a DEM or along triangle sides in a TIN. Contours can be smoothed before they are displayed using splines or similar functions. c) *Slope/aspect calculation.* Slope and aspect can be computed and stored as attributes of the individual grid cells of a DEM or the individual triangles of a TIN. They can then be retrieved to produce thematic maps or to support further analysis such as stormwater and runoff modeling. d) *Cut/fill/volume calculation.* Usually associated with CAD, these functions might also be available in GIS software. e) *Feature extraction.* Functions might be available for locating pits, peaks, passes, ridges, valleys, drainage networks, and viewshed and watershed boundaries.

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 (*7,24,25,26*):

- *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. An early form of dynamic segmentation, called "address matching," was available in GIS before the need for a broader, more powerful function was identified. Address matching computes coordinates for street addresses by interpolating between coordinates and addresses at block corners.
- *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 (*27*, p. II-74; *28*):

- Shortest path analysis;
- Optimum tour routing;
- Location/allocation; and
- Transportation and Transshipment problems.

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. There are three variations: a) *Polygon-on-polygon.* Boundaries of derived polygons are formed by intersecting the boundaries of the separate input polygons. Derived polygons have the combined attributes of the input polygons. As an example, this function could be used to determine the number and areas of wetlands in alternative corridors. b) *Line-in-polygon.* This function breaks lines into segments according to their intersections with polygon boundaries. It could be used to identify the stretches of Highway 51 that pass through either Rock County or the City of Madison. c) *Point-in-polygon.* This function determines which point features are located within particular polygons. It could be used to determine which private wells are within 1000 ft of a landfill (after 1000-ft buffer polygons had been created around all landfills).

Polygon overlay can include boolean operators (e.g., and, or, exclusive or) that determine the geographic extent of the derived features.

2.3.10 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. A number of functions support final output and presentation.

1. *Vector-on-raster display*. Display of vector data over raster images is useful for interpretive purposes.
2. *Multiple maps/single plot*. Presentation of multiple maps on a single plot can tell a story or facilitate comparison of the effects of various functions on the same data source.
3. *3-D display*. Three-dimensional display can provide perspective or stereo views of digital terrain data. A raster images and vector linework draped over a perspective view of the landscape provide a powerful visual interpretation tool.
4. *Animation*. Animation of geographic phenomena in a series of templates or displays is an effective mechanism for visual simulation of temporal change.
5. *Cartographic production*. Tools for the production of maps, for both screen display and plotting, might assist with creating and positioning neat lines, graticules, scale bars, north arrows, map titles, and legends. Cartographic symbols libraries are often available.
6. *Report generation*. Reporting capabilities will depend upon the DBMS that is used for managing attributes.

2.3.11 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. The following 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 upon 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 upon 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.

2.3.12 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.

Spatial data capture technologies 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 during July 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.

2.4 THE TECHNOLOGY CONTEXT OF GIS-T PLANNING AND IMPLEMENTATION

2.4.1 Current and Projected Technology

We live in an age of major and rapid technological changes, changes that will affect the use, scope, and method of transportation in our 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 1990s. The projections are not wild guesses but generally agreed upon predictions. 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 recently compiled by the science and technology writers of the *New York Times* 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.

The items on the list most relevant for DOT planning during the next decade include:

1. New computer architectures exploiting parallelism.
2. Superconducting materials used for electric power transmission and for computer circuits.
3. Very high-resolution, true-color electronic displays used in TV and in computer display screens (which probably will not continue to be two separate things).
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, thus bringing the cost of such systems down by orders of magnitude.
5. Fiber-optic gigabit networks interconnecting computers and computer databases, both local-area and wide-area networks.
6. Computer-aided software engineering (CASE) that uses low-cost computing power to support software development environments, which 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: a) 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. b) Rapid improvement and lower cost of various geographic measurement and data-collection technologies (for example, GPS and advanced photogrammetric technologies).

2.4.1.1 General Information Technology

Within this context of rapid technological change, the task is to draw the implications for DOT plans and strategies and, in particular, to identify and discuss the implications for DOT exploitation of information technology enhanced with GIS capabilities.

A number of principles underly the approach:

1. DOT strategies for adoption and exploitation of information technology in general, as well as GIS technology specifically, should be *needs driven* rather than *technology driven.* New technology should be adopted and used because it meets specific, well-identified needs, not for its own sake and not because it is likely to serve some good, but ill-defined purpose.

However, needs-driven strategies require good knowledge and intelligent appraisal of technological developments and prospects. Only thus can intelligent decisions be made about timely adoption of new technologies, at the point they have become sufficiently cost-effective and reliable for certain needs; and only thus can prospective technologies be anticipated and prepared for, avoiding dead-end approaches that may meet certain short-term needs but that have to be abandoned when a prospective technology does become sufficiently cost-effective and reliable. Thus, the following sections that focus on technology (and do not address specific needs) should not be interpreted as desertion of the important general principle—that needs indeed should drive technology adoption plans and strategies and that technology for its own sake should be avoided.

2. After observing in some detail the GIS state of the art in all 50 DOTs, GIS technology has reached a state of maturity where it can effectively be exploited by DOTs. DOTs are past the stage where yet another feasibility test serves the purpose for a particular DOT of demonstrating that the technology is useful and can cost-effectively meet needs. If a particular DOT has not yet internally had such a demonstration, it can simply appeal to the experience of others. (There might of course be other reasons for starting with a small-scale, pilot project; e.g., to enable data-processing staff and users to gain familiarity with the technology.)

Having reached this stage in its life cycle carries an important consequence for GIS technology, a consequence often missed. In general, GIS technology should no longer be treated as a special case, to be implemented for isolated applications on isolated equipment not connected into the general DOT data processing environment. This means that the plans for GIS implementation and use should be part of, and subordinate to, a DOT's general information technology plans. This is the context within which the proposed, ideal framework is presented.

As with any component of information technology, there will continue to arise, for GIS, cases where some immediate, urgent problem can perhaps best be handled in the short term by bringing up a special, isolated, dedicated system. Compare, for example, isolated minicomputers and workstations that have been dedicated in many DOTs to support engineering modeling and design, and that have been installed and operated quite separately from the general DOT data-processing environment. However, for reasons that should become abundantly clear, this is not the general approach most suitable for GIS applications.

2.4.1.2 GIS Technology

There are over 70 products being sold as "GIS." They differ widely in function and capability. It is important that references to adoption and application of GIS technology are not interpreted simply as referring to acquisition and use of any such product. And it is important that readers not conclude that the benefits attributed to GIS technology are available from just any product with a "GIS" label (a label often attached only for marketing reasons).

GIS technology must be perceived correctly for just what it is if it is to be inserted correctly into an organization and exploited maximally. There are some useful historical analogies. Despite frequent claims to the contrary by vendors, GIS technology is not a simple "end-user technology," such as word processing or spreadsheet technologies—a technology that can be purchased as a software package, installed on a few workstations or PCs, introduced in a short orientation session, and then left to users to learn and use, at their own pace and in their own way. The reason is because its effective use within an organization requires the construction and maintenance of databases, activities that are time consuming, costly and, in the ideal, organization-wide. The costs of database construction and maintenance should be spread across as many different applications throughout the organization as possible, redundancy and duplication should be avoided, and the investment in data acquisition and maintenance should have benefits over the long term that outlive and extend beyond particular applications, particular hardware platforms, and particular software packages.

Indeed, as some DOTs have now demonstrated, once the appropriate databases are available, their use for particular GIS applications can effectively be left to end-user initiative. Thus, the ideal GIS-T implementation strategy is characterized as first top down, then bottom up. The *top down* part is the part that has to do with designing and implementing the required databases. The *bottom up* part is the part that has to do with end-user use of the databases to realize particular applications.

The best historical analogy is to fourth-generation language (4GL) technology, a technology that makes possible application development by end users because it enables application development in terms of high-level, nonprocedural languages—languages much easier to learn and use than older, procedural languages like Fortran and Cobol and easy enough that end users can use them directly rather than requiring the services of specialist programmers. The end user need only specify graphically what input and output user interfaces (data acquisition screens and reports to be generated) are to be used in an application, and the 4GL system automatically compiles the required procedural code. But note that such application development presupposes the availability of the required databases. The analogy to GIS technology is close.

Some GIS products are now being packaged to include certain widely useful databases (e.g., databases containing Census Bureau TIGER data) and indeed, to the extent that applications need only the data made available in this way, the products can be correctly classified as "end-user products" ready for use by end users simply upon installation. But the applications that need only such generic data are usually small and often trivial. They certainly do not include, for example, DOT applications that depend on complete, accurate, and up-to-date data about a state's highway network.

Contrast the spatial knowledge representation used in GISs with that used in other spatially oriented data processing systems, in particular, computer-aided design (CAD) systems, image-processing systems, robot control systems, and cartographic production systems. The last is worth special note: A cartographic production system should not be confused with a GIS. It contains representations of the *surface* symbols that will be explicitly produced when a map is printed in hard copy or displayed on a screen. (Compare the representations used in a text "pagemaker.") A GIS contains *deep* knowledge, knowledge about spatial entities and relations. A GIS system properly so-called may indeed have a capability to translate from its deep data structures to surface-level map symbols and may indeed have as a component a map production module, but it will have several other modules as well.

Note how CAD systems have been extended to enable their use as GISs, and note the widespread practice in DOTs and elsewhere of using as GIS platforms systems originally designed and acquired for CAD purposes.

A GIS has several functionally separable modules, and a particular application will use some but not necessarily all of the modules. They include the following:

1. Modules for data input and editing.
2. Spatial database managers for databases containing locational, geometric, and topological data about spatial entities—points, lines, and polygons.
3. Database managers for databases containing spatially referenced descriptive information. Examples are spatially referenced attribute data, spatially referenced image data, and spatially referenced abstract objects.
4. Modules that combine data from these diverse databases, in particular, by means of overlay operations.
5. Modules that perform aggregation and generalization operations on geographic data.
6. Modules that perform analytic (e.g., allocation) operations on geographic data.
7. Modules for map generation, i.e., for creating the cartographic symbolic structures needed for map printing and displaying.
8. Modules for map printing.
9. Modules for electronic map display, with user control of zooming, cropping, windowing, suppressing or adding details of different kinds, etc.
10. Query and report generation modules, both map-oriented and non-graphic.
11. Application development utilities, e.g., macro languages.

Many GIS products intertwine these modules in ways that do not allow their easy separation nor their independent use—which is to say that, in such products, they exist only as functional modules, not as actual modules. For our purposes, this modularity is an essential aspect of GISs. Logical separation of the modules constitutes a first step in our ideal framework, and their physical separation and assignment to different servers in a server-net architecture constitutes an eventual desideratum.

Characterizing GIS as we have done so far emphasizes its technical functions. An important development has been the recognition that, from another point of view, introduction of GIS capabilities into a data processing environment is important not only because of the new capabilities made available but also because the fundamental concept of location that underlies GIS spatial databases provides an efficient and practical means of integrating data of many other kinds. Benefits of data integration include data-collection cost reduction, data-maintenance cost reduction, improved data reliability, and—most important—applications not otherwise possible.

The importance of data integration for DOTs has been persuasively presented by Briggs and Chatfield (1987) (*1*):

> The collection of highway-related data involves a wide variety of activities: traffic counting, sign inventories, skid resistance measurements, photologging, accident investigation, recording of construction and maintenance projects and funding, right-of-way surveys, inventories of . . . roadside obstacles, bridge inspection, rail-highway crossing inventories, speed monitoring, pavement condition surveys, geometric design inventories, and other data-collection and maintenance activ-

> ities. In the past, these activities were often uncoordinated within highway organizations and across organizational boundaries. Collected data were typically stored in paper files or in single-purpose computer files accessible only to a few people. Because of the lack of coordination, or of a narrow concept of data use and application, data collected for one purpose were rarely usable for others. If two users needed the same data, or very similar data, the data were often collected twice. . . .
>
> Highway agencies have been a fertile breeding ground for independent data-collection activities and the data files that result from them. It has often been easier for organizational units to independently develop the information systems they need to operate their programs, without coordinating their efforts with data-related activity in other organizational units. In some cases, this has been the most reasonable approach to take—duplication of effort has been more apparent than real. There is no question that coordination requires resources and often involves compromises with respect to data specification, editing, and maintenance. But as systems grow and the cost of data collection rises, independent data-collection and data-storage activities become expensive luxuries. Integrated systems permit broader use of collected data, which increases data value. . . .
>
> Integration generally makes it possible to study many relationships among two or more data elements. As an integrated system grows, the cost of providing the linkage is rapidly offset by the value of the increase in information that the system provides. . . .
>
> In practice, integration of data can be relatively complex. It is not always efficient or convenient, for example, for everyone to use the same location reference system when collecting data. It may be best for a traffic-counting team at an intersection to identify the intersecting highways by name, whereas a survey crew recording sight-distance restrictions might use mileage from the county line. This is not a problem if the systems that are used are compatible with each other or with a third system (underlining added) so that location data can be translated from one system to another.

As a matter of fact, the Briggs and Chatfield 1987 report foresaw the centrality of location as an integrative concept, but at that time GIS technology had not progressed to the point where it was obvious that this technology offers the key to efficient and practical *third systems* for achieving location-based integration.

The criticism might arise: What is being proposed here is the use of a concept (viz., location), not the use of a technology (viz., GIS). Why not merely introduce the concept into the basic schemas used for database definitions? Introducing a new schema definition is hardly introducing a new technology.

The criticism is not valid because it misses an essential aspect of using location as a data integrator. The concept of location is basic and idiosyncratic; at least when used as an integrator it is not just another attribute. Its representation, the algorithms required for its efficient processing, and the facilities needed for location data acquisition constitute the core of a GIS. Thus introduction of the concept requires use of at least some of the essential capabilities of GISs. Once these core capabilities are available, it is natural to think of using some of the additional capabilities as well, when they can be put to good use.

Using GIS technology in this integrative role changes radically the strategy most appropriate for its introduction and use in a DOT. In particular, it becomes something more than just one more thing to do with computers. It becomes a central, indispensable component of the organization's overall information technology strategy.

2.4.1.3 GIS-T Technology

GIS technology originated mainly in the areas of environmental resource use and land record information processing, but among many extensions it has now been extended for use in transportation modeling, planning, reporting, and decision making. Also, most of the major transportation planning and modeling packages have enhanced their network editing and display capabilities, and are adding geographic display capabilities. Indeed, some now appear to have been extended to the point where they are full-fledged GIS packages, well-suited for transportation applications but usable as well for a large number of nontransportation GIS applications.

The following question can usefully be raised when GIS products are evaluated for transportation applications: Is the adaptation and extension of systems originally designed for other purposes—CAD systems on the one hand, and GISs for nontransportation applications, on the other—the optimum way to achieve a good GIS-T? Would not design from the ground up of a transportation-oriented GIS result in more suitable data structures and algorithms, and hence result in a system more natural for transportation specialists and more efficient for transportation applications? The answer may well be "yes" given the special requirements of GIS-T (see Section 2.3). Special data structures and topological relationships are clearly required for transportation, both for efficient network representation and for efficient transportation algorithm processing. They can be defined on top of more general structures and relationships but, as always, there is a trade-off between generality and efficiency.

There are several capabilities required for GIS applications to transportation that go beyond those developed for applications in other areas (see Section 2.3). In the ideal—at some cost in efficiency—these should be realizable by acquiring modules that provide them and that can be used in association with other modules that provide core GIS capabilities. In a server net, the different modules might well be supported by different servers. The current state of technology is such, however, that products providing the capabilities are unlikely to be so neatly decomposable into modules. In some cases, the pioneer DOTs that have made these capabilities available to themselves have done so by extending commercially available products with internal development efforts.

2.4.2 Technology Issues Affecting Implementation Strategy

This section presents a more detailed discussion of the contexts within which information technology planning has to be done—the *technology context* and the *institutional context*. The material is, in the main, quite general, i.e., it applies to all information technology planning, not only GIS-centered planning. However, possible special considerations that apply to the latter are noted.

To repeat an important point made earlier: Focusing on technology in order to set a context does not imply advocating technology-driven rather than needs-driven planning.

2.4.2.1 The Moving Target Problem

Note how different the workstation-dominated, open-system, distributed computing environments of the near future are from the mainframe-dominated, star-network environments of the near past. The difference between near past and near future is about 5 years. And it is the latter for which planning must be done.

Also note how rapidly GIS technology has emerged and matured to the point where it is eminently usable. With respect to this technology alone, it will be extremely difficult to plan within the next 5 years if the technology continues to change as rapidly as it has in the last five—as it likely will.

Thus, dealing with the problem of hitting a rapidly, irregularly moving target requires the following:

- Good timing: Avoidance of premature technology adoption vs. obtaining the benefits of a new technology as soon as possible.
- Avoiding investments that will be out of date before fully amortized.
- Investing in something that will not have to be replaced, but that evolves naturally into later developments.

Technology trends can be identified, and the situation is not hopeless. But successful tracking of the moving target does not require study of and investment in technology projection expertise—as essential components of information technology planning. And it requires resisting hyperbole, fads, and vendor selling pressures.

There are a number of aspects of the proposed ideal framework for GIS technology adoption that specifically address these issues: Two of the dominating costs in GIS implementation—data acquisition and staff training—should be planned to carry over many applications and many stages of hardware and software investment. Each should have a usefulness far beyond the hardware and software (the particular generation of GIS technology) used for particular applications. Further, once an appropriate client-server network is established, new and old technologies (including different generations of GIS technology) can coexist within a common network environment, with older technologies being fully amortized before they are retired, but with newer approaches being incrementally introduced as opportunities and needs arise and as the approaches can be justified in terms of their costs and benefits.

2.4.2.2 The Multiple Technology Problem

DOTs need to plan for and combine the simultaneous implementation of several promising technological developments. At the present time, GISs are 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. Those other technologies cannot be held still while GIS technology is inserted. It would be easier if they could be held still, but that is not reality. In particular, at the same time that GIS is being introduced, network connectivity, network capacity, and the computing power of network nodes are being substantially increased.

Treating the different emerging technologies in isolation (i.e., developing a separate plan for each) is to miss the interdependencies and to fail to take advantage of the ways in which they complement each other. There will be significant benefits that accrue from merging them into a single, coherent plan. More will be gained from each—and from the whole.

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, and in every case will be extended beyond the first steps, pilot implementations, and isolated pockets of the recent past to become ubiquitously applied, generally accepted state of the art.

It is interesting, and worrisome, that some of the strategic statewide and DOT information technology plans developed in the recent past do not include all of the following new technologies. In particular, GIS is sometimes omitted. The only thing that can be worse than omitting one of these technologies from an information technology plan on the belief that it is so weakly connected with the others it can be planned for in isolation, is omitting it from ignorance.

The list of new technologies includes:

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 (computing as what economists call an "abundant resource") 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.) Two changes in computing configurations and their uses that derive from computing being an abundant resource should be explicitly noted: (1) there is no longer an economy of scale that applies to computing engine size and (2) 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. [The researchers commence noting deficiencies in most, if not all, current GIS products. *GIS Product Deficiency 1*: Lack of user-controlled, system decomposability into modules that can be distributed across separate computing platforms.]

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. For present purposes, 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), 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, 3-D) 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. Note the projected $/GIS-seat trend line: from $30,000 in 1988 to $5,000 in 1992.

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 our 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 prototyping and incremental prototyping capabilities. [*GIS Product Deficiency 2*: Lack in GISs of rapid and incremental prototyping capabilities. *GIS Product Deficiency 3*: Lack of connections with CASE environments in a way that enables easy use of location as an integrating concept. Conversely, this can be considered a deficiency of the CASE products.]

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, soft-copy photogrammetry, total station data collectors, electronic notebooks, and telemetry systems such as those for pavement condition and traffic counts.

2.4.2.3 The Data Integration Problem

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, and with resulting 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 of integrating many other kinds of data.

Data that can be shared across applications need to be considered as a corporate resource, rather than as being "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 they are potentially useful for so many different applications. (Special problems are raised by the fact that the general usefulness of DOT spatial data is not limited to DOT applications. DOTs report frequent external requests for their GIS spatial data, not only from other state agencies but from other units of government and from private corporations.)

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 due to enlightened MIS management, some of which we discovered in our 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 our ideal framework, we are reaching for a *golden mean* for effective GIS implementation: First top down, then bottom up.

2.4.2.4 Spatial Databases and Applications

Different applications require spatial data at different scales. No one scale can support all necessary and feasible DOT applications. As depicted in Figure 3, it is reasonable to suggest that DOTs might support GIS spatial databases at three 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 wide-area, 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.

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 3 (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.

All applications at each of the three suggested levels of scale maintain and operate on the same geographic space. Moreover, decision making at higher levels (smaller scales) depends on data that is gathered at lower levels (larger scales), combined with other data (horizontal integration), and then aggregated upwards (vertical integration) (*29*). Programmatic decision making, in turn, invokes strategies and operations

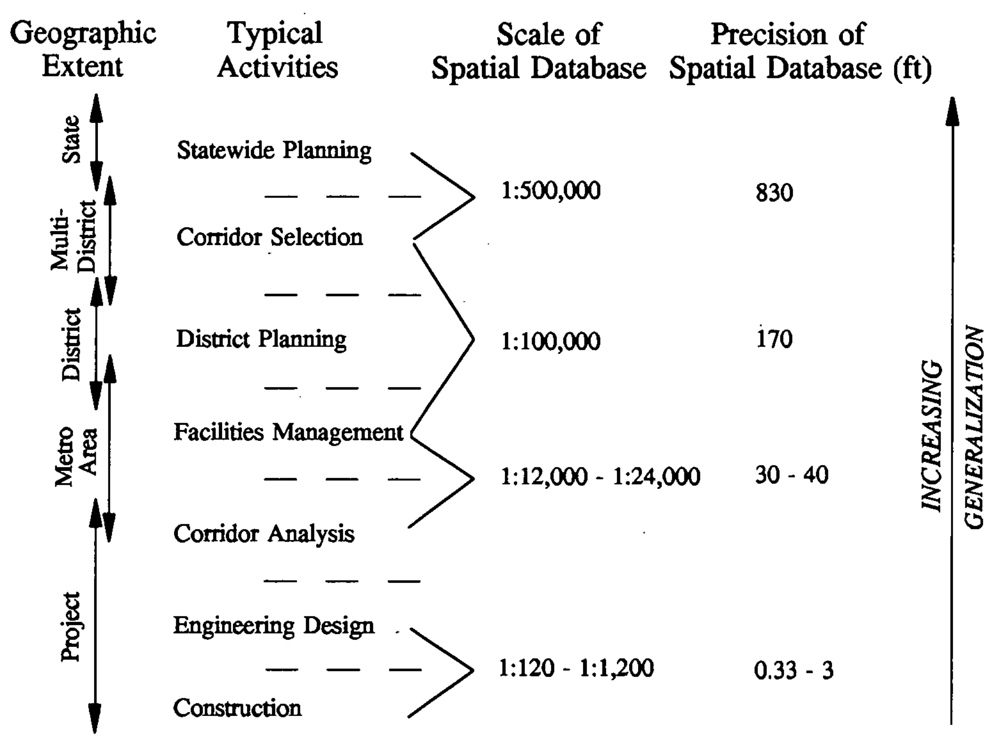


Figure 3. Relationship among geographic extent, typical activities, and scale and precision of the associated spatial data.

at lower-levels that drive renewed data-collection efforts. This holistic view of information requirements and flows within an organization leads to a comprehensive, corporate information system design.

2.5 INSTITUTIONAL CONTEXT OF GIS-T PLANNING AND IMPLEMENTATION

2.5.1 Funding Issues

Main costs involve hardware acquisition, software acquisition, staff and user training, spatial database development, and data maintenance. Spatial database development costs dominate for initial applications (*29*, pg. 244) and data maintenance costs dominate over the long term.

A complete statewide spatial database for any one of the three scales suggested in Section 2.4.2.4 represents a major investment. For example, the Wisconsin DOT began with statewide 1:100,000 USGS Digital Line Graphs and invested 7.7 person-years (including training) in preparing and integrating the data before their spatial database was complete for the State Trunk Highway Network only (*4*).

The expense is such that the use of complete spatial databases should in no sense be limited only to transportation, which raises the difficult but vitally necessary problem of statewide planning across different agencies and of coordinating GIS implementations by DOTs with GIS implementations by other agencies, in particular, those responsible for natural resource management and environmental protection and those responsible for economic development. Further, coordination and data sharing with counties and municipalities and with utilities are necessary and desirable.

Initial applications typically are required to shoulder the lion's share of development costs, including data acquisition. Later applications are required to stand only marginal costs. Can it possibly be done differently? One problem is that this typical approach makes the costs of the initial applications appear prohibitively high. Another is that data collection and maintenance are unlikely to be designed and organized in a way to easily support later, different applications.

There have been several unexpected applications, e.g., Arizona's right-of-way litigation support system. It is important to distinguish between those application implementations that have been primarily pilot projects or technology feasibility tests, as opposed to those that have been the implementation of production systems.

An argument can be made that construction of spatial databases ought to be funded directly and undertaken top-down by a centralized MIS organization, as part of building up a data infrastructure of wide usefulness across the entire organization but, as indicated above, there can be political and organizational problems with this approach. At the very least, data collection must be coupled with some initial applications that manifest reasonably quick, visible payback and that can be used for persuading high-level management and the public to see the construction of the data infrastructure through to completion.

A number of applications likely to be important for DOTs in the future need to be considered. Federally mandated management systems are logical applications that are discussed more fully in Chapter 3. In addition, IVHS applications will be important in the future as discussed below.

Because of their potential for significantly increasing traffic-carrying capacity of the currently available road system (without requiring new land acquisition), for significantly increasing safety, and for significantly increasing ease and convenience of road use, intelligent vehicle highway systems (IVHSs) will almost certainly play a major role in the future of automobile, truck, and bus transportation—and thus in the future of DOT responsibilities. (Prototype IVHS projects, in which DOTs are centrally involved, are underway in several states including Florida, Minnesota, Illinois, and California.) For present purposes, this means that a major if not dominating reason for building and maintaining spatial databases will be that they are required by IVHSs. This needs to be factored into current GIS planning by DOTs even though widespread use of IVHSs may be several years off.

There are a number of considerations here that will affect GIS planning by DOTs. Federal programs supporting IVHS developments will be critical, but so will be product developments by the automobile industry. In particular, in-vehicle navigation systems being proposed and already marketed in limited form in some expensive automobiles, systems that compute position from GPS positioning, dead reckoning, and map matching, may become much cheaper and much more widely popular in a very few years. They do not depend on the construction of major, additional government-provided infrastructure, although the laser-disk-based, on-board maps they use will require the development of a large amount of digitized map information. Commercial concerns will likely be heavily involved in this development, as will DOTs through their traditional map production units.

There is need to coordinate development of these digitized navigation spatial databases with other GIS applications, among other reasons, so that DOTs can take advantage of the commercial interests and funding that will be available, and so that the required data acquisition can be influenced by other GIS applications possibly able to use the data.

Increasing the usability of these in-vehicle navigation systems with publicly provided, dynamic information (e.g., about weather conditions, traffic incidents and resulting congestion, and alternative-route evaluations) will of course be a follow-on development and will involve public-sector transportation organizations like DOTs even more centrally.

2.5.2 Justification Issues

Each of the following issues is important:

1. *Winning initial commitment of budget resources.* The researchers recommend the preparation, by AASHTO or some other national group, of videotapes and documentation that present the general justification. There is no need for each DOT to develop its own. Included in the documentation—and maybe the videotapes—should be in-depth case studies of GIS projects that have paid off for DOTs, with each case presented in sufficient depth that DOT managers and planners can draw careful and reliable analogies to their own particular circumstances. The case studies should provide useful dem-

onstration materials, and might well be accompanied in some cases by portable demonstration software.

The development of such case studies is a next step beyond the data-collection efforts of the current research project. The efforts of this project can serve to identify cases that would be worth the effort. Those GIS-innovation projects funded by FHWA that have survived and have been put into production use are promising candidates.

2. *Maintaining commitment*—in the face of budget crunches, shifting priorities, urgent problems that compete for resources, and rotating managements—by demonstrating short-term and continuing payoff is essential.

Fortunately, this is not especially difficult for GIS, if the need for continuing, visible payoff has been incorporated in the GIS development plan from the beginning. As has been observed, "GIS technology demonstrates well to generals." It is easy for them to see its value, e.g., how it can improve the quality of their planning and decisions. There are dangers if too much time and too many resources are being invested in spatial data collection before useful applications become available. This is why a pure top-down strategy for GIS implementation appears unwise. A balance must be struck in investment of resources between building the data infrastructure and relatively quick realization of useful applications.

Obviously it is important to gain and maintain commitment without building up undue expectations. The history of data processing is replete with the bones of projects that lost continuing support because they were not able to satisfy the unrealistic expectations that had been built up for them when they were initially justified.

2.5.3 Staffing Issues

Consulting firms are being used by some DOTs (and/or at the statewide level) for GIS plan development. But such dependence on outside expertise cannot be continued beyond initial planning and plan justification, and a workable plan must include time and resource allocation for the generation of internal staff capability.

It is important that DOT GIS planners and implementers realize the special nature of the GIS 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 fact, traditional data-processing experience can sometimes be an obstacle rather than an asset. Geographic information systems realize genuinely novel ways of representing and processing data, and people whose data-processing expertise was shaped by older ways of doing things have to engage in a great deal of unlearning, to break old habits and to expand imagination in order to fully understand and exploit the potential of the technology.

The existence of GIS champions in those organizations that have so far successfully exploited the technology has been almost universal. As a matter of fact, this is not unusual for new information technologies (e.g., expert systems, computer support of cooperative work, desktop publishing, fourth-generation computer languages, data visualization, personal information systems, many others), but it does raise some special management problems. Managers must create the conditions for potential champions to emerge, must be able to recognize them when they do, and then must support them. Often they emerge from application areas rather than from centralized data-processing staff. The fact that such champions often emerge from application areas constitutes yet another reason to be wary of excessive centralization and delegation to MIS departments of all responsibility for GIS planning and implementation.

2.5.4 Technology-Organization Fit

Note the misfit and the resulting, sometimes damaging results of serving decentralized organizations with centralized, mainframe-based, data-processing operations. Computing technology is an influential organization change agent. It is important that it be recognized as such in plans for its introduction into, and expanded use within, an organization.

A major effect of current information technology developments is that economy-of-scale arguments no longer dominate in determining whether data-processing operations should be centralized. As far as the technology per se is concerned, data-processing style can be made to fit, not to dictate, desired organizational style.

However, there are considerations that continue to favor some degree of centralization and some degree of top-down planning: 1) the need for sharing data across applications and departments and for considering data as a corporate resource (considerations especially important for spatial data); 2) the need for setting and maintaining data-processing standards across an entire organization. (Note that such standards setting and maintaining can take different forms, ranging from requiring that all departments in the organization use identical hardware and software to enunciating and supporting the use of open systems standards. The former stifles decentralized initiative with respect to new technology introduction; the latter need not); and 3) the need for establishing and maintaining a modern networking infrastructure.

These considerations apply not only to DOTs but across state agencies at a level above DOTs, and they are the basis of several recently developed statewide computing plans swinging back toward centralization at a statewide level.

2.5.5 Larger Organizational Context

DOTs and DNRs (state natural resource management and environmental protection agencies) must play a pioneering role in statewide GIS development efforts, as they have in several states—not only because GIS and geographic data collection are so important for them and they may well be the first organizations to mount production GIS applications, but also because they are such large land owners. Coordination activities must be an integral part of state DOT GIS strategies, whether or not they are externally imposed.

Principal actors besides DOTs in coordination efforts include: 1) other state agencies; 2) private corporations (especially utilities); 3) federal agencies (e.g., FHWA, NGS, DOD, EPA, USGS, BLM, and USDA); and 4) regional, county, and municipal government agencies.

Also, important aspects of the larger institutional context within which DOT information technology planning must be done are various standards movements. The open-systems movement within computing is of special importance.

The goal of the open-systems movement is to achieve standardization of operating systems, networking protocols, user interfaces, and program-to-program communication conventions so that software modules and databases can be implemented in client-server network environments (see Chapter 3, Section 3.2.1). Different network nodes are each to provide some kind of specialized computational or data-providing service. A given program running at one of these nodes is to be able to communicate efficiently with other nodes of the network, nodes providing services to the program or, as its clients in turn, obtaining services from it. The various programs are possibly to be coded in different programming languages, and the different network nodes are possibly to be realized on different kinds of hardware. And the various large software systems, e.g., GIS systems, that in the past have been available only as all-or-none "black boxes," are to be decomposed into different functions possibly available from different servers.

The potential cost benefits from open systems are large and thus are forcing rapid development of open-systems standards and their adoption by hardware and software vendors, even the large ones who have in the past emphasized proprietary systems in order to lock customers into their particular products.

There are competing standards groups—e.g., Open Systems Foundation (OSF) and Unix International—and the various standards development and maintenance efforts that are part of the open-systems movement are far from mature, but already there are several well-defined and usable open-systems standards, for example, in the areas of networking protocols (TCP/IP) and user interface conventions (X Windows and Motif). Within the next few years there will be many more.

The open-systems movement has achieved a momentum where, in general, data-processing planning of any kind by any organization and, in particular, GIS planning by DOTs, can beneficially exploit it to plan and implement client-server networks. Stated more negatively but more strongly, the movement has achieved a momentum where data processing planners who ignore it do so at risk of producing an unnecessarily constrained and unnecessarily expensive plan.

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATIONS

3.1 INTEGRATED INFORMATION SYSTEMS STRATEGY

For reasons that should now be clear from previous sections, effective introduction of GIS technology into a DOT is far more than acquiring a software package and installing it on a few PCs or workstations. It must be done in coordination with the introduction of other new technologies, and it must include the development of large and expensive databases containing the right kinds of locational and other spatially oriented data. Thus, it involves the development and implementation of an organization-wide information strategy. This chapter addresses that development and implementation.

3.1.1 Planning Process

3.1.1.1 General Approach

Database schemas and data acquisition and maintenance policies need to be worked out. If done correctly in ways that avoid costly redundancy and that enable sharing across applications, this is an organization-wide, *top-down* activity. Once databases are designed and in place, GIS technologies can be exploited to bring up particular applications on the basis of decentralized, *bottom-up* user initiative.

The process is not entirely sequential. The initial database planning and specification have to be done with certain high-priority, quick-payoff applications in mind. Among other reasons, this is required because the database development must be accompanied by early and regular application demonstrations that keep the point of it all obvious and in front of high-level management and the public. It won't do to delay such demonstrations until the databases have been completed. By that time, the interest and the required continuing funding commitments will—more likely than not—have been lost.

3.1.1.2 The Role of MIS and the Role of User Departments

Because it is the part of the organization charged with maintaining and supporting organization-wide interests in information technology, the MIS department must be involved in the database design and development. In addition it must support the development of the required networking infrastructure and it must help the various application departments develop required GIS expertise.

Historically, the initiative for introduction of GIS technology into a DOT has most frequently come from user departments, e.g., planning. Care must be taken that such initiative continues to be nurtured and supported. But full and correct GIS implementation is not a task that falls entirely, or even mainly, within the mission of any particular user department.

3.1.1.3 Considerations for 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 isn't 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 on the market of usable 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 doesn't have any operational significance—because technological developments cannot be precisely enough predicted. Certainly there will be surprises and breakthroughs that cannot be predicted, and the precise time of availability and precise capabilities of new products cannot be. But the general shape of the technological future can be predicted and prepared for. In the present case, this applies to two important matters:

1. There is no question but that computing environments of the future will be network based and will use some form of the client-server model.
2. There is no question but that GISs will play an increasingly central role in the computing armamentarium 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 the spatial databases of GISs 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.

3.1.1.4 Planning the Funding

What should be the initial, driving applications can depend on a number of things, e.g., relative urgency of needs, available Federal funding, political priorities, persuasive cost/benefit ratios, which user departments have recognized the potential of GIS and have taken some initiative, or which user departments can free up required funding for new GIS developments. Three comments:

1. In general there should be in place an information systems development strategy that contains priority-setting criteria somewhat more rational than "loudest squeak," and determination of the initial, driving GIS applications should obviously not be exempt from these criteria.
2. It is important to state once again the importance of planning being *needs driven*, not *technology driven*.
3. There is much to be said for making an organization's first GIS project a "pilot" whose primary justification is technology introduction and development of organizational experience, and which may not be expected to serve as a production system. (A number of the DOTs surveyed had proceeded in this way. There may be less justification for this approach as the technology matures and as latecomers to the technology need not make their own mistakes but can benefit from those already made by others.)

It is a mistake to let the initial applications shoulder the full development cost burden, in particular, the full cost of spatial database development—and then to justify and introduce later applications, that can exploit the same spatial database, in terms only of their marginal costs. One important reason is that the cost of potential initial applications can thus be unrealistically inflated, their justification can become more difficult, and there is danger that they will be aborted before completion—or perhaps never undertaken in the first place.

This constitutes one of the more difficult parts of working out an information technology strategy centered around GIS (although the same problem potentially exists for other, nongeographic kinds of data). To solve the problem, some DOTs are considering installation of decentralized data "ownership" and chargeback policies, where particular applications (usually the ones initially requiring the data) are considered "owners" of a particular spatial database and are delegated responsibility for its construction and maintenance. However, they can recover a large part of their costs by charging other applications that can make cost-effective use of the database. An alternative, of course, is to set up the shared database as a centrally funded, corporate resource, but this complicates and perhaps endangers the justification. Both approaches have their problems, and there appears to be no easy solution.

3.1.1.5 Coordinating with the Plans of Other State Agencies

Some of the same problems and possible solutions raised in these discussions for DOTs apply more generally to statewide information technology planning—planning, which is underway in some states, both for information technology in general and for GIS technology in particular. For example, there is significant potential for sharing, between transportation applications and natural resource management applications, of at least some spatial database construction and maintenance costs. Much of what is presented here applies to the statewide planning situation. In any case, an integral part of a DOT's information technology and GIS plans must be coordination with other state agencies.

The researchers have not discovered, in any of the statewide planning efforts, an awareness of the central importance of GIS technology for the future of information technology in general. This lack of awareness is apparently due to inadequate technology surveillance as well as to a failure to understand the potential for the technology because so much of all human thinking, language, and information use is spatially oriented. But—whatever the explanation—the important point for present purposes is that many if not most DOTs are well ahead of other state agencies in this regard. Consequently, as part of coordinating their information technology plans with those of other state agencies, DOTs will have to play a leadership role in the introduction of GIS technology throughout state government activities, not just in the performance of their own specific missions.

3.1.2 Prerequisites for Successful Planning

The following prerequisites for successful planning are obvious enough, but they bear repeating: 1) *Sufficient resources*, which include both money and time. 2) *Staff competence*. Some GIS planning efforts, both DOT efforts as well as larger statewide efforts, are depending heavily on external consulting firms. Such firms may be useful for a jump start when required expertise is not internally available, but an essential and early part of the jump start must be the development of internal expertise. If information and GIS technology planning is to become the continuous, ongoing activity that is recommended, it cannot be done for a DOT (or for a state) by somebody else. 3) *Initial and continuing management support*. As with other aspects of a GIS implementation effort, management support will not be retained long for a continuing planning effort unless it spins off short-term, visible benefits as it goes.

3.2 RECOMMENDED TECHNOLOGICAL FRAMEWORK

The framework proposed here is intended as a goal for planning. Note that it includes adopting and exploiting more technological developments than just GISs. There is no other intelligent way to respond to the multiple technology problem. Several new technologies in the offing and of importance to DOTs complement each other and should not (indeed, cannot) be planned for, and introduced, in isolation from each other. They constrain and enable each other.

3.2.1 Server-Net Model

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 with respect not only to specialty, but also to capacity. That is, some nodes may be supercomputers or mainframes while others may be 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 the 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. Figures 4–7 depict four stages in the evolution from mainframe-centered computing to server-net computing. Good technical overviews of the server-net concept are presented in References *30*, pp. 1–52; *31*; *32*, pp. 454–465; and *33*. Good popular overviews are presented in References *34* and *35*, and Reference *36* discusses application of the concept specifically to GIS environments. 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 the literature (*37,38,39,40,41,42*).

The alternatives to immediately implementing a server net are 1) not networking computers together at all (clearly unreasonable and benighted); 2) assigning so many functions to single nodes (probably mainframes) in an undifferentiated way that those nodes are indispensable to continued functioning of the network; and establishing incremental devel-

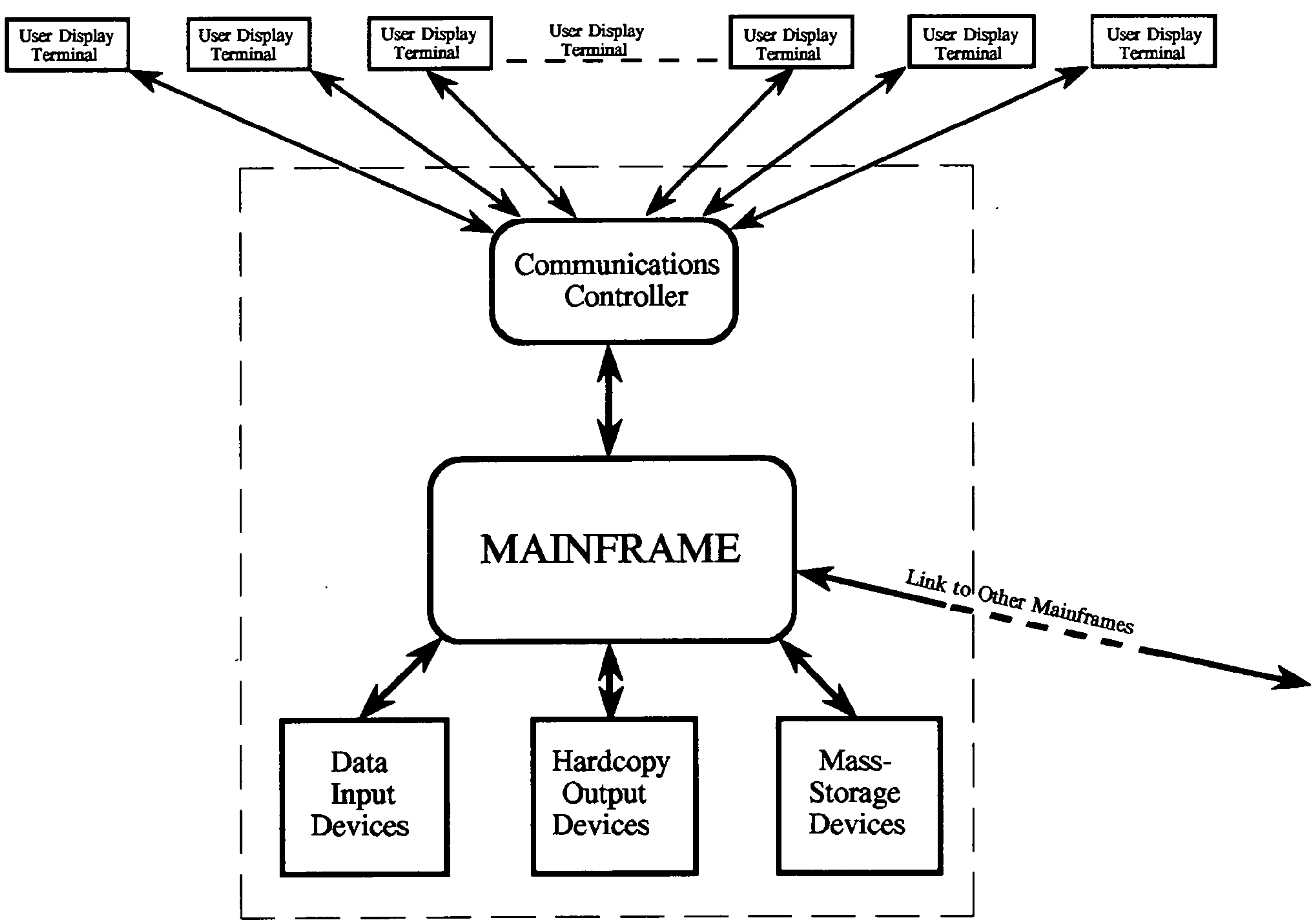


Figure 4. Simplified top-level view of a conventional mainframe-centered computer environment.

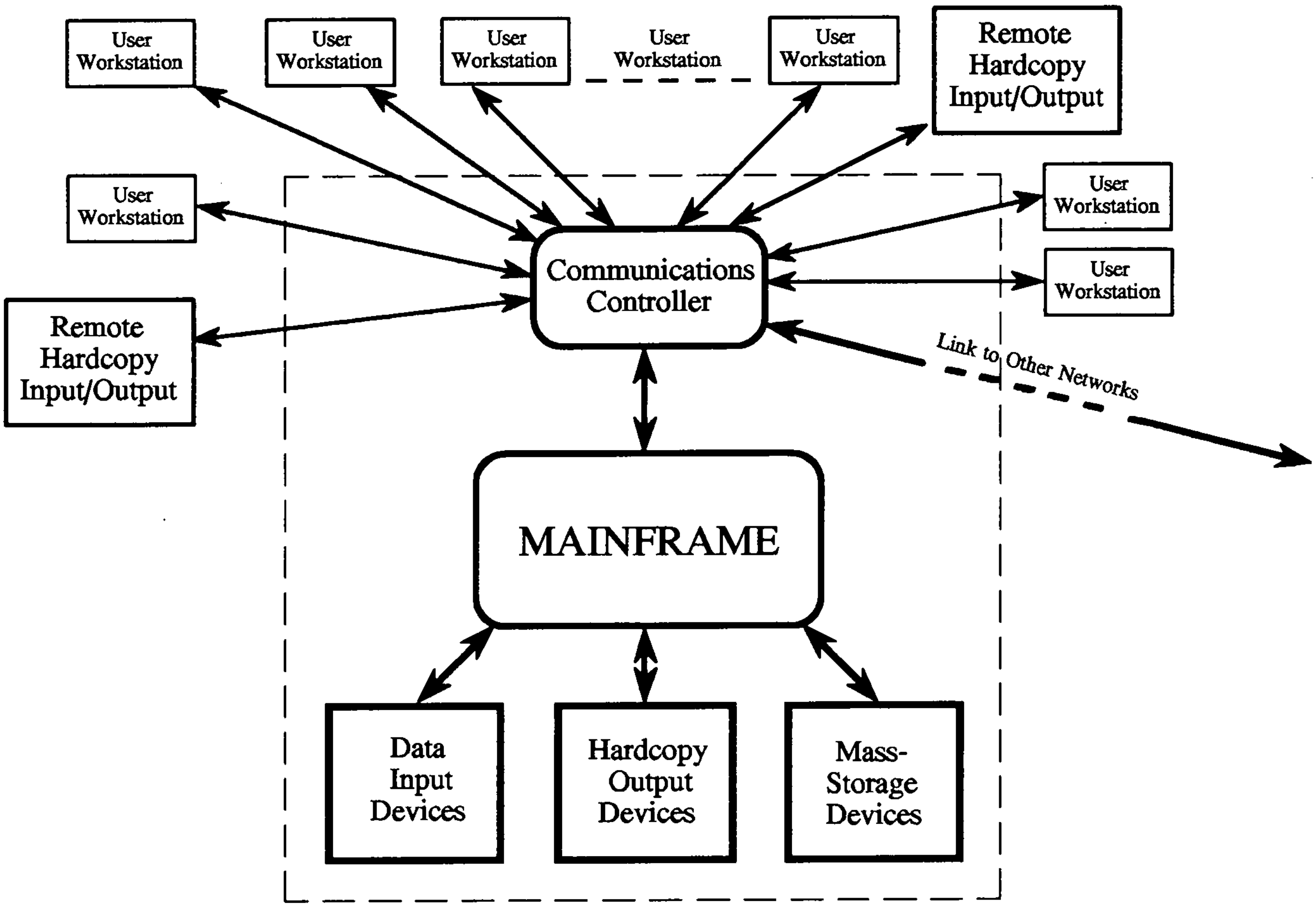


Figure 5. First step toward a client-server network.

opment 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.

Judging from what currently exists in computer science research environments and from the direction of movement of leading data-processing organizations, server nets of the near future will have labor divided so that the following functions are delegated to specialized servers:

- Printing.
- Phototypesetting.
- Plotting.
- Input digitizing.
- User file backup and archiving.
- E-mail store and forward.
- Gateways to other networks.
- Databases (with different servers supporting different databases).
- User stations (with different servers supporting different users).
- 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 node by node. System capacity can be increased relatively smoothly. (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.)

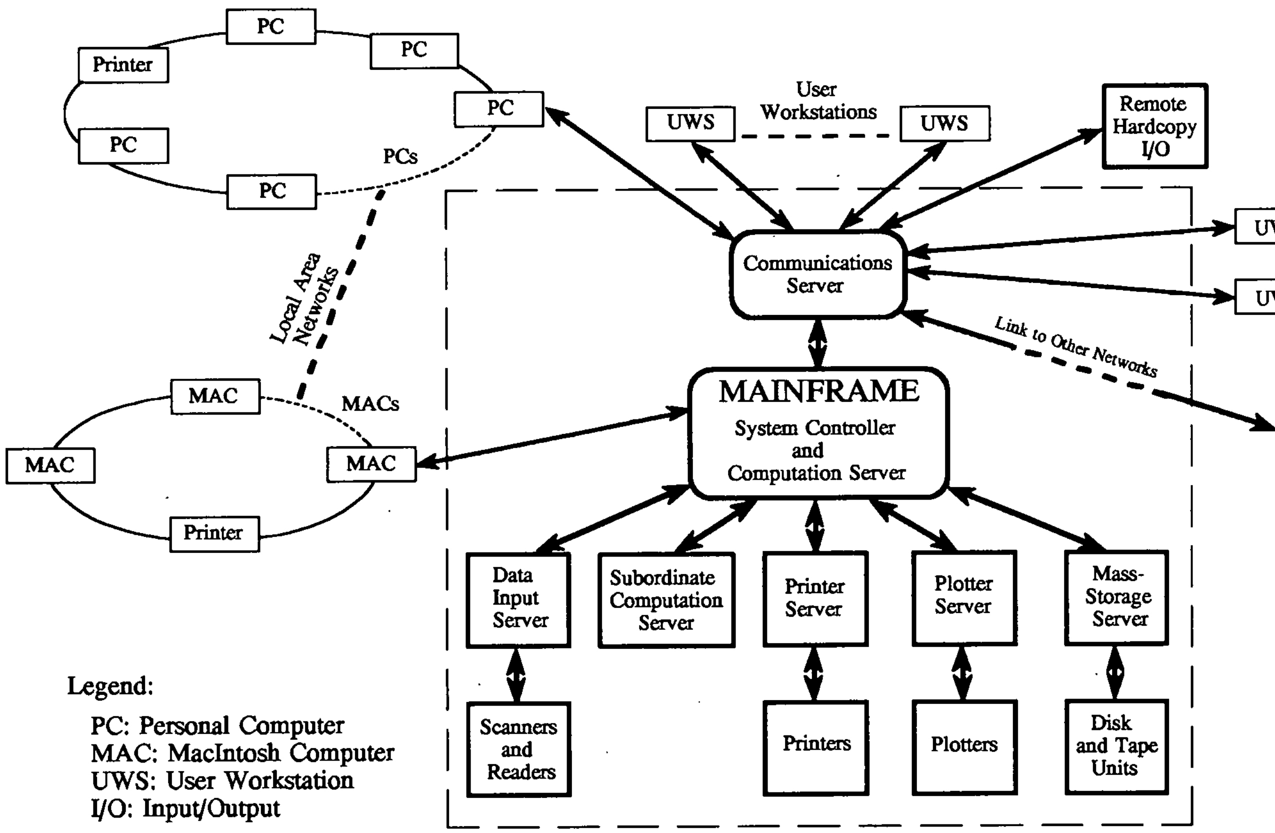


Figure 6. Second step toward a client-server network.

A new technology (e.g., GIS) can be implemented in stages, with earlier, more visible payback from initial costs. (Again, readers should not misinterpret what is being claimed. Those initial costs might still be quite large, e.g., in the GIS case because of base-map development costs.)

Further, organizations are provided the opportunity to better stay abreast of rapid technology changes because introduction of a new technology (once again, e.g., GIS) does not require replacement of 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. Obviously such a transformation is facilitated if the services provided by the mainframes at the centers of the stars have earlier been rationalized and modularized according to a conceptual client-server architecture. Thus, not only investments in hardware but also investments in software, training, and data can be more fully amortized.

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 with the ability to perform the same server functions, thus providing backup for each other (backup that, in some cases at least, can be transparent to a user).

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.

3.2.2 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 functions to be 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 the physical transfer of significant amounts of data often by disks or tapes. But this is a beginning. Sneaker nets can eventually mature into electronic nets, as the required

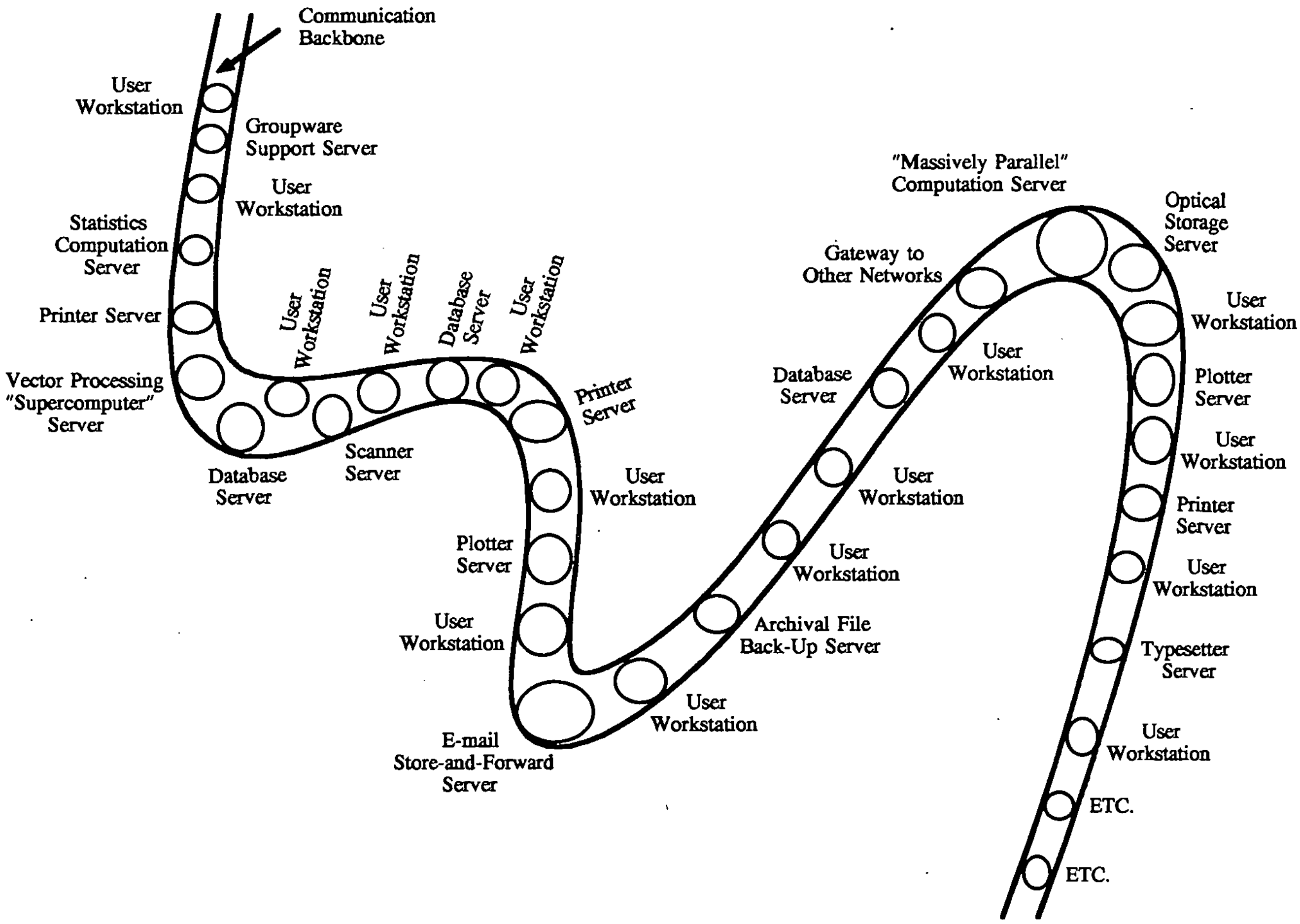


Figure 7. A full-fledged client-server network.

technology becomes available and affordable. 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, and 15) specialized application servers.

Figure 8 depicts a GIS-T server net. There will be several, in some cases many, servers of each kind in a given network. The 15 different kinds of servers are discussed here in some detail. Doing so serves not only the purpose of articulating the architecture of an idealized GIS-T server net, but also the purpose of articulating the required and desired functions of a GIS-T system whether or not it is implemented physically within a server net with the different functions being supported by different servers.

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 is very useful for understanding the criteria for distinguishing between good and bad modularization (*43*).

3.2.2.1 Spatial Data Servers

Servers of the first kind, *spatial data servers*, contain and provide their clients with access to spatial entities such as coordinates and shapes, and to topology (relations among spatial entities). In general, these data constitute digitized maps represented as vectors. [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). See Section 3.2.2.3.]

More specifically, spatial data servers provide information about points, lines, areas, and networks—plus topological

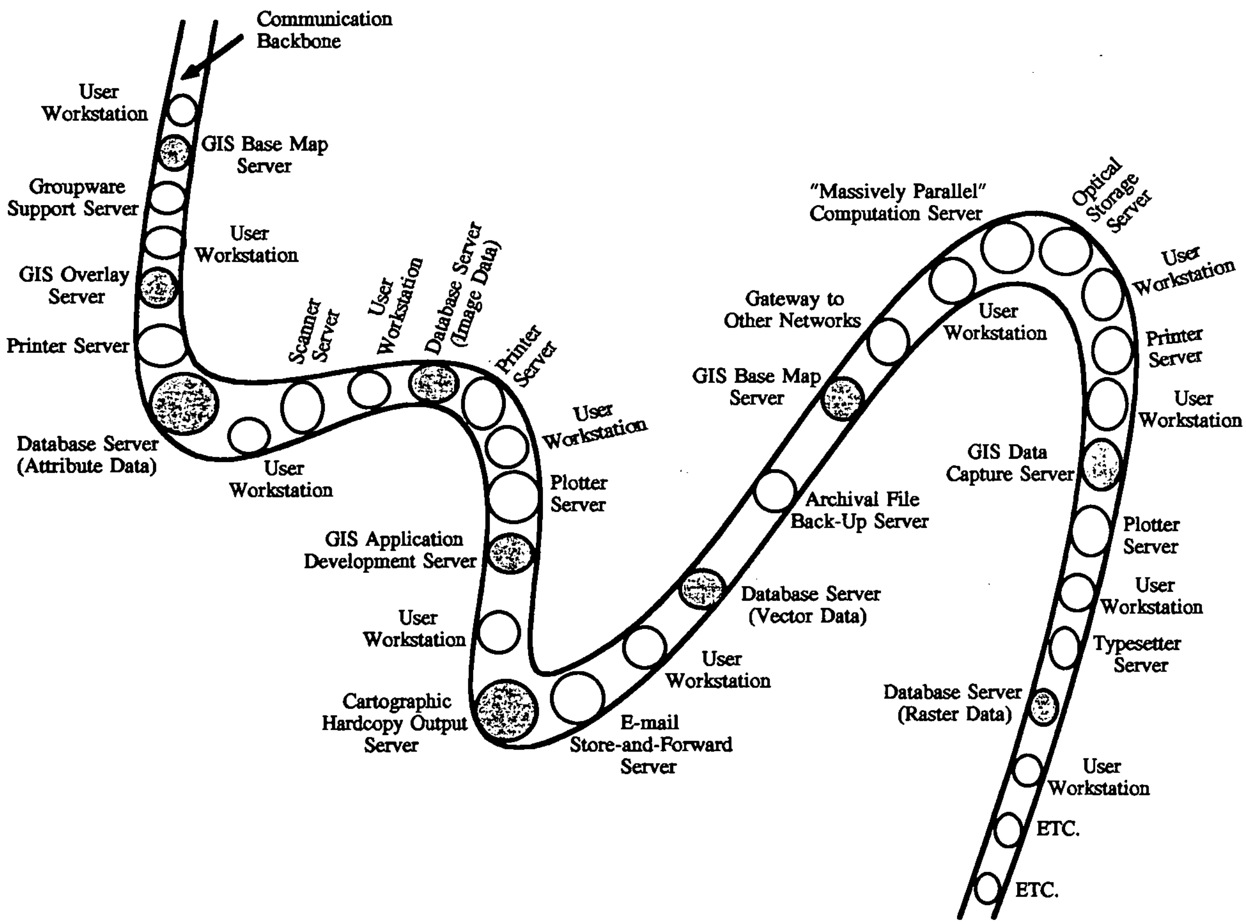


Figure 8. A GIS-T client-server network (as for Figure 7 but with various GIS-T specific servers added).

relationships among entities of these types. (Network data types and relationships are especially important for GIS-T, as opposed to earlier GIS applications in the areas of natural resources and land records.) Although current digitized maps are usually only two dimensional, spatial data servers might also provide information (elevations, slopes, aspects, and volumes) about digital elevation models 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, consider 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) as 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 possibly 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 (with the milepost method being especially important for transportation applications); 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 and/or made at different times) or from other sources (e.g., construction plans). For the present purposes, the researchers considered all of these spatial data servers.

As indicated in earlier sections, the data controlled and provided by any given spatial data server are potentially useful to many different applications. When this is the case, the data may well represent a valuable corporate resource, although the initial construction of the spatial database will likely have been driven by a specific application.

3.2.2.2 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 modeling or GIS output, e.g., thematic maps or overlays of maps over 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 schemas used must in many cases be extended to include location fields that enable linking of the attribute data to spatial-data references as will be required, for example, for the production of thematic maps or for various kinds of analytic modeling.

3.2.2.3 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.

3.2.2.4 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.

3.2.2.5 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 herein may best be implemented as object-oriented. Object-oriented database systems would obviously be well suited for the complex object data servers addressed in this report, 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.

3.2.2.6 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.

Specific and different overlay programs are required for each coupling of two different data types used by different data servers. Programs for widely and generally 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. [Note as *GIS Product Deficiency 4*. Such development environments represent another example of how GIS and CASE technologies need to be brought together.]

For transportation applications, overlay operations frequently involve network overlay rather than, or in combination with, the polygon and line overlay capabilities familiar from other kinds of GIS applications. Further, the network and line 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.

The coupling between overlay servers and user-station servers required to enable direct, interactive, What-You-See-Is-What-You-Get (WYSIWYG) user editing control over the overlay process will have to be so tight as to suggest that the two functions of overlay and overlay-editing display should be on the same server. They shouldn't be (because each of the two kinds of server has so much else to do that doesn't involve the other), but the problem raised and the difficulty of specifying the required communication protocol well illustrate why decomposing computation into separate modules supported by separate servers is seldom obvious or easy.

3.2.2.7 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, e.g., network analysis models or traffic demand assignment 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 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 applications, e.g., personnel applications or financial management applications, might well be the same attribute data servers needed for various GIS 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 functions.

Significant disagreement exists as to whether the various transportation computation applications that require geographically oriented input data and that produce geographically oriented output displays and documents (among other kinds), should necessarily be considered a part of GIS-T systems per se. However, the question is important only in a context where GIS-T systems are being considered as isolated, stand-alone "packages" of some kind. Once a GIS client-server architecture is specified, transportation computing is decomposed into separable kinds of services and activities (that both provide and use GIS capabilities) and these services and activities are in turn allocated out to separate server and client nodes as appropriate, the question fades to insignificance. It becomes a word usage issue dependent on where one arbitrarily chooses to draw a boundary around clusters of interdependent servers.

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 work station 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 work stations will be performed.

3.2.2.8 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 for data formatted and related as required for static map displays.

Once again, let it be emphasized that the researchers are not proposing construction of a server-net computing environment devoted exclusively to GIS applications. 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 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 user support on general workstations available to all their managers, engineers, and other employees, and integrated into the general DOT computing network—rather than planning only the installation of isolated, specialized GIS user stations. The goal should be to use GIS technology as a general database integrator and to make it available to everybody, not just to certain specialists. The failure to see the potential of GIS across a broad spectrum of human activity within DOTs and elsewhere is, to repeat (see Section 3.1.1), a failure to see the ubiquity of spatial referencing and representation in all human thinking and language—and constitutes for information technology planners a serious failure of vision.

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 run-of-the-mill work stations. 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 (e.g., removal of slivers) or data input editing (e.g., removal of undershoots or overshoots), are 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. Similar comments apply to editors that enable users to request and interactively monitor the generation of topological relations among the entities described in spatially oriented databases.

All this might suggest that one should specify a geographic user station 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.

3.2.2.9 Application Development Servers

Similarly, there is an apparent need for special user stations for GIS application developers as opposed to the stations required for general GIS 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, the researchers do specify as servers of a ninth kind, *GIS application development servers*, intending by this not separate servers for each individual programmer but servers that provide source code databases (with capabilities required for version control), coordination support for programmer teams, documentation databases, linkers, optimizing compilers (note 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.

Essential to the present discussion is the fact that these application development servers need to be something more than database and CASE systems for supporting programming in general, although they must be that as well. They need, for example, capabilities supporting fast prototyping and interface prototyping that involve structuring, using, and displaying spatial and nonspatial data from the data servers in a GIS-T server net.

3.2.2.10 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 they 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).

3.2.2.11 Cartographic Data Servers

Servers of the eleventh kind, *cartographic data servers*, construct and store symbolic structures (map surface symbols) that drive electronic map displays and hardcopy map printing and publishing devices. Once again, there is a question of appropriate division of labor between individual-user work stations 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 work stations. 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.

3.2.2.12 New Technology Servers

Servers of the twelfth kind, *new technology servers*, are introduced as place holders. They are 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 the knowledge bases (formalized as deductive rules) and the 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 using animation to be produced and stored (possibly on optical disks) as video. Other media would likely also be involved—voice for sure.

One may usefully speculate about 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, users currently know how to implement them, they just can't afford the computing power required.) Others will result from artificial intelligence and other kinds of computer science research, and others have yet to be invented.

Such servers might include collaboration servers, "virtual reality" servers (an extension of the animation generator servers just mentioned), neural-net-based image recognizers and map readers, and "knobots" that constantly monitor external networks and databases for data of interest.

3.2.2.13 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, typesetter drivers, etc. 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. One such kind that will be available in every server net of the future is worth mentioning, however. *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.

3.2.2.14 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.

3.2.2.15 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.

3.3 OBSTACLES TO FULL IMPLEMENTATION AND STRATEGIES TO OVERCOME

An ideal is seldom fully realized. It is useful to note the obstacles that stand in the way of the information technology planning advocated, and in the way of realizing the proposals for implementing server-net computing environments and for using GIS as a data integrator.

The main obstacles are listed as follows with a brief comment on whether and how they might be overcome:

1. *Institutional inertia*, often justified in terms of investments (in older ways of doing things) that have to be fully amortized.

What is needed is leadership capable of perceiving and articulating the benefits of emerging technologies like networking and GIS, benefits that include satisfying certain important needs either not satisfiable in any other way or not satisfiable by any alternative for as low a cost. The recommended approach—incremental, evolutionary introduction of GIS and other emerging information technologies—recognizes the importance of, and enables, the full amortization of previous investments in information technology.

2. *Urgent, unanticipated needs* that don't fit into, and that take priority over, general plans.

In no case should plans be cast in stone. The researchers have emphasized the importance of continuous, ongoing planning—a process able to change plans as required by unforeseen circumstances. The danger lies not in change but in making investments and undertaking actions that respond only to short-term exigencies, failing to consider larger context and likely effects for the longer term. An ongoing planning process should be able to provide this larger context and longer-term perspective.

3. *Staff deficiencies* and, in particular, absence of a GIS champion.

There is no easy solution here. External consulting firms are available to get the planning process started, but the ongoing planning process must be moved in-house. The initial plan must, of course, include components that deal with acquisition, training, and retention of requisite GIS expertise on the part of everybody in the organization.

Without exception, the DOT GIS adoption efforts that have succeeded have involved a GIS champion (or perhaps several)—from data processing technical staff or from staff of a user department. As observed above, this is not an unusual situation for new information technologies, and it is yet another aspect of technology introduction that argues against stifling bottom-up initiative. In general, the champion is not a high-level manager. If they are doing their job well, high-level managers are spread too thinly to have the focus needed by an effective champion. Champions cannot be created by plan fiat, but an environment can be created that encourages their emergence and that supports them once they have emerged.

4. *Absence of the resources required for planning*.

This is often used as an excuse. Stated more precisely, the situation is not absence of resources but how resources are being allocated. Planning is not being given a high enough priority to rate the resources it requires. The excuse is an indicator of bad management.

5. *Lack of management support*—for planning in the first place, and then for doing anything with a plan once it has been articulated.

The problem of gaining and retaining management support, for planning as well as for plan implementation, is part of the human condition, not just a problem for information technology and GIS planning and implementation. There are aspects of GIS technology that are conducive to gaining management support. It demonstrates ways that make it easy for high-level managers and the general public to see the importance and usefulness of GIS technology. But, as we have emphasized several times, a successful implementation strategy includes early and continuing visible payoff.

6. *Interference from higher, centralized authority* (i.e., above DOT level).

DOTs have played and should continue to play a leadership role in statewide GIS coordination and planning efforts. But those efforts have very frequently stifled and will likely continue to stifle initiative at the DOT level.

7. *Required technology that is not yet mature and available* (e.g., networking).

It will be available over the next few years (there just simply is not disagreement about this), and it needs to be prepared for. Thus the recommendation is that DOTs start with a conceptual server-net architecture, and physically realize it gradually and stepwise, at whatever pace is allowed by technology maturation and the appearance of the required commercially available products. Similar comments need to be made about starting with the conceptual organizing principle of using location as an integrative concept, an organizing principle underlying all future database schematizing, and then gradually designing and redesigning database schemas in ways that allow for the actual use of the concept of location in this way, as the required spatial databases are populated and become available.

8. *Required standards not yet established* (e.g., open systems standards).

The required standards will be in place in the next few years, and thus the comments just made for Item 7 will apply here also.

3.4 PARTIAL REALIZATION

Despite good intentions and best efforts, the ideal of a full server-net will be only partially realized in many cases. Two barriers to full realization are outlined below.

3.4.1 Piecemeal Application Development

In the past, with GIS initiative usually coming from user areas rather than as a result of a centralized planning effort, DOT GIS implementation has usually been case by case, application by application. Each implementation decision has been based on short-term and marginal cost considerations.

It can be said for such an approach that it enables DOT user areas to take advantage of new GIS products quickly, and minimum planning and management continuity are required for success. Some of the GIS applications are flashy and attractive, and they demonstrate and sell well.

But the success is shallow, likely to be short lived, and the basis of major lost opportunities. Data-collection costs are not shared across applications, and taken as a group the applications almost certainly will be more costly than need be because of redundancy and duplication. A diversity of software products across the organization increase overall training and maintenance costs and, most important, with the geographic data being used by the various departments themselves being unintegrated, there is no opportunity to use them as a basis for generally integrating data—of all kinds—across the organization.

At the very least, DOTs can and should move toward coordination of their decentralized, piecewise GIS implementation projects. Efforts at coordination will soon make clear the significant savings possible from shared data collection and maintenance, and the coordination activity can be the seed that grows into the more ideal, larger planning effort here recommended—an effort that integrates GIS technology adoption with network technology adoption, and that works toward realizing all possible benefits of GIS technology, especially data integration benefits.

3.4.2 Continued Monolithic Databases

The mainframe mentality dies hard, and there are a lot of people around who fail to understand the potential of the server-net model and who fail to perceive that the technologies for realizing it are at hand, e.g., very powerful microcomputers eminently suitable as server nodes of various kinds. Thus many DOTs continue to plan for and implement GIS capabilities based on large, mainframe-centralized, monolithic databases.

It can be said for such an approach that it enables continued use of a now, well-understood technology, more congenial to the responsible data-processing staffs than the approach that decomposes the single, monolithic database and allocates its parts out to separate albeit networked servers, with responsibility for construction and maintenance of the separate parts probably also delegated out to primary user departments. There are now appearing software products (e.g., from Software AG) that provide the data structures and algorithms for efficient storing and processing of spatial databases mounted directly on mainframes, along with everything else that is part of a monolithic, centralized corporate database.

But doing it this way misses most if not all of the benefits of the server-net approach. Large, centralized, monolithic database approaches have proven unwieldy. The required database schemas are very complex and very inflexible, and seldom if ever are they successful at achieving the data integration that at least partly motivated their development in the first place. Many DOT efforts to build such databases, efforts that have been aborted or at best have been only minimally successful, can be adduced. Clearly, the use for integration of spatial databases mounted separately but within a server-net environment offers a most attractive alternative.

At the very least, such mainframe-based, monolithic databases with integrated GIS capabilities should be planned and designed in terms of an underlying *conceptual* server-net architecture, so that they can be decomposed and the parts allocated out to networked, specialized servers sooner or later. It would be a great loss financially, if, when adoption of the server-net approach can no longer be delayed, data definitions and schemas—and the operational procedures based on them—have to be radically revised, maybe even totally replaced.

3.5 APPLICATIONS

Because almost all information used by DOTs can be linked to location, a wide variety of applications of GIS-T are possible. In order to identify applications that will be most useful to DOTs, a framework for application development is needed. The next section proposes such a framework. The framework is then used to describe existing GIS-T applications. Analysis of the context within which existing GIS-T applications have been developed leads directly to use of the framework to identify possible future GIS-T applications.

3.5.1 Framework for Application Development

This section provides decision makers with a framework to help structure the selection of GIS-T applications. As depicted in Figure 9, the proposed framework has six steps: 1) select transportation mode(s), 2) select spatial and temporal dimensions, 3) select spatial database component(s), 4) identify transportation system attributes, 5) identify related databases, and 6) identify GIS-T functionality.

The framework is general in that it covers applications relevant to any of the seven basic functional areas covered by DOTs: planning, design, construction, operations, maintenance, management, and research. The relationships among these functional areas are assumed to follow the sequence of activities required to develop a new transportation facility as shown in Figure 10. Management is shown as an oversight function with links to all of the other functional areas. Research is viewed in this context as an extension of the management function.

Because of the potential of GIS-T for the integration of information, many GIS-T applications are likely to involve management activities. The remaining functional areas can be grouped for simplicity into planning or engineering (design, construction, operations and maintenance) functions with research included as a management function. The three broad functional areas—planning, management, and engineering—will be used to categorize existing and future GIS-T applications in terms of the six-step selection process.

3.5.1.1 Transportation Mode(s)

In many cases, GIS-T applications are generic and can be applied with little or no modification to several modes. The primary question at this level is whether a multimodal focus is important for a particular set of applications.

3.5.1.2 Spatial and Temporal Dimensions

The spatial and temporal dimensions of GIS-T applications are considered jointly because there often is a close link between the two. As shown in Table 1, the attributes of the spatial

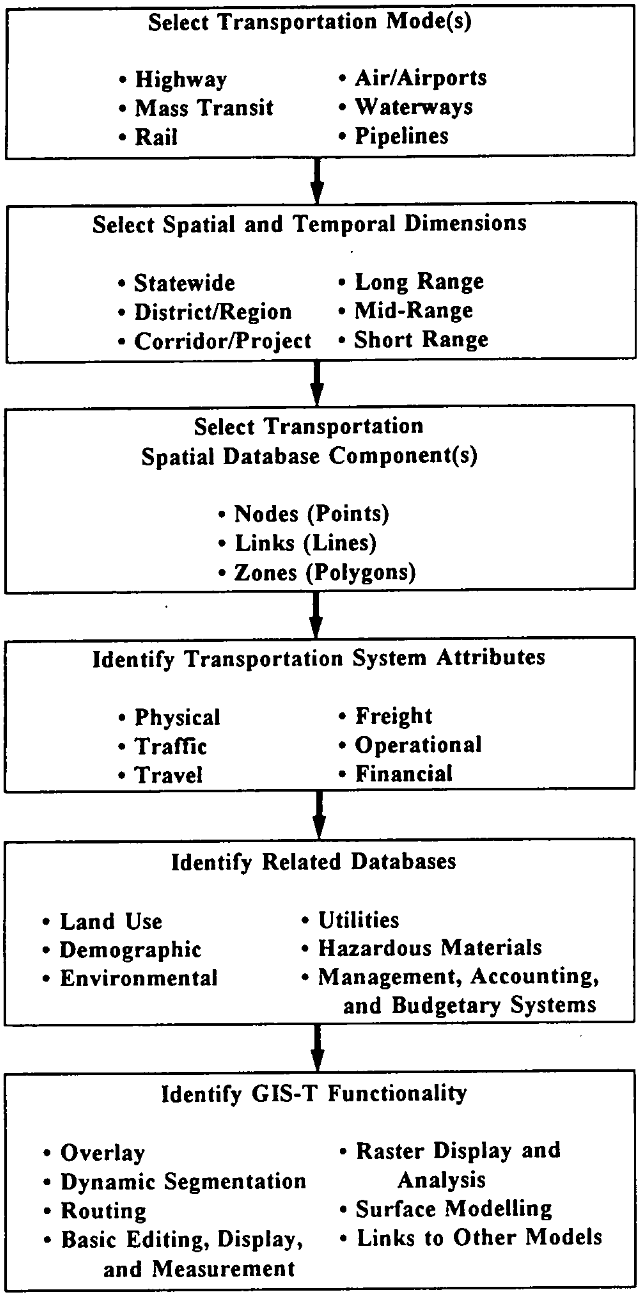


Figure 9. GIS-T application selection process.

dimension are 1) application level (spatial database scale), 2) network type, and 3) area coverage.

The spatial dimension describes the geographic area of interest (application level), the type of network needed (grid versus linear), and the part of the geographic area of primary interest for most applications (area coverage). A grid network, consisting of a set of topologically related links and nodes, is required in order to determine routes through the network. Typically, minimum time or distance routes are used but other more complex objective functions may also be used. In contrast to a grid network, a linear network is simply a set of links (and the associated nodes) arranged end to end.

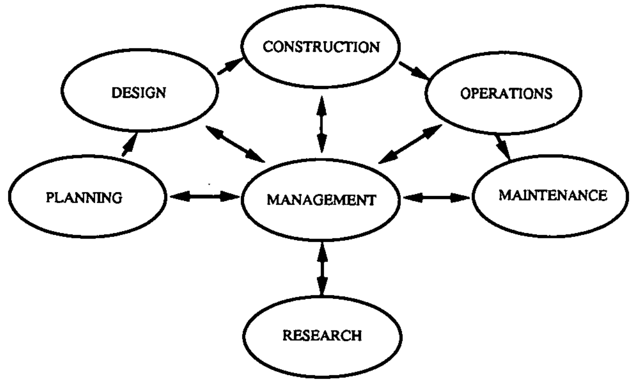


Figure 10. DOT primary functional areas and information flow.

A grid network is fully described by a set of links and nodes, although specialized nodes called "centroids" may be used to represent zonal (polygon) based data such as population or trip ends. A linear network, however, may also be represented as a series of polygons (zones), where the polygons represent, for example, the right of way of the highway or of the traffic analysis zones traversed by the highway.

The attributes of the temporal dimension are 1) time horizon and 2) analysis cycle. Table 1 also shows the general relationship between the spatial and temporal attributes and the three general functional areas—planning, management, and engineering. Planning applications often do not need highly precise locational data. Thus they can be developed at the statewide level with a grid network that covers the entire state. The statewide network will be primarily useful for long-range strategic level planning with infrequent updates (perhaps every 5 years).

Management applications often require more detailed locational data that are available at the regional or district level. A linear network would typically encompass a corridor or sub-area of interest. For a sub-area, a grid network may be required. The regional applications would focus on a short- to mid-range time horizon of 1 to 5 years with a wide range of possible update cycles. Continuous or hourly data may be required for some applications with annual updates as the most common cycle.

Engineering applications are generally restricted to the project level involving a single narrow corridor. A high level of spatial accuracy is required. The focus is on a short-range implementation period of up to 3 years. Most applications are a one-time effort for the area of interest, but engineering review may be required as part of planning and management review cycles.

3.5.1.3 Spatial Database Components

Historically, the spatial databases for transportation models at both the statewide and urban area levels have consisted of only nodes and links with zones (polygons) represented implicitly as single nodes, that is, centers of zonal activity called "centroids." More explicit consideration of zonal attributes through overlays or buffering was not incorporated into

TABLE 1. Spatial and temporal dimensions of GIS-T applications

GENERAL FUNCTIONS	SPATIAL			TEMPORAL	
	Application Level [Spatial Database Scale]	Network Type [Spatial Database Components]	Area Coverage	Time Horizon	Analysis Cycle
Planning	Statewide [1:500,000-1:100K]	Grid [Node, Link]	Total Area	Long Range	Multi-Year
Management	District/Region [1:100K-1:24K]	Grid [Node, Link]	Wide Corridor	Mid-Range	Wide-Range[2]
Engineering	Corridor/Project [1:12K-1:120]	Linear [All][1]	Narrow Corridor	Short Range	One-Time Effort[3]

[1] Node, link, polygon (zone)
[2] Continuous, hourly, weekly, monthly, annually
[3] Updates depend on planning and management cycles

the transportation models. For many applications, node- and link-based spatial databases may still be adequate; however, more extensive analysis using GIS functionality will require the inclusion of zonal data as polygon overlays.

3.5.1.4 Transportation System Attributes

DOTs have many hundreds of data items that describe transportation system attributes. A recent study of information systems by the Wisconsin DOT identified a total of 94 separate information systems for the highway mode alone (*44*, Chap. 3). Each information system may contain dozens, even hundreds of data items. At a higher level of abstraction, however, transportation system attributes can be grouped into six categories: 1) physical, 2) traffic, 3) travel, 4) freight, 5) operations and maintenance, and 6) financial.

Each of these primary categories can be subdivided for the highway mode as shown in Table 2. The list of attributes is not designed to be fully comprehensive; rather it describes the data that DOTs typically have or could include in their corporate database.

In fundamental terms, transportation involves the interaction of *supply* (physical attributes) and *demand* (traffic attributes). Analysis of the interaction between supply and demand is enhanced by travel attributes that explain why traffic exists at one location and not another. The operations attributes provide information on the control of the transportation system and how the system is maintained. Finally, financial attributes are needed to address resource allocation questions.

To be useful for GIS-T applications, transportation system attributes must be placed in the context of the prior steps of the application selection process. Table 2 describes the major transportation system attributes in terms of spatial database components and the most likely analysis cycle. Data-collection requirements are included in the table because of the importance of data collection to the feasibility of many GIS-T applications.

As shown in Table 2, the physical attributes of highway systems are primarily link-based attributes. The geometrics of a highway are described by tangent sections and horizontal and vertical curve sections. Intersections are nodes while structural attributes may include both nodes (such as bridges) and links (such as pavement depth over a section). Changes in physical attributes typically require major expenditures. Thus, except for annual monitoring of condition, the analysis cycle covers many years. Often 5 to 10 years are required to complete major changes. The physical attributes are recorded *as built* in inventory files although design attributes may be substituted where *as built* data are not available. Deterioration of the physical condition may be recorded periodically through field surveys.

Data on traffic attributes are collected at point locations, which is adequate for intersections, but may require multiple count locations to fully describe traffic on a link. For most purposes, annual estimates of traffic are adequate. For accidents, monthly or even weekly updates of accident location maps would be useful. Real-time data are needed for some traffic and demand-management applications. The time period of interest is most frequently the "average day" for a year, but peak hour and even peak 5- or 15-minute data may also be needed. Collection of traffic data requires sampling and extrapolation because making traffic counts on each highway link in both urban and rural areas for each hour of the year would be prohibitively expensive. GIS-T applications will make existing traffic data more useful and may require a more extensive counting program in some states.

Description of travel attributes requires the full range of spatial database components. In contrast to most of the other transportation system attributes, the trip-end and demographic attributes require zonal (polygon) level data. Description of trips and routes is also more complicated and requires multiple nodes or links. Historically, travel data have been linked to the long analysis cycle used to plan, design, and construct transportation facilities. Much of the data is derived from the U.S. Census which has a 10-year cycle. Forecasts of travel are typically required for a 20- or 30-year time horizon. Multiple forecasts may exist that reflect alternative development scenarios. For project level applications, the regional travel forecasts must be augmented with subarea data in order

TABLE 2. Description of transportation system attributes (highway mode)

Transportation System Attributes	Transportation Spatial Database Components	Analysis Cycle	Data-Collection Requirements	
			Time Period	Method
Physical				
-geometrics	link	multi-year	as built	inventory
-number of lanes	link	multi-year	as built	with updates
-intersections	node	multi-year	as built	(annual to
-structural	node/link	annual/ multi-year	as built/existing conditions	multi-year)
Traffic				
-speed	node/link	annual	Hour	count program
-volume	node/link	annual	Hour/Day	count program
-composition	node/link	annual	Hour/Day	count program
-accidents	node/link	annual	Single Point	acc. reports
Travel				
-trip ends	node/zone	10 year	avg. day/peak hr.	O-D survey &
-trips by mode	two nodes	5-10 year	avg. day/peak hr.	U.S. Census
-routes	set of links	various	avg. day/peak hr.	computer
-demographics	node/zone	5-10 year	Point estimate	model
				U.S. Census
Operations				
-traffic signals	node (set of)	1-5 year	time of day	inventory
-traffic signs	node/link	multi-year	as built	inventory
-pavement markings	link	multi-year	as built	inventory
-detours	set of links	one time	various	operating
-winter maintenance	set of links	annual	seasonal	repts.
-pavement maint.	link	annual	seasonal	operation
				repts.
				operation
				repts.
Financial				
-construction cost	node/link	one time/ann.	as built	contract
-maintenance cost	link	ann./multi-yr	current	records
-vehicle operating cost	node/link	annual	current	maint. records
				model based

to generate more detailed travel estimates (trips and routes). Route data, however, may also be required for current conditions including real-time applications. Computer routing algorithms can easily generate the required routes given the relevant attributes of the transportation network.

The operation of the highway system involves providing information to drivers through traffic signals, signs, pavement markings, and detour signs—as well as to maintaining the physical condition of the surface (regular and winter maintenance). As with travel attributes, operations attributes require a more complicated spatial database. Many traffic signals need to be described in terms of a network of signals. Detours and winter maintenance may be described as a set of links that in some cases would be determined in real time. The analysis cycle varies from multiyear for traffic signs and pavement markings to a one-time effort to detours. Data-collection requirements vary considerably from simple inventories of *as built* conditions to daily or seasonal summaries of field activities.

Financial attributes cover a wide variety of costs, which can be grouped into the three main categories of construction, maintenance, and vehicle operating costs. In general, financial attributes are associated with both nodes and links. Polygon overlays may be required for detailed consideration of right-of-way costs associated with construction. Costs are typically updated annually based on current records and prices.

3.5.1.5 Related Databases

A number of databases should be available for use in GIS-T applications including land use, demographic, environmental, utility, and hazardous materials databases. The first three involve polygon overlays generated by other agencies. The full range of attributes associated with these databases is potentially relevant for GIS-T applications. Utility systems such as sewer and water can be represented as networks using nodes and links with appropriate attributes. Hazardous materials can be represented as a "travel demand" with an origin and destination for a hazardous cargo, or as point or polygon overlays in the case of a contaminated site.

In addition, the corporate management, accounting, and budgetary systems should be available for GIS-T applications. The management systems will include the allocation of staff resources through work orders and project assignments. These activities may be directly tied to specific highway links or to nodes that represent the work location. Accounting systems will include payments to local governments (shared revenue disbursements) and revenue generation from motor vehicle registration fees and other sources. These two attributes are associated with geographic areas (polygons) and are typically on annual or monthly cycles.

3.5.1.6 GIS-T Functionality

For the purpose of identifying and classifying GIS-T applications, seven GIS functions or groups of functions are used:

1. Basic functions (editing, display, measurement),
2. Overlay,
3. Dynamic segmentation,
4. Surface modeling,
5. Raster display and analysis,
6. Routing, and
7. Links to other software (e.g., transportation modeling packages).

The basic functions are used to edit, display, and measure base maps. The editing function allows the user to add or delete points, lines, or polygons and change the attributes of these features. The display function generates thematic maps that show the attributes of selected features using a variety of symbols and colors. The measurement function is needed to determine the length of lines and the area of polygons.

The overlay function permits two or more base maps to be displayed simultaneously. The union of two base maps displays all the features of both maps while the intersection of two base maps only displays the features that are common to both base maps.

Dynamic segmentation involves the division or aggregation of network links into segments that are homogeneous for the specified set of link attributes. The segmentation is dynamic because it is created in response to the current attributes of the network. If the attributes are changed, then "dynamic segmentation" will create a new set of homogeneous segments.

Dynamic segmentation has been introduced into GIS software in order to integrate and analyze link-based transportation system attributes. For example in pavement management, the highway base map may be initially "dynamically segmented" by bituminous versus concrete pavement type so that each network segment only contains bituminous pavement or only concrete pavement. Specification of both pavement type and number of lanes as attributes for dynamic segmentation would result in network segments with the same number of lanes for each pavement type.

The surface modeling function creates a three-dimensional model of land forms or other surface features. The digital topographic map created by the surface modeling function is essential for highway design. The actual highway design may be done with separate design software that imports the topographic map from the GIS. The resulting highway alignment is then exported to the GIS for further analysis.

The raster display function permits photographs and other images to be incorporated in a GIS. Overlays of aerial photographs with highway base maps can be used to update the base maps by adding new links, new features such as bridges or intersections, and correcting errors in alignment. Overlays with zonal (polygon) base maps can be used to code land use and other attributes.

Routing capabilities based on minimum time paths have been available in travel demand software for many years. Integration of routing in GIS software directly reduces the need to create links to other models and software. Links to other models and software, such as transportation planning demand models and highway design software, however, will still be necessary if the full power of GIS-T is to be realized.

While the applications selection process shown in Figure 9 is sequential, in reality there are clear interactions among many of the components. The functionality of existing GIS-T software may constrain choice of the spatial database and the transportation modes. The available spatial databases will at least initially constrain the selection of the spatial and temporal dimensions of the possible applications. The availability of related databases will also initially impose similar constraints. In projecting future GIS-T applications, these constraints will be relaxed.

3.5.2 Current Applications and Case Studies

Examples of GIS-T applications are limited by the lack of digitized transportation networks and the lack of a full set of transportation system and related database attributes. In addition, the full range of functionality required of GIS-T software has not generally been available in GIS software products. For example, dynamic segmentation functionality has only recently been added. Nevertheless, a wide range of prototype and even fully operational GIS-T applications have been identified. Examples are available for each of the general functional areas—planning, management, and engineering. Description of several of the primary examples of GIS-T applications in terms of the six steps of the application selection process will reveal some of the limitations of current applications. These limitations then provide the starting point for identifying most probable future applications.

3.5.2.1 Planning Applications

The first planning application shown in Table 3 is actually a hybrid of several applications. An early application of GIS to urban system plan development in San Diego used GIS software only for network editing and display of traffic assignment results (*45*). Conventional travel demand software was

TABLE 3. Examples of existing GIS-T applications

Application Selection Step	PLANNING		MANAGEMENT		ENGINEERING	
	Urban System Plan Development	Hazardous Material Routing	Thematic Maps/Highway Inventory	Pavement Management	Highway ROW Acquis.	Urban Corridor Design
Mode	Highway/ Transit	Highway/ Transit	Highway/ Rail	Highway	Highway	Highway
Spatial Level	Urban Region	Multiple Regions	All	District	Corridor	Corridor
Temporal Level	Long Range	Short-Mid Range	Short-Mid Range	Mid-Range	Short Range	Short Range
Base Map Components	Node/ Link	Node/ Link	Node/ Link	Link	All[1]	All[1]
Transportation System Attributes						
-Physical	X	X	X	X	X	X
-Traffic	X		X	X		
-Travel	X					
-Operations				X		
-Financial	X			X		
Related System Attributes						
-Land Use	X				X	X
-Demographics	X	X				
-Environmental						X
-Utilities						X
-Hazardous Materials						
GIS-T Functionality						
-Basic editing, display, measurement	X	X	X	X	X	X
-Overlay[2]		X			X	X
-Dynamic Segmentation			X	X		
-Surface Modelling						X
-Raster display and analysis						X
-Routing	X	X				
-Other Models	X			X		X

[1]Node, link, and polygon (zone)
[2]Point, line, and polygon

used for network analysis and travel demand forecasting. In another case, detailed parcel level information on land use and zoning in a GIS database was used to generate trips under alternative development scenarios. In this case, conventional travel demand software was used for the remainder of the travel demand modeling process.

More recently, GIS software was used by the Saskatchewan Department of Highways and Transportation to build a regional highway network using their corporate highway database including traffic count data (*46*). Separate travel demand software was still used. Software that fully integrates GIS and travel demand modeling capabilities has been available for only a short time. Examples of applications are limited because few agencies have had the financial resources and staff time to invest in the newly available software.

The second planning application shown in Table 3 requires overlay and routing GIS-T functionalities. Hazardous material routing uses the overlay function to generate estimates of population within a specified distance of each link in the highway or rail network. Thus, population exposure can be included in an objective function for route selection.

Other planning examples of GIS-T applications include evacuation planning, planning for hazardous material release incidents, development of new traffic analysis zones from census tracts, and development of new urban highway networks. The attribute and GIS-T functionality requirements for these examples are similar to those shown in Table 3. The applications are relatively simple. Only limited information on transportation system attributes is required and only overlay, routing, and basic functionalities are required.

3.5.2.2 Planning Case Study

The North Central Texas Council of Governments (NCTCOG) has begun using GIS as part of their long range transportation planning program for the Dallas-Fort Worth urban area (*47*). GIS software is used for spatial analysis, data coding, and attribute display in support of their travel forecasting model.

NCTCOG maintains four primary data sets for input to their travel forecasting model: 1) the regional highway network (Major Thoroughfare Link file), 2) the regional transit network (transit line file), 3) zonal attributes (zonal activity file), and 4) traffic count data. Prior to implementation of the GIS, maintenance of these data sets required many separate computer programs and considerable manual effort. Now with the GIS the data sets can be easily edited and updated using the GIS graphical interface and the results verified using a variety of thematic maps. In addition, the data sets can be interrelated using the GIS overlay function.

NCTCOG develops many different versions of its regional network in order to test alternative development scenarios. Subarea highway networks are also required for more detailed analysis of travel in communities within the region. Considerable additional coding of centroid connectors is needed to represent the local street network adequately. The coding and graphical analysis of the highway networks is automated by using the GIS macro programming capability to create a menu system. The menu system can be used by staff with no prior experience with GIS. Highway network attributes such as geographic area type, zone number, and city code can now be automatically coded using the GIS overlay function.

Editing of the highway network using GIS is enhanced by the ability to overlay the highway network on different base maps that show the location of features such as rivers and railroads. Coding of new highway links can take these obstructions into account directly rather than requiring review of separate maps or aerial photos. Display of zones as a base map is also very useful in coding centroid connectors as well as other highway links.

The highway network can be represented more accurately using "shape points" that are permitted in the GIS network. Without GIS, the highway network links are displayed as straight lines between two nodes, although the coded-link distance may not correspond to the straight line distance. With the GIS, a series of intermediate nodes (shape points) can be added to more closely approximate the location of the physical highway link. Consequently with the shape points, the link distances can be calculated directly using the GIS.

NCTCOG also created a transit network coding menu system using GIS macros. The menu system automates the coding of transit lines and transit network attributes such as headways. As with the highway networks, transit network coding is enhanced through the use of various base map overlays.

The information in the zonal attributes database is now much more accessible through GIS-produced thematic maps. Maps showing zonal level population, population density, trip ends, and change over time can easily be generated. Zones can also easily be subdivided or aggregated as needed for more detailed or more macroscopic analyses.

Much of the traffic count database is updated annually. Because of the large volume of data, the updating process was automated. A GIS menu was created to enter the new traffic counts either interactively or in a batch mode. The GIS will be used to produce maps of average daily traffic and comparisons between traffic counts and travel forecast volumes.

The GIS will provide a wide variety of maps from the output of the travel demand models ranging from travel time contours to mobile source emissions. Forecasts of highway link volumes can be displayed using band widths or as numerical values and compared with link capacities. Using the GIS buffer and overlay functions, transportation system impact measures such as the population within a specified distance of high-volume links and the population within specified travel time ranges of a major generator can easily be created and displayed graphically.

The GIS provides the framework for data integration and data sharing both within NCTCOG and between NCTCOG and agencies at the state and local levels. With GIS demographic, economic, land use, and natural resource data from other NCTCOG departments can be added to the transportation data bases. Similarly, the transportation networks and the outputs of the travel demand models can be used by the other NCTCOG departments for land use planning, environmental impacts assessment, and other infrastructure planning studies. Because subregional transportation networks are easy to create with the GIS, data sharing with local governments is facilitated. With more direct access to the regional data bases, the local governments are more likely to become involved and upgrade their own data-collection efforts.

3.5.2.3 Management Applications

The most frequent GIS-T application involves the creation of thematic transportation system maps. Thematic maps are a simple, yet powerful tool to make transportation system attributes accessible to the user. As shown in Table 3, only the dynamic segmentation functionality is needed beyond basic display capabilities. For each attribute of interest, the only data required are the points on the transportation network where the attribute changes in value. Examples of thematic maps include traffic-count maps, functional-classification maps, and pavement-type maps. Any attribute included in a highway inventory file can be mapped if the location data are available. The visual display of inventory information provides for rapid identification of missing data and incorrectly coded data. Similar applications have been developed for the Union Pacific railroad (*48*).

The second management application shown in Table 3 is pavement management. In their simplest form, pavement management applications using GIS-T involve the creation of thematic maps of pavement condition and other relevant highway network attributes. The analyst then develops alternative improvement scenarios and uses the GIS-T to compute the costs of the improvements and display the resulting pavement-condition maps. In Wisconsin, a rule-based decision support system was developed and incorporated in the GIS-T to formalize the scenario development process (*49*).

The first GIS-T application in Wisconsin involved the use of the statewide highway spatial database to access photolog images stored on optical disk (*50*). The initial location for display of photolog images is obtained from the GIS-T display using the cursor. Then the photolog display software is used to identify the length of segment to display and the running speed over the segment. The application is now fully operational in all Wisconsin DOT district offices.

Other initial GIS-T management applications include bridge management, safety analysis, routing of oversize and overweight vehicles, project tracking for statewide transportation improvement plans, and traffic signal and sign inventory management.

3.5.2.4 Management Case Study

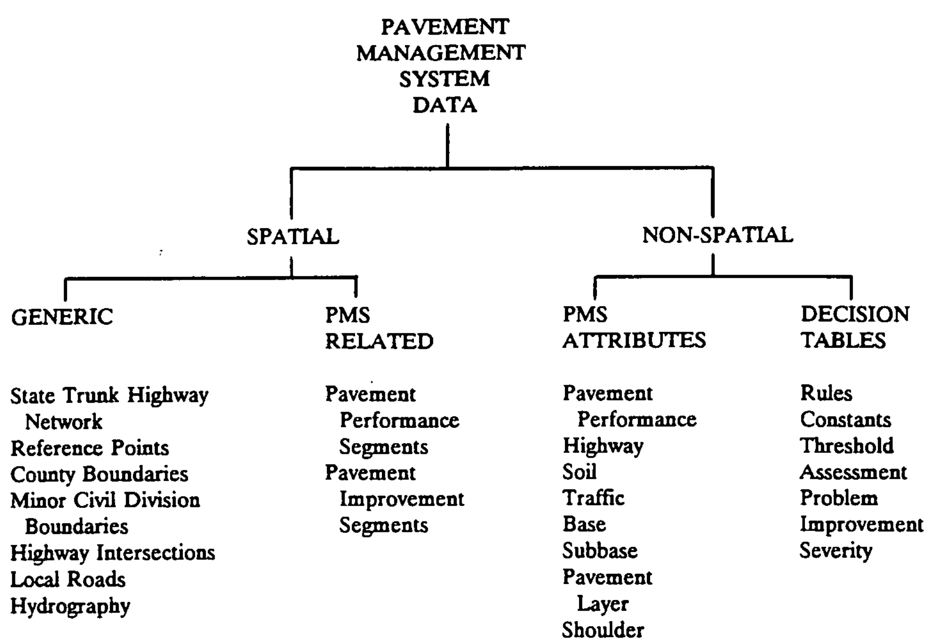
The Wisconsin DOT has developed a pavement management system (PMS) that integrates GIS technology with an expert system (*49*). The GIS provides the tools to develop the spatial database required for input to the expert system. The expert system codifies the knowledge and experience of pavement engineers in evaluating pavement condition and making recommendations for maintenance and improvements. The results from the expert system are then displayed graphically using thematic maps created by the GIS. These maps provide a visual check of the reasonableness of the expert system recommendations and greater understanding of the problem solution. The results may also be summarized in tables.

On the GIS side, the PMS required the production of a 1:100,000 scale geographic base map for the entire 12,000-mile state trunk highway system. A pilot base map for one of the eight State Highway Districts was completed initially in about 6 months. The remaining seven District base maps were completed a little over a year later. The PMS is currently limited to rural, non-Interstate pavements which cover about 8,000 miles statewide.

The data required by the PMS are drawn from a wide variety of both spatial and nonspatial databases as shown in Figure 11. The geographic base map is indexed by Reference Points (RP) and Log Miles (LM). Any WisDOT data that has spatial attributes (RP and/or LM) can be added to the geographic base map. For the PMS pavement performance, soil, traffic, base, shoulder, and other attributes are needed. The GIS provides the tool for extracting the required attributes from the nonspatial corporate databases.

The PMS expert system uses the relational database that is built into the GIS. The relational database contains tables that are queried by the expert system logic to 1) assess pavement performance, 2) identify pavement problems, and 3) recommend pavement improvements. Given the recommended pavement improvements, cost estimates are computed for each improvement segment. Both the assessment tables and the improvement tables can be easily modified by the system user to "fine tune" the PMS system to reflect local conditions and experience. The changes are made interactively using a menu system that requires no programming skills. In contrast, the problem identification tables form the heart of the expert system logic and thus cannot be modified by the user.

The PMS was designed to be used for operational evaluation and decision making in the WisDOT Districts. Because district-level staff are likely to have limited computer programming and UNIX system operation skills, the PMS is totally "menu driven." All of the PMS commands are selected using a mouse from a series of menus displayed on the computer workstation screen.



Source: Reference *(19)*.

Figure 11. Pavement management system spatial and nonspatial databases.

The PMS was validated initially in one district by comparing the PMS recommendations for improvements with the existing District Improvement Program recommendations. Agreement was obtained on about 80 percent of the 346 pavement improvement sections. In addition, the PMS was able to identify deficient sections of pavement that had not previously been included in the District's Improvement or Maintenance Programs.

The graphical display capabilities of the GIS were evaluated as well. The graphics interface provided an effective check on pavement data quality and completeness. Graphical display of the improvement projects made the location of the projects easy to identify and clearly revealed the scope of work required. Also the graphical displays of pavement problems and other pavement data made the reasons for the improvement recommendations more understandable to the user. Finally, the displays should be useful for internal field reviews as well as for public hearings.

In addition to providing recommendations for pavement improvements, the PMS provides a tool for more in-depth evaluation of problems based on data on base, subbase, and soils as well as pavement layers. To identify highway segments that are homogeneous across all of the relevant attributes (layers, base, subbase, and soils), a "dynamic segmentation" capability was built into the GIS. The attributes of each unique highway segment of interest can then be displayed graphically as a cross-section of the segment and also recorded in tabular form.

The prototype application of the PMS in a WisDOT District was successful. Consequently, the PMS has been extended to all eight districts. The expert system will need to be continually reviewed and upgraded to incorporate new pavement improvement strategies.

3.5.2.5 Engineering Applications

The first engineering application shown in Table 3 involves analysis of the impacts of highway right-of-way (ROW) acquisition. The Arizona DOT used GIS-T to support their acquisition of land for an urban freeway (*51*). Land use overlays based on zoning and current land use were developed. Trends in commercial land development were identified and compared with the availability of vacant commercial land within one quarter mile of the proposed freeway ROW. The analysis provided support for severance damages resulting from partial acquisition of property. This application requires the integration of transportation system attributes with data from other agencies, in this case municipal data. Because most municipalities have not digitized their land use data for the application, DOTs would have to generate the required data within the corridor of interest. The Arizona DOT found the savings in ROW acquisition costs to far outweigh the costs of the GIS-T application development.

The urban corridor-design application shown in Table 3 is similar to the highway ROW application in that the physical attributes of the highway are mapped onto the spatial databases of related systems. The primary differences are in the scope of the related systems and in the GIS-T functionality required. The impacts of ROW location decisions on land use are analyzed, but also detailed highway design decisions are integrated with environmental and utility impacts. GIS-T functionality is extended to include surface models for land forms and raster displays of aerial photographs. In addition, the GIS-T software is linked to highway design software so that the spatial analysis can be integrated into alignment decisions and vice versa.

Several management applications can also be applied in an engineering context. Wisconsin's photolog application is often used by engineers as part of design or operational analyses. Safety applications often lead directly to engineering analysis in order to improve hazardous locations. Highway strip maps may be used in both planning and engineering applications.

3.5.2.6 Engineering Case Study

An example of the generalized urban corridor-design application outlined in Table 3 is provided by the 5 billion dollar Central Artery/Tunnel (CA/T) project in Boston (*52*). GIS is an integral part of the CA/T program for automation of project management, engineering and construction. Because of the density and complexity of the existing urban infrastructure in downtown Boston, GIS technology was required to provide and manage the enormous amount of data needed for general highway alignment, determination of clearance and interference with existing buildings and other structures, utility relocation, and environmental impact studies. The first step in the use of GIS was to develop the GIS base maps, which could then be used for a wide range of applications from preliminary design to final design and construction.

Since the GIS base maps must support final design, a highly accurate and dense geodetic control network was required. GPS technology was used to establish the primary geodetic control network. Creation of base maps was divided into two efforts—one for surface features and one for subsurface features. The surface features were obtained at a large scale (1:240) using aerial color photography and digital photogrammetry. For design purposes, the initial surface feature base maps were reformatted to a smaller scale (1:480). Base maps for eight groups of surface features were obtained: 1) geodetic control, 2) hydraulic and hydrologic, 3) lot and buildings, 4) railroad, 5) roadway, 6) topographic, 7) surface utility, and 8) vegetation. The subsurface features were limited to existing utilities, but 27 different types of utilities were identified. A comprehensive utility inventory was completed resulting in digital base maps for four major groups of utilities: 1) gravity, 2) pressure, 3) electrical, and 4) signal.

The CA/T project used two separate GIS packages. The first GIS package was used for developing the databases. The GIS data bases were then transferred to the second GIS package for integration with Computer-Aided Design and Drafting (CADD). The integration of GIS and CADD permitted highway design engineers to create "electronic mylars" for preliminary design. All of the GIS base maps were available as background overlays for design purposes. The utility base maps were particularly useful for resolving highway and utility conflicts.

In addition to preliminary highway design files (in digital form), final highway design files will be produced for the project using a GIS/CADD system. Other GIS applications include 1) generation of soils profiles, 2) identification of ROW needs and environmental remediation sites, 3) traffic surveillance and control during construction, and 4) identification and mitigation of adverse construction impacts on the community. These applications are feasible because of the extensive database that was developed early in the project.

The GIS will also be needed during the construction phase to monitor progress and record the as-built facilities. The existing utilities database should be used to record the relocation and redesign of utilities. Finally, when the facility is in operation, the GIS can provide the basis for facility and maintenance management systems.

The CA/T project has demonstrated that highly complex GIS databases can be transferred from one GIS package to another. The successful transfer required precise definition of the standards and specifications for digital data transfer. The CA/T project has also demonstrated the need for GIS in support of preliminary and final design of a major urban highway design project. The GIS is expected to have continuing utility for the construction and postconstruction phases of the project.

3.5.3 Potential Future Applications

For the short term, the main focus of GIS-T applications is likely to be on the display and analysis of transportation system attributes. DOTs can use their existing corporate database enhanced as necessary to include location and only need to develop spatial transportation databases (highway base maps) at the appropriate scales. Most of these applications will be management-oriented since there is less need to integrate data from non-DOT sources. In contrast, planning and engineering applications typically require data from other agencies, including such data items as demographics, land uses, soils, utilities, and many others. These data are not readily available and the required spatial databases are often costly to develop independently.

In identifying future GIS-T applications, constraints on the integration of transportation system and related system attributes are assumed to be minimized by the availability of common spatial databases. Also, real-time data acquisition for transportation system attributes is assumed to be feasible. The resulting *prototypical* future GIS-T applications are shown in Table 4. Just as with existing applications, the prototypical applications are described in terms of the six-step selection process.

3.5.3.1 Future Planning Applications

The *enhanced urban system plan development* application described in Table 4 involves enhancement of all technical components from the spatial database to GIS-T functionality. The spatial database is expanded to include zones as polygon overlays rather than as centroids (points). Operations data for intersections are added as transportation system attributes. Thus the impact of traffic signal timing can be modeled more effectively. A broad set of related system attributes including land use, demographic, and environmental attributes are modeled as polygon overlays. Finally, the full range of GIS-T functionality is included with the exception of surface modeling. The routing functionality is enhanced to include a full range of travel demand modeling capabilities. Links are made to air quality and noise models that are enhanced to make use of the broader range of data available directly from the GIS-T application.

A similar application for statewide highway plan development would use the same range of technical components as the enhanced urban system application. Environmental attributes such as soil, wetlands, and vegetation would be more important than in urban areas. Surface modeling might be a useful addition to GIS-T functionality. Links to regional economic models may be relevant.

At the urban area level, a wide variety of future applications are possible to support the comprehensive planning process. GIS can be used to inventory vacant land, to analyze development patterns, and to help forecast land use. GIS should also be incorporated in air quality, noise, and stormwater runoff models. Other transportation applications include parking inventory and demand models and transit accessibility and sketch planning models.

3.5.3.2 Future Management Applications

Because of the ease of working within the corporate data environment and the links between management and all other DOT functional areas, management applications are likely to dominate future GIS-T use. 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.

As shown in Table 4, 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 could be displayed for evaluation and implementation. Arterial street system operations could be evaluated in real time and included in the decision-making process. Enhanced GIS-T functionality would be required for routing and for links to other models such as traffic signal timing optimization models.

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-T will provide the data retrieval, integration, and display capability for evaluation of current transportation system operation including freeway ramp metering and traffic signal control.

The air quality management application shown in Table 4 is used to illustrate the extension of management applications to include related system attributes as well as a broader range of GIS-T functionality. Air quality impacts need to be quantified in terms of the land use and demographics of the affected zones. Environmental attributes such as prevailing winds must be incorporated directly into many air quality models. In terms of GIS-T functionality, the overlay function is needed to map plumes and pollutant loads onto population and land use databases. Surface modeling is needed because of the impact of terrain on wind flows and plume formation. Raster display and analysis may be useful in conjunction with plume and other data.

TABLE 4. Examples of future GIS-T applications

Application Selection Step	PLANNING	MANAGEMENT		ENGR
	Enhanced Urban System Plan Development	Freeway Incident Detection and Management (IVHS)[1]	Air Quality Management	Integration of Corridor Planning and Design
Mode	Highway/Transit	Highway	Highway	Highway
Spatial Level	Urban Region	Urban Region	Urban Region	Corridor
Temporal Level	Long Range	Short Range	Short Range	Short Range
Base Map Components	All[2]	Node/Link	All[2]	All[2]
Trans. System Attributes				
-Physical	X	X	X	X
-Traffic	X	X	X	X
-Travel	X	X	X	X
-Operations	X	X	X	X
-Financial	X			X
Related System Attributes				
-Land Use	X		X	X
-Demographics	X		X	X
-Enviromental	X		X	X
-Utilities				X
-Hazardous Materials				X
GIS-T Functionality				
-Basic editing, display, measurement	X	X	X	X
-Overlay[3]	X		X	X
-Dynamic segmentation	X	X	X	X
-Surface Modelling			X	X
-Raster display and analysis	X		X	X
-Routing	X	X	X	X
-Other Models	X	X	X	X

[1]Intelligent Vehicle Highway System
[2]Node, link, and polygon (zone)
[3]Point, line, and polygon

Other applications that will require data on related system attributes include right of way (ROW), maintenance, environmental impacts, and construction management. For example, ROW and maintenance management will require data on vegetation as well as on utilities such as gas, power, and water. Monitoring environmental impacts of noise and air pollution will require data on surrounding land use and population and possibly topography. Construction management will potentially require an even broader range of data including surrounding land use, demographics, and environmental features as well as utilities.

The new Federal transportation legislation (ISTEA) mandates the development of six management systems by state DOTs: 1) highway pavement, 2) bridge, 3) highway safety, 4) traffic congestion, 5) public transportation, and 6) intermodal transportation facilities. As documented in the previous section, the Wisconsin DOT already has an operational GIS-based pavement management system. Other states should soon be following Wisconsin's lead with similar GIS-based systems.

Once a GIS-based pavement management system (PMS) is in place, the system can easily be extended to bridge management. Bridges can be viewed as simply a more complex segment of pavement with additional attributes. Many of the attributes needed for bridge management can be obtained directly from the PMS. The additional data needed for full-scale bridge management should in turn enhance the pavement management decision-making process because bridge repair and reconstruction can be a major component of the cost of pavement improvement projects.

GIS-based highway safety management systems are also a logical extension of PMS. The highway network base map and associated attributes, such as, traffic volumes, pavement condition, and roadway geometrics, needed for pavement management are highly relevant for safety management. The Wisconsin DOT has already begun developing a safety management GIS using its PMS GIS as the starting point (*53*). The GIS will provide easy access to the wide range of data in the corporate database that may be relevant for safety analyses.

Traffic congestion management systems are an integral part of the IVHS program discussed earlier. Initially, GIS-based congestion management systems can start with the highway base maps and attribute databases used for long-range transportation planning in urban areas. These regional base maps will provide the framework for identifying and monitoring congestion from a regional perspective. Additional more detailed base maps and databases will be needed to manage congestion in real time in critical corridors.

Management applications for public transit systems will also rely heavily on corporate databases. Facilities such as bus shelters, signs, park-and-ride lots, and rail system routes and stations can be managed more effectively with GIS-T. For bus systems with automatic vehicle location systems, GIS-T can display vehicle location in real time. The displays can support performance monitoring, dispatching, and customer information service functions.

Finally, GIS-based intermodal transportation facilities management systems are a logical extension of public transportation management systems. An intermodal transfer terminal is just a more complicated, specialized node that is part of a composite network of two or more modes. GIS provides the tools for integrating the base maps and attribute databases for the relevant modes. A more detailed base map and database will be needed for management of the flow of persons and goods within a terminal, but links to the macro-scale GIS can still be maintained.

The six federally mandated management systems will be the responsibility of different divisions or groups within a DOT. The systems will produce the detailed information needed by managers. For overall corporate management purposes, the detailed information from the individual management systems must be summarized and integrated where appropriate. A GIS-based corporate level or executive information system (EIS) will be able to extract the relevant information from the individual management systems, add other corporate data and display the results at the appropriate scale. The ultimate EIS would permit top managers to start with statewide macro-scale base maps and summary data and move seamlessly to more detailed base maps as needed to interpret and understand the macro-scale summaries. The top manager could then provide direction for additional analyses and documentation needed to support strategic planning and management decisions.

3.5.3.3 Future Engineering Applications

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. As shown in Table 4, this integration requires the full range of transportation system attributes as well as related system attributes. The full range of GIS-T functionality can also potentially be used.

An example of the integration of highway corridor planning and design is provided by the small town by-pass route selection problem. The process would start with the identification of preliminary alternative routes using nodes and links based on digital terrain maps, soils, wetlands, property boundaries, and other natural and man-made features. All data are in digital base map form and thus can be viewed simultaneously in various combinations through the GIS overlay function. Alternative corridors are then defined using the GIS buffer function. Next, highway design software is run to select the optimal highway alignment within each corridor. In identifying the optimal alignment, a wide range of performance measures are considered because trial alignments with specific right-of-way requirements are easy to overlay on digital base maps. The overlays can give measures of wetlands impacts, property costs, impacts such as home and business displacements, and construction costs related to soils and cut-and-fill.

Engineering applications can also use many of the corporate database display and analysis tools developed for management applications. Joint 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 could be evaluated more easily for both local and through traffic. Similarly, utility system overlays and surrounding land use could be integrated to evaluate the impacts of utility cut-offs.

Traffic control system design is an engineering function that could benefit from GIS-T. Graphical display of system demands and performance will help identify limitations of alternative designs and areas for improvement. These designs are a key element of congestion management systems.

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

4.1 CONCLUSIONS

The application of GIS to transportation problems is still relatively new. The entire community has only a few years of experience in GIS-T design and implementation. Within these years, several deficiencies in off-the-shelf GIS vendor products have surfaced for transportation applications, and vendors have responded positively by adapting their products for this new market. However, in adapting GIS to their organizations in ways that will realize its full potential, the transportation user community has had relatively little success, with a few noteworthy exceptions and a number of other efforts that show considerable promise.

This study has characterized both *technological* and *institutional* contexts for successful GIS-T design and implementation planning. The following are principal components of the technological context:

1. *The moving target problem.* Information technology, in general, is changing rapidly and will continue to do so. (As if the problem in isolation were not difficult enough, it is compounded by the fact that at the same time the requirements for which the new technology is needed are changing at least as rapidly.)
2. *The multiple technology problem.* GIS is one of a number of technologies that must be planned for in concert.
3. *The data integration problem.* Because of the costs of acquiring and maintaining spatial data, GIS-T data must be shared and integrated across as many applications as possible. On the other hand, GIS technology offers a means of integrating data of many other kinds across a wide variety of applications.

The following are principal problems that shape the institutional context:

1. Determining the most critical initial applications.
2. Sharing development and maintenance costs across applications.
3. Gaining and retaining support of high-level management.
4. Coordinating 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.

4.1.1 Significance of GIS-T

The major significance of GIS-T for DOTs is in its potential to serve as the long-sought transportation data and systems integrator—to serve as a basis for the organization of information and the design of information systems. Given that nearly all DOT data (with perhaps the exception of some personnel and accounting data) are, or can be, referenced to geographic location, *location* becomes much more than just one more data element to manage, and GIS concepts become a framework for the restructuring of information systems and the design of new ones.

4.1.2 Potential Impact

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 has become 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.

Not only can GIS-T serve the all-important integrative role, but it can also provide the analytical and data management tools needed for development and use of recently mandated systems such as those required by ISTEA (traffic monitoring systems and management systems for pavement, bridge, safety, congestion, public transportation facilities and equipment, and intermodal facilities and equipment). All of these systems require geographically referenced data, as do those mandated by the Hazardous Waste Act and the Clean Air Act and those that will be required to support intelligent vehicle highway systems (IVHSs). In fact, the potential range of GIS-T applications spans all of the primary functional areas of transportation agencies, from planning, design, and construction through operations and maintenance.

The potential impact of GIS is more than agency wide. The problems of today require the interaction of agencies at all levels of government, with each other and with the private sector. More often than not, this interaction involves the exchange and sharing of data—in many cases, *spatial* data. This is because the broad problems that are driving the interaction typically involve environmental and economic development issues; and their solutions will require the integration and analysis of geographically referenced data of many kinds from many sources.

4.1.3 Recommendations

A brief description of recommendations follows:

1. DOTs should institute an agency-wide strategic planning process for information systems and/or put high priority on any such process that might already be in place.

2. A *top-down*, then *bottom-up* approach should be adopted by DOTs for GIS-T planning and implementation. Database design and data acquisition and maintenance policies and procedures should be undertaken as an organization-wide, top-down activity. GIS-T applications should then be undertaken on the basis of decentralized, bottom-up initiative.

3. The DOT strategies for adoption and exploitation of information technology should be *needs driven* rather than *technology driven*. New technology should be adopted and used because it meets specific, well-identified needs, not for its own sake and not because it is likely to serve some good, but ill-defined purpose.

4. Planning for GIS-T should be done by DOTs in conjunction with planning for other technologies such as networking, engineering workstations, distributed and cooperative computing, client-server network architectures, computer-based graphics, computer-aided design, and new database system capabilities. These are complementary technologies and should be addressed accordingly.

5. Data should be viewed as a corporate resource rather than as "owned" by a particular application or unit of a DOT. Further research may be necessary to help facilitate adoption of this view (see Section 4.2).

6. The DOT GIS-T and information systems planning process should address a range of time horizons, say 10 years, 5 years, and 1 year. Longer-term plans lay a basis for and initiate preparation for future technological developments. Shorter-term plans assure relevance to current conditions and responsiveness to unpredicted constraints or opportunities.

7. DOT GIS-T plans should address the full range of application scales. If spatial databases at more than one scale need to be developed (there will probably be at least three that are needed), the application scales should be prioritized. Methods should be developed for spreading the costs of spatial database development and maintenance across all applications.

8. DOT GIS-T plans should address staffing and training issues. A GIS-T implementation team and core staff should be identified. Methods for training of the core staff and of users should be explicitly addressed.

9. Coordination with other state agencies should be an integral part of the DOT GIS-T planning process. DOTs are often in a position to play a leadership role in this regard.

10. Long-term DOT GIS-T and information systems plans should put a *conceptual* server-net architecture in place as an organizing principle even before physical realization is feasible. This will facilitate incremental physical implementation as the requisite standards, networking technology, and appropriate hardware and software products become available.

11. The concept of location as a data integrator should likewise be initiated as a conceptual organizing principle. An immediate operational impact of this approach will be on how attribute databases are henceforth schematized.

The recommended GIS-T server-net architecture divides up data-processing labor among different kinds of servers of which the following 15 kinds are illustrative: 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) data capture and transformation servers, 11) cartographic data servers, 12) new technology servers, 13) general purpose servers, 14) history servers, and 15) specialized application servers.

See Chapter 3, Section 3.2.2 for details. This particular division of labor among server kinds should be considered as an example and a guideline. In practice, the appropriate division of labor will be dictated by demand for different kinds of services, by the required tightness of coupling among processors responsible for different services, and by network traffic flow.

4.1.4 Impediments

The general lack of awareness of the profound potential of GIS-T (even on the part of vendors) is understandable just because that potential is so profound. It is not often that a technology and a set of concepts holds so much promise. It may be easy to view GIS solely as a mapmaker's tool, similarly to the way some view CAD solely as a design engineer's tool. This being the case, GIS may often be regarded as tangential to an agency's overall information management mission. Such attitudes, if they cannot be overcome, will be fatal for full realization of GIS-T potential.

The required technology and standards to fully implement the recommended server net are not yet in place, but they will be over the next few years. Starting with a conceptual server-net architecture (that is then realized in incremental physical steps) is responsive to this situation, as is the recommendation of using location as an integrative concept for all future database schematizing (even before the GIS and other technologies that can fully exploit such schematizing are completely in place).

There are four specific deficiencies in current GIS products that the research has identified as impeding their fitting well into the distributed computing environments of the future and into the information system strategies recommended for DOTs. The vendor survey does not bode well for vendors giving high priority to removal of these deficiencies (see Appendix C.3, Section 15).

Until these deficiencies are removed, they constitute serious impediments to realization of these recommendations by DOTs—but it is the vendors, not DOTs, who must create the improved products. However, DOTs and DOT organizations can at least put pressure on them to recognize the need and undertake the improvements. The four deficiencies are summarized as follows:

1. Lack of user-controlled system decomposability into modules that can be distributed across separate server platforms in a client-server network. (See Chapter 2, Section 2.4.2.2, Item 3.)

2. Lack of rapid prototyping and incremental prototyping capabilities. (See Chapter 2, Section 2.4.2.2, Item 7.)

3. Lack of connection with CASE environments in a way that enables easy use of the GIS product defined and controlled concept of location as an integrating concept in the database scheme as specified with those CASE environments. (One way of responding to this deficiency would be extension of GIS products to include CASE capabilities.) (See Chapter 2, Section 2.4.2.2, Item 7.)

4) Lack of CASE capabilities for specifying overlay programs for spatial data types between which overlay operations are not provided as a built-in part of the GIS products. (See Chapter 3, Section 3.2.2.6.)

4.2 Suggested Research

There are a number of open questions yet to be addressed concerning GIS-T and its successful implementation within transportation agencies, questions that deal with technology, data, and institutions. In addition, there is further need for studies and resulting materials that will objectively present the case for GIS-T and that will help transportation managers make intelligent decisions about it.

Eight possible research undertakings are presented. This range of research will require both theoretical and empirical methods. It includes both technology assessment and technology transfer.

A conceptual framework for GIS-T research appears in Table 5. The suggested research undertakings are indicated by numbers that correspond to their subsections within Section 4.2 of this report. This current research project is indicated by an asterisk. Bold type indicates heavy emphasis. Normal type indicates light emphasis. Absence of a character indicates lack of a relation. The research method was primarily that of technology assessment, and the research results address primarily technology with some considerations for data and institutions. The eight suggested research efforts are 1) data and functional models, 2) detailed case studies, 3) experiments with a GIS-T server-net simulation prototype, 4) prototype applications, 5) data collection, 6) database maintenance, 7) data administration, and 8) GIS-T and IVHS.

As another example of interpretation of Table 5, the first suggested research effort, on data and functional models, would be theoretical in that new models would be derived, but empirical methods would also be used to examine existing data and functional requirements. Impacts of that research would be equally balanced between the data area and technology area (for the functional model).

4.2.1 Data and Functional Models

Although dynamic segmentation and network overlay are generally realized as critical for GIS-T, the concepts are so new that there is confusion concerning their distinction and their meanings (*54*). There is lack of consistency in terminology and differences in approaches to implementation. In some cases, dynamic segmentation and network overlay are being implemented as extensions to existing GIS network data models.

There is a need for development of consistent data and functional models for GIS-T that integrate networks, coordinates, and distance referencing. Until they are available, the effectiveness of GIS-T will be limited. Dynamic segmentation and network overlay were identified as necessary when transportation professionals first began applying GIS to their problems. As GIS-T grows and begins to be used in response to ISTEA management system requirements and other mandates such as the Clean Air Act, the need for consistent, central data and functional models will become even greater. Moreover, as GIS-T becomes more closely linked to routing analysis and flow analysis, a need may very well arise for development of additional data models and functional models in these areas. Research in this area should consider three- and four-dimensional aspects of the problem.

4.2.2 Detailed Case Studies

Going beyond the data-collection aspects of the present research, there is need for detailed case studies of successful GIS-T implementation efforts. Each case should be presented in sufficient detail and in a form that planners and managers can draw reliable comparisons to their own circumstances, seeing both the similarities and the differences. Documentation of completed feasibility studies should be included to help DOTs select initial applications and justify their initial investments in GIS-T. Critical factors, such as methods for spatial database development and maintenance, and choice of reference system, should be identified. In addition to doc-

TABLE 5. Areas and methods for suggested research

Methods	Areas		
	Technology	Data	Institutions
Theoretical	**1**	**1** 6	7
Empirical	1 2 **3**	1 2 **3 6**	**2 7**
Technology Assessment	* **3 5** 8	* 5 **8**	* **8**
Technology Transfer	2 3 **4** 8	2 4 8	2 8

Notes: 1) Asterisk (*) indicates current project (NCHRP 20-27).
2) Bold type indicates heavy emphasis.

umentation, products of the case studies might include demonstration software and videotapes.

Candidates for case studies should include those agencies that have implemented mandated applications such as pavement and bridge management systems. The GIS innovation projects funded by FHWA are also promising candidates. Finally, it may be desirable to include a range of implementation strategies within the case studies. The *top-down then bottom-up* strategy recommended herein should be included but, if at all possible, *more centralized* and *more decentralized* strategies should also be included, thus enabling planners and managers to see the differences in terms of actual cases.

4.2.3 Experiments with a GIS-T Server-Net Simulation Prototype

The recommended server-net model should be studied, evaluated, and further articulated with a simulation prototype. Although migration towards server nets is technologically inevitable, such prototyping of a GIS-T server net will, among other things, demonstrate their effectiveness, expedite the process, and initiate the accumulation of empirical data of use in determining optimum computer network capacity, preferred computer network topology, feasible task decomposition scale, practicable division of labor among the network nodes, and appropriate data models for spatial and other kinds of databases distributed across a server net.

Although some early work on the prototype (e.g., development of components, their initial testing, and preliminary logical design of the model) might best be done in a laboratory, the final logical design and the actual physical design (and implementation) should be done within the technical, physical, and institutional constraints of a major transportation agency.

The best candidate agencies are those that have significant GIS-T experience and that are already moving towards the server-net model. The prototype should be complementary to the candidate agency's plan and can serve as an accelerator for some aspects of that plan. Nonetheless, there must be incentive for the candidate agency to participate. Such incentive could include providing prototype hardware and software at the conclusion of the project, enabling agency personnel to gain in depth experience with a new way of doing things, and funding staff positions for agency personnel who participate.

4.2.4 Prototype Applications

The development of demonstration and prototype applications will promote GIS-T and provide generic products that can be tailored to individual agency needs. Initial application design should be at the generic, conceptual level. In the next phase, multiple logical designs might be appropriate (e.g., object-based and geo-relational). It would be most beneficial to implement the prototypes with the GIS software of more than one vendor (certainly all those who provide the required functionality and who will support the prototype implementations, especially those aspects that have to do with making the prototypes fully compliant with emerging open-systems standards). Possible applications for prototyping include safety, congestion management, air quality management, and IVHS (see Section 4.2.8).

A safety application prototype might include linkages to data on accidents (including scanned photographs and police sketches), highway geometrics (including CAD files or scanned design drawings), site conditions (including photolog data, pavement and signage data, and records on weather), traffic volumes, and accident rate models.

An air quality management application should test the bounds of current technology and will require integration of data from external sources and linkages among models that have been independently developed (e.g., air quality and urban planning models.)

All application prototyping will require use of real DOT data and access to the expertise of experienced DOT personnel. Related potential research includes technology transfer between agencies. Procedures, standards, and practices that expedite and simplify transfer of operational applications from one state to another should be studied and developed. For example, the experience of California DOT (CALTRANS) in porting Wisconsin DOT's pavement management system will unquestionably be of interest to many others besides just California and Wisconsin.

It will be desirable to target one or two applications for executive information systems (EISs) based on GIS-Ts. Development of such prototypes will provide not only design guidelines but also demonstrations persuasive to top managers, legislators, and the public.

4.2.5 Data Collection

The range of technologies for the collection of spatial data and spatially referenced data is rapidly expanding, as is the demand for a wide variety of data to support decision making (*55*). These technologies include GPS, video, digital photography, softcopy photogrammetry, high-resolution satellite imagery, high-resolution document and image scanners, and real-time systems and sensors.

The list of such real-time systems and sensors is long: weather radar, vehicle ID scanners, traffic counters, pavement temperature sensors, weigh-in-motion (WIM) sensors, and vehicle navigation systems that are part of intelligent vehicle highway systems (IVHSs). IVHSs will not only greatly increase the demand for spatial data and spatially-referenced data but will also be a major source of data usable for many other purposes. They will undoubtedly spur the development of even more new technologies for data collection. All of these technologies will of course impact the design and implementation of GIS-Ts.

Potential research includes projection of the various technologies, assessment of their current state as well as of their prospects, articulation of their interaction and possible integration, and projection of demands from and possible uses by transportation agencies for the data that the technologies will make available. Within the context of GIS-T development, the research should lay out and compare alternative strategies for adoption, integration, and exploitation of these imminent new data collection technologies.

4.2.6 Database Maintenance

Many DOTs are completing development of their initial spatial databases. These databases must now be maintained (e.g., updated with changes in alignment, topology, and reference systems). Spatial database maintenance will be a new experience for transportation agencies. There are a number of associated research questions. For example:

1. What will be the impact of new data-collection technologies like GPS on spatial database maintenance? What are the appropriate techniques for merging newly acquired two-dimensional or three-dimensional GPS data with existing smaller-scale, linearly referenced spatial data? (Section C.1.6.3 contains more detail.)
2. What are the appropriate linkages (topologic and coordinate-based) among the different levels of abstraction (scales) of spatial data required for different applications? To what extent and how can spatial database updates (based on, for example, CAD highway design files) be automated through the two or three (or more) GIS-T spatial database scales?
3. What data other than alignment geometrics can be captured from CAD? What linkages can be developed between CAD and GIS-T data models?
4. How can remotely sensed data be used most effectively, not only for highway network updates but also as land use and other environmental data required for current and future analyses (*56*)?
5. During updates, what are the most effective means for ensuring referential integrity among coordinate-based, topologic, and linear referencing components of spatial databases and of linear references in attribute databases?
6. How can the overall quality of spatial databases be assured over time? What are the appropriate methods for tracking lineage and for associating lineage information with spatial databases to facilitate its use? What are the appropriate methods for testing the quality of on-line spatial databases over time?

4.2.7 Data Administration

The cartographic operations, large-scale (project) mapping operations, CAD operations, and GIS operations of many agencies are often independent or, at best, very loosely connected (*57*). Potential research includes investigation and description of current relationships among these functions within transportation agencies and development of general alternative scenarios for their closer coupling, particularly from the standpoint of the agencies' information products and needs. There is potential for elimination of redundant effort and for more efficient and effective information management (in many respects, but certainly with regard to further development and maintenance of GIS-T spatial databases.)

Research is needed to develop the view of data as a corporate resource, from explication of the underlying general concepts to articulation of generally applicable data models that implement the view. Institutional aspects of this research should include identification of factors in many organizations that lead to the perception of data as something that is and should be "owned" by a particular unit or group of people, and identification by contrast of the factors in other organizations that have led to understanding and acceptance of the corporate-resource view. Possible approaches, when the latter view is adopted, to implementation of both data collection and data maintenance should be studied and evaluated. The research should suggest alternative institutional arrangements that might lead to productive and efficient information management environments.

Related research should address policy and legal aspects of data sharing among agencies. Arrangements that have succeeded in practice need to be documented. The roles of data custodianship and data brokering need to be explicated. And the data-sharing analogues of the liability-law concepts of "truth in labeling" and "fitness for use" need to be clarified.

4.2.8 GIS-T and IVHS

In the next decade the effective integration of three rapidly developing technologies—GIS, IVHS, and GPS—promises major economic and social benefits. Among the benefits will be increased efficiency in the use of highway capacity, enabling significant increase in transportation volume without construction of new highways; an increase in highway safety; and an increase in the coverage, resolution, reliability, and convenience of in-vehicle, real-time, electronic navigation systems for automobiles, trucks, and buses.

Currently, the appropriate linkages (both technical and institutional) among these technologies are not well understood (*58*). Thus, there is a need for research that addresses the following:

1. Analysis and evaluation of the current state of each of the three so-far independently developed technologies, and projection of their future directions and potentials.
2. Development of detailed suggestions for how each needs to be extended and adapted to enable effective integration, and determination of the difficulty and feasibility of such extension and adaptation.
3. Development of a model of such integration as would be required for its operation in different international areas, initially North America, Europe, and the Far East.
4. Construction of a simulation prototype that demonstrates, and enables testing of, the model.
5. Specification of the model's spatial data requirements.
6. Investigation of and detailed suggestions for the spatial data standardization that will be required for IVHSs that utilize GPS navigational aids.
7. Study and clarification of the economic and political issues involved in creating and maintaining the GIS databases required for cross-national IVHS systems that use GPS navigational aids (for example, the issue of determining appropriate division of labor and responsibility between the public and private sectors).

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APPENDIXES A, B, D, AND E

UNPUBLISHED MATERIAL

Appendixes A, B, D, and E contained in the report as submitted by the research agency are not published herein. Their titles are listed here for the convenience of those interested in the subject area. Qualified researchers may obtain loan copies of the agency report by writing to the Transportation Research Board, Business Office, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

The available appendixes are titled as follows:

APPENDIX A	Example State Agency Questionnaire
APPENDIX B	Vendor Letter
APPENDIX D	Summary of Expert Panel Session
APPENDIX E	GIS-T Management Guide

Appendixes C, F, and G follow this section.

APPENDIX C

STATE OF THE ART: COMMERCIAL SOFTWARE PRODUCTS†

C.3 Commercial Software Products

We surveyed vendors of GIS software to determine software trends and plans, and to determine adequacy of commercially available products for use of GIS technology by DOTs in the ways we recommend. Although we are confident that we have correctly characterized technology trends in general and GIS technology potential in particular, there remains the question of whether GIS product trends are such as to support relatively nearterm realization of this potential. In other words, to what extent can use by a DOT of GIS technology in the ways we recommend be primarily exploitation of off-the-shelf products and to what extent must it, at least in the near term, involve significant software adaptation and extension on the part of the DOT? Then, of course, there are derivative questions such as "For the adaptation and extension required, what kind of development aids do the vendors make available and how hard will they be to use?"

For the survey, we used the questionnaire in the letter attached to this report as Appendix B. We sent the letter to the chief executive or the senior GIS executive of all organizations that describe themselves as vendors of GIS software in the 1991-92 *International GIS Sourcebook* (available from *GIS World*). The response was good. Although many of the respondents sent us mainly packages of relatively unreliable and unusable glossy marketing brochures, all of the companies that we knew ahead of time to be major players in the GIS software arena took the questionnaire seriously and took the time to answer our questions directly and specifically.

There were a number of surprises. There are clearly more major players than we knew of ahead of time. The field is not as dominated as might sometimes appear by the two or three most visible companies. And many of the companies are in agreement with our emphasis on client-server networks, on open systems, and on the integrative potential of GIS,. two of them so completely that our first reaction was that in responding they were hypocritically just feeding us what they had figured out we wanted to hear. However, we had deliberately phrased our questions to avoid biasing the answers, and those companies could not have known our recommendations when they generated their responses because those recommendations had not yet been published. Further investigation of the companies and their histories convinced us that their responses were genuine.

We cannot in this report name names or in any way make comments that imply endorsement of particular products. Therefore, the operational importance of the previous paragraph is that, as they investigate commercially available GIS products (for example, with requests for information and requests for proposal), DOTs should cast their net beyond the few well known companies and, if they characterize their plans and requirements in line with the recommendations of this report, they can expect the replies (both from the well known companies and from the little known companies) to be quite responsive.

In what follows, we will discuss responses question by question, beginning in each case with a brief explanation of why the question was used. In general these explanations could not be included in the questionnaire because they would have biased the responses.

C.3.1 Definition of GIS

Question 1: *How do you define "GIS"?*

The point of this question was to determine whether the industry is converging on any kind of general agreement about the many different functions that can and should be included in a complete GIS system, or whether there are still companies that characterize systems specialized for particular applications (for example, facilities management or automated cartography) as GISs.

The answer : Yes, there still are companies that are calling their products GISs even though very incomplete with respect to the full spectrum of potential GIS functionality. The term "GIS" has clearly not achieved any kind of standard usage, and the response to vendor characterization of a product as a GIS must continue to be *caveat emptor*.

To the extent that there is any progress toward definition consensus, the definition used by the National Science Foundation (in describing available support for GIS research and development) has obviously been influential. Many companies are using a variant of the NSF definition: "A GIS is a computerized database management system for capture, storage, retrieval, analysis, and display of locationally-defined data."

C.3.2. Implementation Language and User Access to Source Code

Question 2: *In what languages are your GIS products implemented? What parts of the source code do you make available to customers?*

The points of these questions were (1) to determine whether product implementation languages are the modern, hardware independent languages conducive to adaptation of a product to an open system environment and (2) to determine the degree to which resources are made available to a customer for product customization (for example, that required for adaptation to an open system environment).

By far the most frequent answer to the first question was the language C, which bodes well for open system developments because C is now available on almost all hardware platforms, although it is not rigidly standardized across them all. The second most frequent answer was the language FORTRAN, which is actually more standardized than C but is a much less capable and structured system implementation language. Only one company answered that any part of its implementation is in a hardware specific, assembly-level language (370 assembler).

Surprisingly, only two companies reported implementation with object-oriented programming languages for their implementation, something that would significantly contribute to their own internal development productivity as well as to easier user customization. One company will henceforth be using C++ for all further developments beyond their existing implementation in C, and one company has implemented ground up in a variant of Smalltalk. There were claims, however, that several of the capabilities (for example, encapsulation and class inheritance) of object-oriented programming languages were in use for implementation even though their use was not the result of the language used.

There was a wide range of responses about prospects for customization and about customer access to source code. The most typical response was that no access was provided, but that the company would be happy to customize for a price. One company does not provide access to source code but makes available extensive descriptions of the many subroutines that constitute its system, thus enabling users to develop system extensions with programs that call those subroutines. Another company will provide information about the internal structure of its system, especially data structure descriptions, specific to and as required for a well-defined customer specification of a proposed extension. Another company will make available source code, but only that which has stabilized to the point that the company itself is making no further changes in it!

C.3.3 Available GIS (Including Specific GIS-T) Functions

Question 3: *For your GIS products, please provide us with technical descriptions, including if possible a full detailing of their functionality. What plans do you have for increasing that functionality? Are your current products designed to include functionality of specific applicability to transportation? In particular, do the products include network description and network overlay capabilities, linear referencing capabilities, dynamic segmentation capabilities, and transportation analysis and modelling capabilities? If your answer for any one of these capabilities is "yes", please tell us what you mean by the capability.*

The points of these questions were to discover the range of GIS functions offered, in particular, functions known to be required for transportation applications.

Other parts of this report discuss GIS and GIS-T functionality in detail and from several different points of view. Nothing new was discovered from the vendors' responses. What was clear from the responses, however, were two facts of major importance for DOT evaluation of vendor products:

(1) Different GIS systems vary widely with respect to the functions of which they are capable. There is a common core, but it is surprisingly small. Many of the systems, including all the better known ones, include a relatively full suite of functions, but many others contain only a small part of that full suite. In no case will it ever suffice just to acquire a "GIS" without specifying what it is that it must be able to do.

Only a few vendors offer as part of their GIS any significant number of transportation analysis and modelling capabilities. Several more claim that they will be including more such capabilities in future releases.

(2) There is a comparable wide variation among what vendors mean when they say that their products contain certain functions. This is especially noteworthy with respect to *linear referencing* and *dynamic segmentation*. Thus, in no case will it ever suffice just to name these functions in a GIS acquisition without including a technical definition -- and then it will be well to require an explicit demonstration that that definition is satisfied.

C.3.4 Operating System and Hardware Platform Environments

Question 4: *Within what operating systems and on what hardware platforms do your GIS products run? What plans do you have for extending the products to additional operating systems and/or hardware platforms?*

The points of these questions are obvious. Answers are of special interest for open system planning.

Far and away the most popular operating system environment is Unix, which bodes well for open system planning, although it should be noted that there were many different varieties of Unix reported and, with a couple significant exceptions, there was no mention of specific intent with respect to the various Unix standardization efforts (OSF, Unix International, Posix). One company develops and supports its own variety of Unix, described as "essentially AT&T System V with Berkeley extensions." (In fact, words to that effect showed up several times as describing the variety of Unix used.) Another company offers separate implementations for seven (!) different Unix versions, distinguishing among the different versions according to what runs on the workstations sold by different workstation vendors.

The second most popular operating system environment is MS-DOS, with several vendors having already modified or promising soon to modify their DOS implementations so that they run under Windows 3.0. DOS machines are becoming powerful enough (with the use of Intel 486 and 586 processors) that they can easily support good performance of a full-function GIS. Therefore, this will likely be the system of choice for many GIS users in the future, despite the fact that at least at the present it is hardware specific and not included within the open systems movement.

Several of the vendors of DOS-based products claim that they will have Unix-based implementations available in the near future and, conversely, several of the vendors of Unix-based products already have or will soon have cut down, so-called "PC versions" of their systems that run under DOS. As DOS systems increase in power, these versions won't need to be any longer "cut down".

Surprisingly no vendor reported plans for an OS2, Presentation Manager implementation and no vendor reported having a MacIntosh implementation, although there were reports of plans for the latter as well as reports of use of MacIntoshes as user stations in networks with all but the display aspects of the GIS processing being done on servers of other kinds. MacIntoshes were reported as the basis of several "desktop mapping" systems but, so far as we can tell, no such systems contain functionality sufficient to justify calling them GISs.

There were two vendors that reported IBM 370 mainframe implementations (under both the VM/CMS and MVS operating systems) and quite a few more that reported DEC VAX mainframe implementations under the VMS operating system. Without exception those that reported VAX implementations reported that they have moved or will soon be moving to a Unix implementation, frequently DEC's Ultrix variety of Unix.

C.3.5 Past and Projected GIS and GIS-T Sales Levels

Question 5: *What are the current gross sales levels of your GIS products and services, and what are the growth curves that you project for them? What fractions of these sales levels are related to transportation?*

The point of these questions was to determine whether a company's GIS and/or GIS-T activities were large enough to have reached "critical mass", that is, will DOTs be able to count on their continuing to maintain an interest in and support transportation applications and/or continuing to be around at all.

The results were surprising. Companies in general appear willing to provide such information, even some of the privately held companies (although a couple of these rather testily refused to answer these questions). However, they often don't maintain information that enables them to know for what application areas (e.g., transportation) their products are being used (which indeed is surprising and bodes ill for their survival because they have such limited knowledge about what their customers are using their products for!), and one of the large companies asserted that it considers proprietary information about the distribution of use of its products over different market sectors.

At the very least, the responses we received suggest that this is a question worth including in requests for information and requests for proposal.

C.3.6 Modularization of GIS Products

Question 6: *What are the possible configurations of your GIS products purchasable by a customer? To what extent are your products decomposable into separate modules, and are the modules purchasable and usable separately?*

The point of these questions was to determine whether there is any discernible trend toward the prospect of being able, once GISs are implemented in server-net environments, to place on different specialized servers modules from different vendors (e.g., servers that divide up labor such that one supports overlay, another supports analytical modelling, and another supports cartographic publishing).

Although several of the vendors offer systems that are indeed sufficiently modular that a tailored subsystem containing only specifically required functions can be configured for particular customers, there is clearly no movement whatsoever toward the standardization that would enable a customer easily to use in combination different modules from different vendors.

The primary source of the lack of standardization is the use of incompatible spatial data structures by the different vendors. There do exist in many cases conversion routines for converting from the spatial data structures of one vendor to those of another, but needing to attach such routines to the links among servers in a server net would be clumsy and inefficient, to say the least.

C.3.7 History of Vendor's Involvement with GIS

Question 7: *How long have you been vending GIS products? Were the products originally intended to be or were they originally labelled as GIS products? Were they originally intended to be or were they originally labelled as in any way specific to transportation? Are they so labelled now?*

The point of these questions was twofold: the longer an existing track record in vending GIS products the more likely continued survival and interest in the area on the part of the vendor, and having converted to GIS status a product from an original purpose other than geographic processing may reflect on the functionality and usability of that product.

With respect to the first issue: It comes through very clearly from the responses that GIS is a new technology with many of the companies involved having existed for less than ten years and many of their GIS products having appeared only in the last two or three years. The companies are manifesting high annual growth rates in the range of 15 to 50 per cent. None of this makes for stability that can be counted on. There clearly will be a major shake-out of companies and even some of the relatively larger ones will likely fail or be absorbed into larger corporations (where they may lose their current sharp focus on GIS, their responsiveness to individual customers, and their willingness to spend time providing information to curious researchers).

With respect to the second issue: Our concern here seemed largely to be misplaced. GIS has now become sufficiently well defined that it is clear to most vendors that they don't have a GIS just by relabelling a CAD system or an automated mapping system. The major vendors that were CAD vendors before they became GIS vendors have now largely designed and implemented the significantly different data structures needed for GISs, although there may be one or two cases where CAD data structures are still being used. (They lack explicit representation of topological connectivity. If a GIS product has originally been built on top of a CAD product, whether such connectivity is now present is a question that should be investigated before acquisition.)

One important fact emerging from the responses to these company history questions that shouldn't have been surprising but that should definitely be noted: The vendors that showed the most awareness of the potential of GISs for integrating data, across an entire organization and across applications not directly geographical, were those vendors with company experience in system integration. There were two companies where this background obviously influenced their understanding of and their answers to our questions about integration, and there may be more that we missed.

C.3.8 Open Systems Plans

Question 8: *What plans do you have for moving to open systems? This includes plans for bringing your products up on Unix platforms, but that is not the only thing in which we are interested. We are also interested in plans for compliance with open-system database standards, open-system GUI standards, open-system networking standards, and open-system data exchange standards. Of which, if any, of the various open-system organizations is your company an actively participating member? If there are some, define what you mean by "actively".*

Given the thrust of this report, the reason for these questions is obvious.

The widespread use by GIS vendors of Unix workstations as their primary hardware platform has already been noted, in C.3.4 above. It is worth repeating that, without exception, the vendors who have DOS implementations already have Unix implementations as well, or report nearterm plans to develop such. It is also worth repeating that all of the VAX VMS implementations have been or are being moved to Unix implementations. Of similar interest is the fact that one of the vendors with IBM 370 mainframe implementations had a Unix implementation first and the other, although the original implementation was for proprietary IBM mainframe operating systems, now has the processing part of its product up and running on a Unix platform. (No mention was made of plans for converting the other part, the spatial data management part. This is probably because of the continuing belief in some circles that large mainframes continue to be the best vehicle for servers supporting large, shared databases. Unix workstation capabilities as well as implementations of relational database management systems on Unix workstations are rapidly reaching the stage where the evidence no longer supports this belief.)

There was almost universal use of X-windows as the GUI base, and very frequent reports either of an implementation's already using the GUI Motif (the OSF standard) or of plans for it to do so in the near future. Open Look is used apparently only for implementations that use Sun hardware platforms. A number of the DOS implementations have been or are being upgraded to use Windows 3.0. No use of or plans for use of Presentation Manager were reported.

With respect to database standards, for attribute databases all vendors can now link to SQL databases (with Oracle being far and away the most popular). However, there was surprising lack of awareness of the deficiencies of SQL for GIS database purposes, in particular, of the need to extend it significantly if it is to be used for efficient spatial data structuring and querying and if it is to be used for identifying database "blocks" or "segments" of the kind that need to be transferred among servers (as opposed to identifying tuples of the kind that need to be delivered to human users). Only one vendor reported active participation in the standards working group investigating spatial extensions of SQL.

Conformance with open system standards for networks appears even further along, with all vendors making use of SNA or DecNet protocols saying that they can also handle TCP/IP protocols and that they have plans for moving to full ISO networking standards as those standards become more fully developed.

With respect to data transfer, several vendors reported interest and/or participation in the USGS guided development of a standard for spatial data transfer, but the current state of the art is largely one of including in GIS products data translators for converting among formats. One vendor claims the inclusion in its product of 22 such translators!

C.3.9 Plans for Client-Server Networks

Question 9: *What plans do you have for making your products usable within client-server networks? In particular, what separate parts of your products might be put on separate servers, and what are the interfaces among those parts?*

Given the thrust of this report, the reason for these questions is obvious.

In general there was manifested in the vendor responses appreciation of the general trend in computing away from mainframe dominated, star networks to networks consisting of many different kinds of specialized nodes each performing both as a client of other specialized nodes on the net and as a server of yet others. Given the relative youth of these companies this is not surprising. Most of them have come into existence only after the client-server approach to computing has come to dominate.

However, the bad news is that with only two exceptions the vendors look upon GIS processing, including management of the spatial databases (the GIS digital base maps), as one "specialty" to be allocated to *the* "GIS server". What they propose to allocate to other servers are only such functions as management of attribute databases and hardcopy output (plotting and printing). This is indeed a client-server division of labor but at only very low resolution compared to what we are recommending. Even those vendors with highly modular systems, and for which the coupling among at least some of the modules is fairly loose, failed to see the point of making different servers responsible for different modules (or for tightly coupled subsets of modules). We foresee decomposition of GIS functions and their allocation out to separate servers at a much finer resolution. (See Section 3.2.2.)

Usually the server node on which the vendors see the GIS processing being done is a Unix workstation or a relatively powerful DOS PC which is at the same time serving as a user display station. A few of the vendors at least see the point of putting users in front of display stations specialized for display (both X-Windows terminals and MacIntoshes were mentioned for this purpose) and letting these be separate from the GIS server whereon is done the GIS processing *per se*. One vendor emphasizes (as do we) that the user's GIS display station ought to be the the same station on which he does his word processing, runs his spreadsheets, accesses his e-mail, and accesses any and all other kinds of computing and data services. Clearly the station on which this general variety of end-user functions is performed shouldn't also be responsible for complex (and in many cases, quite computation intensive) GIS functions like overlay. And this is just the beginning of the desirable and eventually feasible division of GIS labor among different specialized servers.

Although our survey showed disappointing results in this respect, it is unlikely that this strange blind spot of current vendors will seriously delay realization of the potential of client-server structuring of GIS systems. If the blind spot persists, other and more client-server savvy vendors will enter and win the race.

C.3.10 Focus on Transportation

Question 10: *On what application areas do you focus your marketing and in what ways are your products specialized to those areas? If one of the areas is transportation, what particular advantages do you claim for the products with respect to transportation applications? If one of the areas is not currently transportation but you plan to make it so, what features and capabilities do you plan to add to make the products more useful for this additional area?*

This question unintentionally overlapped Questions 3 and 5, and there is no point in repeating here what was said above in Sections C.3.3. and C.3.5.

It is important to note that use of GIS technology for transportation applications has developed later than its use for other applications, and as a result some of the early GISs lacked features specially needed for transportation. However, at least for the vendors that attempt to include within their products a full suite of GIS functions, this deficiency has now been remedied with the additions to the systems of network representations that correctly symbolize transportation networks (for example, as graphs they have to be non-planar), efficient route representations and computations, dynamic segmentation, and other capabilities useful for transportation applications. Of course, the caveat needs to be re-iterated that different vendors mean different things by these words so product evaluators need to look behind the words.

One vendor designed its GIS system from the ground up to have spatial data structuring and other resources especially optimized for efficient support of transportation modelling. That vendor's GIS should indeed be included in the mix of GISs considered for acquisition by any transportation agency, but its development history no longer suffices as a reason for making it the only GIS to be so considered, given the capabilities that have now been added or that will likely soon be added to several other systems with different development histories.

C.3.11 System Extendibility and Customizability

Question 11: *In what ways are your products extendible and adaptible to particular environments and applications by the user? What are your plans for connecting your products to CASE (computer-aided software engineering) systems and/or for including CASE capabilities in your products? Do you offer programming services to specially tailor your products?*

The point of these questions was to determine the ease with which DOTs would be able to extend and adapt particular GIS products to their unique environments and to their specialized needs. The answers are important even for those DOTs that don't have the resources to do much internal software development. The vendor responses discussed in Section C.3.2. above should be read as relevant to this question also.

All vendors offer programming services to customize their products, but beyond this there was great divergence among the vendors in their answer to this question. Clearly we have identified here a major difference among the GIS products. Its importance will vary from one DOT to another.

One vendor makes available for a price detailed descriptions of the many subroutines that consitute its system, and system extension and adaptation is expected to occur by adding to the the vendor-supplied subroutine library user-written (C or Fortran) subroutines. Another vendor who has implemented its system in a "Smalltalk-like" object oriented programming language makes this language available to users along with "sufficient" information about the vendor supplied objects that constitute the system that users can customize their systems by specializing and instantiating the supplied objects, as well as by creating new object classes.

The availability of such detailed descriptions and/or extensive development aids is the exception, however, and several of the systems would be very difficult for a user to extend and customize except in relatively trivial ways.

None of the vendors specifically incorporates CASE capabilities in their products, despite the claim by one that its macro language is so easy to use that it ought to be considered equivalent to CASE capabilities. In general, there is failure on the part of all the vendors to appreciate just what constitutes a modern CASE system and just how much the productivity of GIS system extenders as well as application developers would be increased from adapting a good CASE system for use in connection with a GIS or from integrating certain essential CASE capabilities directly into the GIS.

Several respondents pointed out the possibility of using CASE systems to schematize the external relational databases which their GISs can use for holding attribute data, but this particular task is only a small part of extending and applying GISs.

C.3.12 Linking to External Databases

Question 12: *What are your plans for enabling coupling of your products with external databases? We are especially, although not exclusively, interested in databases on IBM mainframes.*

This question turned out to be useless as a discriminator. The problem that it was getting at, namely that GIS applications should be able to use data from external databases originally populated for other reasons and not a subordinate part of the the GIS, is a problem that has been almost universally recognized by the vendors. In response, again almost universally, they have provided their systems with the capability to generate SQL retrieval expressions, execute them against external relational databases, and correctly interpret the answers that are returned. The only difference among the vendors is which particular kinds of relational databases they can access. Almost all of them can handle Oracle databases. Some can handle at least some of the kinds DB2, Informix, Ingres, Rdb, SQL/DS, SQL/400, and Sybase as well.

For the DOS-based systems, rather than accessing SQL databases, access of several different kinds of PC databases is possible. Almost all such systems can access DBase III databases, and some can access FoxBase, Paradox, and DBase IV databases as well.

It should be noted that, although GISs can now in general access attribute data stored in external, relationally structured databases, no mention was made by any vendor of a GIS ability to access databases with other kinds of structure (e.g., hierarachical or network), nor was any mention made of plans to provide a GIS with such an ability, although these older forms of database structure are still in wide use by many organizations, including many DOTs.

C.3.13 Use of Object-Oriented Structuring

Question 13: *What are your plans for incorporating into your products the technology of object-oriented programming and object-oriented databases? If you have such plans, what do you mean by "object"?*

Object oriented programming languages and database management systems are the subject of intense investigation by computer scientists at the present time, and the point of this question was to discover whether GIS vendors are making any use of the emerging technologies or have any plans for such use.

Given the variability and the complexity of the objects dealt with in geographic reasoning and computing, object oriented databases would appear to be well suited for GISs and GIS applications. This is especially so since few if any developers have figured out how to use relationally structured databases for the efficient storage and retrieval of spatially described objects, the very essence of GISs. However, the general response by the vendors was that they are waiting and watching; that at this point object-oriented database technology is too immature for insertion in robust, high-performance production systems; that it lacks the generality and the the underlying theory of relational database structuring; and that object oriented database standards are in a very primitive and inchoate state. There appears to be a general awareness that no vendor has yet been successful in using an object-oriented database for storing and retrieving GIS spatial data, although several have tried. No vendor, including the ones known to have tried and failed in the past, owned up to being in the process of making any more such attempts.

Object-oriented programming is another matter. Several of the vendors are using it for their product development, several have used its principles as a basis for their software engineering practices even though they did not use an object-oriented language for their development programming, and some support object oriented approaches for user GIS extension and application development. However, there is a long way to go before object oriented programming becomes the primary vehicle used and made available by GIS vendors for these purposes.

C.3.14 Coupling with External Programs

Question 14: *What are your plans for enabling coupling of your products with external programs, e.g., expert systems?*

This question is of importance because of the possibility of increasing GIS potential by enabling GIS components (e.g., those that generate map displays) to be called by other kinds of programs that can put them to good use, thus obviating their re-implementation by the developers of those other kinds of programs, and because of the potential of letting other programs (e.g., models or expert systems) rather than human beings be the users of GISs.

Many vendors claimed relative easiness of coupling their GISs or their GIS components with other programs, e.g., transportation models, but in general offered no uniform way of doing this and did not report on any use of "standardized application interfaces" (another goal of the open systems movement). There is clearly a lot of coupling of this kind done by the vendors and by their users but it would appear that, at this time, it is done on a case by case basis with communication among the programs occurring through *ad hoc* buffers or files constructed specifically for the purpose or through the relatively inefficient methods of having the producer program place data in a database and then immediately afterward having the consumer program take them out.

There would appear to be a general lack of awareness on the vendors' part that there are better ways to effect communication among programs, for example, to enable external programs to call GIS constituents as subroutines or to send messages to them as objects. The former is certainly possible for the GIS vendor who is willing to provide good documentation of the subroutines that constitute its system, and the latter is a likely possibility for vendors of the future who structure their GISs as object libraries. In the meantime, most GISs stand in splendid isolation, systems for which coupling with human users, not coupling with other programs, is the predominating mode of use.

Obviously developments in this area are important for the future marriage between GIS technology and client-server technology, because the external programs for which GIS coupling is desired may well reside on servers different from those where reside the GIS resources being tapped.

C3.15 Overcoming GIS Product Deficiencies

Question 15: *In our report we characterize current GIS products as in general having certain deficiencies with respect to their ideal use within state DOT computing environments. Please respond, for each of the following alleged deficiencies, whether you believe it fairly applies to your products and, if it does, what plans you have for removing it.*

In the following paragraphs we present each of the four deficiency descriptions and then immediately follow it with our summary and analysis of vendor responses.

GIS Product Deficiency 1 : Lack of user-controlled, system decomposability into modules that can be distributed across separate server platforms in a client-server network.

Deficiency 1 was raised to get at, in different words, the same point previously raised by Questions 6 and 9. There was manifested no better understanding by the vendors, in their response to this revised wording, of the reasons for or of the problems associated with dividing up GIS labor among different nodes of a server net.

GIS Product Deficiency 2 : Lack of rapid prototyping and incremental prototyping capabilities.

The answers received with respect to Deficiency 2 manifest surprising ignorance on the part of vendors concerning just how hard it is with their current products to generate an exploratory application program for purposes of trying out ideas - before a commitment is made to a particular way of building a production strength version of the program. It would appear that GIS product designers and vendors need to have their imaginations stretched by getting some firsthand experience with how programming productivity is increased in other areas (e.g., artificial intelligence research) with fast interface mock-up techniques, techniques for simulating behavior of subroutines without actually having to write them, and other techniques aimed at getting a good idea of how a program will look and feel before actually programming it. Making such techniques available for application development with any of several GISs on the market would clearly give them a significant competitive edge. The wider use of the principles of object-oriented programming will be significant step in this direction.

GIS Product Deficiency 3 : Lack of connection with CASE environments in a way that enables easy use of the GIS-product defined and controlled concept of location as an integrating concept in the database schemas specified with those CASE environments. (One way of responding to this deficiency would be extension of GIS products to include CASE capabilities.)

There were only two of the vendors who clearly indicated in their responses that they see the potential of using the concept of location as a basis for integrating databases across all applications of an "enterprise", e.g., a DOT. As indicated earlier, both have a history of dealing with system integration problems in a major way, as well as a history of developing and applying GISs. Having had experience in both areas clearly contributes to being able to see how they complement each other and, in particular, to being able to see the integrative potential of GIS technology.

Those who failed to see this important potential of GIS technology just simply missed the point we were making by pointing out Deficiency 3. It should be noted that the deficiency can be considered a problem for CASE technology just as much as it is a problem for GIS technology. What is needed is an accommodation of each to the other, and this accommodation must incorporate an efficient way of storing locational, geometric, and connectivity information in the same kinds of databases used for storing attribute data. The two vendors who understood what we were getting at claimed progress in this direction.

There are indeed serious questions of efficiency involved in storing spatial data in a relational database, but there are ways of doing it, ways preferable even at the cost of some inefficiency to use of *ad hoc*, often proprietary data structures internal to GISs. Indeed, the cost of computation is so rapidly declining because of exponential increases in micro-electronic circuit densities and speeds that efficiency (expressed in terms of computing cycles required) becomes a less and less important consideration in data processing planning - of all organizations, certainly including DOTs.

Some of the vendors who responded consider their particular *ad hoc* spatial data structures so novel and important that they refuse to reveal them because, they argue, the structures give them a competitive edge, presumably due to improved efficiency over alternative structures. But at best such a competitive edge will be short lived. As the cost of computation continues its precipitous decline, the vendors who have the competitive edge will be those who support storage of spatial data in a way that is uniform with how other kinds of data are stored and in a way that facilitates use of those spatial data as a basis for integrating all the other kinds.

GIS Product Deficiency 4: Lack of CASE capabilities for specifying overlay programs for spatial data types between which overlay operations are not provided as a built-in part of the GIS products.

The typical response with respect to this alleged deficiency was that all needed overlay operations are built in. They may be when the spatial data types involved are the usual ones, the spatial entities involved are the ones given explicit identifiers in the spatial database, and there are explicit links between the base map layer and the various thematic layers that are being registered against it. They are not and can not be built for cases of overlay where the spatial entities involved are dynamically created as part of the overlay process, created for example using dynamic segmentation of linear spatial entities or some other kind of spatial aggregation or generalization process. In general they cannot be built in when the linkage among layers is not explicit, for whatever reason, but has to be computed. It is exactly the programming of this computation, in a way that produces a desired overlay result, that is at issue.

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†Appendix C, Sections C.1, State DOTs, and C.2, MPOs, as contained in the report submitted by the research agency are not published herein. Copies are available by writing to the Transportation Research Business Office, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

APPENDIX F

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APPENDIX G

GLOSSARY

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.
CAD Computer-Aided Design.
CASE Computer-Aided Software Engineering.
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 Resource.
DOD Department of Defense.
DOT Department of Transportation.
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.
FHWA Federal Highway Administration.
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.
GIS 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.
GIS-T Geographic Information System for Transportation.
GPS Global Positioning System; a constellation of satellites and a tracking and control network developed by the U.S. 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; and 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.
IVHS Intelligent Vehicle Highway System.
LAN Local Area Network; a computer network for enabling computers within a small area (e.g., a single building) to interact efficiently with each other (contrast with Wide Area Network, a network with an entire campus or city or state as its extent).
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).
MPO Metropolitan Planning Organization; the agency in an urban area that is responsible for planning and coordination of a number of federal and state programs including transportation.
MS-DOS MicroSoft Disk Operating System; an operating system for personal computers utilizing the Intel 86 series of microprocessors as their central processing units—a widely used but proprietary system, i.e., it has been developed and is sold by MicroSoft and IBM.
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 currently popular computer programming style that builds programs as complexes of modules ("objects") that 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 reused many times over in different programs.

O-D survey Origin and Destination survey of travel.
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.
PC Personal Computer.
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 Systèm 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 database 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 nonoverlapping 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).

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