# ISSUES IN GIS FOR TRANSPORTATION

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## Acknowledgement

## Disclaimer

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# CHAPTER 1

# INTRODUCTION

Geographic Information System (GIS) support display, analysis and management of maps and associated attributed data. GIS has been successfully applied in many fields outside of the transportation industry. Many transportation organizations have made commitments to GIS technology, largely because spatial information is of basic importance in the management and operation of transportation infrastructure and in analysis of many related issues. However, the full capabilities of GIS for transportation have yet to be realized.

Transportation organizations are currently faced with increasing demand for information to support effective decision making throughout their organizations, from individual project level to statewide planning and management. In addition, the broad environmental and economic development problems of society imply that there is value in data sharing and cooperation among multiple government agencies at all levels. These demands for improved information can manifest themselves as mandates such as the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. This act requires systems for traffic monitoring and for management of pavement, bridges, safety, congestion, public transportation, and intermodal facilities and equipment.

According to an informal survey by Roger Petzold of the FHWA, 15-20 state Department Of Transportations (DOTs) are in the process of implementing a GIS system most of the others are considering adoption. The prospects of increasing use of Geographic Information Syatems for

Transportation (GIS-T) technology are also increasing, because of the management systems mandated by the ISTEA are best implemented through GIS technology.

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

All of the data required by the ISTEA management and monitoring systems, the Hazardous Waste Act, the Clear Air Act and most other data managed by transportation agencies can be geographically referenced. The concept of location as an integrator for transportation data was promoted by Briggs and Chatfield in (1987). GIS now provides the means.

This new information technology is a driving force for increasing integration of data and increasing interdependence of database users and maintainers. It also has the effect of "taking a broom to the closet" (Lewis and Pietropola, 1993) of existing databases by exposing gaps and errors in the data as they are presented for the first time in a spatial (map) format. This new data visibility is both a boon and a bane, because this induces an effort for data cleanup in "legacy" databases of state DOTs.

## 1.1   Purpose

The purpose of this report is (1) to provide a basic understanding of GIS and GIS-T; (2) to discuss the possible GIS related applications and activities in trasportation; (3) to describe the factors and issues involved in successful planning and implementation of GIS for transportation; and (4) to describe the emerging uses and future applications of GIS-T.

## 1.2 Organization

The report is divided into four parts. Part I contains three chapters that focus on the definitions, elements and tools of GIS.

Chapter 2 introduces GIS technology. Chapter 3 discusses the elements of GIS. The data representation schemes and spatial data structures are described. Chapter 4 describes GIS tools. Data entry, data analysis functions, data manipulation and display information are discussed.

Part II of this report contains chapters that are oriented towards either applications of GIS-T or the GIS related activities in transportation.

In Chapter 5, the GIS-T technology is introduced. Chapter 6 discusses the applications of GIS-T, while Chapter 7 reviews the GIS-related activities in State and Federal transportation departments.

Part III of this report contains five chapters that focus on issues associated with implementation of GIS.
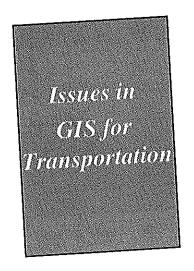
Chapter 8 discusses the design and implementation of GIS in transportation. Chapter 9 discusses the five implementation stages. Sixteen steps involved in the five implementation stages are described in detail. Chapter 10 discusses the issues in GIS-T implementation process. Chapter 11 describes and compares the available GIS softwares. Chapter 12 describes the implementation issues in the technical and organizational perspective.

Part IV of this report contains two chapters that focus on the issues associated with emerging uses in GIS-T.

Chapter 13 discusses the emerging uses in Intelligent Vehicle/Highway Systems (IVHS). Chapter 14 discusses the other upcoming uses of GIS-T. Chapter 15 discusses the issues related to modeling with GIS. Model Integration into GIS, in terms of modeling technique is discussed.

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# *PART I*

## INTRODUCTION TO GIS

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# CHAPTER 2

## INTRODUCTION TO GIS

Geographic Information System (GIS) provide a computer-assisted and integrated environment for geographic data creation, storage, retrieval, management, manipulation, analysis, and display (Lai, 1990). A GIS relies on the integration of three distinct aspects of computer technology, data base management, routines for displaying and plotting graphic representation of the data, and algorithms and techniques that facilitate spatial analysis as shown in Figure 2.1 (Antenucci et al., 1991).

Database

**GIS**

Graphic                    Spatial Analysis
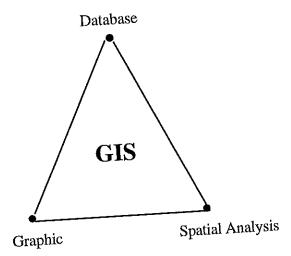
Figure 2.1. Three Distinct Aspects of GIS
(Antenucci, 1991)

## 2.1    Components of GIS

GIS are comprised of sophisticated software, but they all contain the following major components

as subsystems (Marble, 1987):

**Data input subsystem** - Collects and/or processes spatial data derived from such things as existing maps,

and remote sensors.

**Data storage and retrieval subsystem** - Organizes the spatial data in a form which permits it to be quickly

retrieved by the user for subsequent updates and corrections to be made to the spatial database.

**Data manipulation and analysis subsystem** - Performs a variety of tasks, such as changing the form of

the data through user-defined aggregation rules, or producing estimates of parameters and

constraints for various space-time optimization or simulation models.

**Data report subsystem** - Displays all or part of the original database as well as the manipulated data and

the output from spatial models in tabular or digital cartographic map form.
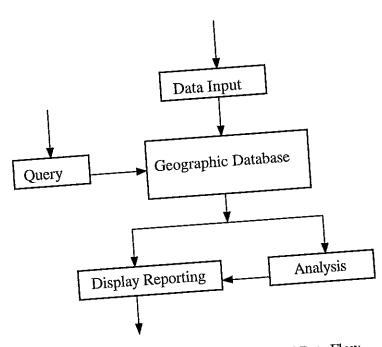
Figure 2.2. Major Components of GIS and Data Flow

The main components of a GIS are shown in Figure 2.2. A GIS can be thought of as a Data Base Management Systems (DBMS) in the sense that the basic function is data processing. The type of data GIS deals with, however, is relatively specialized, and an advanced GIS provides sophisticated data manipulation functions for various types of spatial analysis. Therefore, a more precise description of the relationship between a GIS and a DBMS is that a DBMS is a part of a GIS. Raster (1978) argues that the core of any GIS is the database management system.

The next section discusses spatial data and data models that must be developed in a successful GIS.

## 2.2    Applications of Geographic Information Systems

There are numerous specialized uses for GIS. The application usually determines the name given to the system. Possiblities include Land Information System (LIS), Land Related Information System (LRIS), Natural Resource Information System (NRIS), Urban Information Systems (UIS), Regional Information System (RIS), and Automated Mapping/Facilities Management (AM/FM). All of these titles are used for GISs to emphasize domain-specific information requirements. The difference is in the type and application of the information system. The differences and similarities are explained below.

All LISs are GISs, but the exact application of an LIS varies somewhat. A LIS has a strong focus on coordinate accuracy, and is often used in engineering and cadastral recording applications. A LIS can also refer to a natural resource information system. In general a LIS is specific to spatially referenced information.

A Land Related Information System (LRIS) concentrates on property and land parcel data. Any information system related to land, its ownership, use, and physical characteristics is a GIS, but it is more specifically a LRIS.

Natural Resource Information Systems (NRISs), Urban Information Systems (UISs), and Regional Information Systems (RISs) are all applications of GISs for different uses.

Automated Mapping/Facilities Management (AM/FM) is another form of GIS, developed by utility companies for keeping track of their inventory and assets distributed around the countryside. One definition indicates that "AM/FM is a representation of projects and systems that use computers and graphics techniques to store, retrieve, analyze, edit, maintain and produce geographic and descriptive technical data that are in a unified system" (Hazen, 1988).

## 2.3    Trends in Geographic Information Systems

Computerized geographic information system were first used in the 1960s and were multi-disciplinary in design, with influences from the fields of spatial analysis, cartography, and computer science. Until that time, all three of these fields were not sufficiently developed to create a computerized geographic information system. However, the combination of these fields made it possible for researchers to develop a multitude of potential applications. Most of the development of computerized GISs occurred in governmental agencies and universities.

Natural resource management was one of the first applications for a GIS. The U.S. Forest Service has been using a computerized GIS for the analysis of hydrology and recreation facilities since the mid 1960s. The Canada Geographic Information System (CGIS) was developed in 1964 to address Canada's problems with development and rehabilitation of agricultural lands.

Urban modeling was a forerunner to the modern GIS. Urban models were created in the 1960s to assist in the decision-making process of government. The first generation urban models were large and complex, with questionable accuracy and limited usefulness. The urban models of 1970s were simpler in design, and the goals were attainable. By the early 1980s, they evolved into the modern computerized GIS.

In the last six to seven years, the field of GIS has exploded with new users, due to the rapid development of relatively low cost microcomputers and GIS software. In the past, due to the tremendous cost, only government agencies, universities, and large metropolitan areas could acquire a GIS. Now, a city with a population of 50,000 people or a business can afford a GIS. Boyce Thompson (1989) reaffirms this idea. He states:
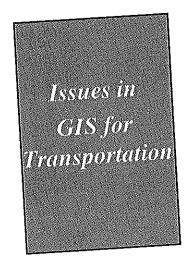
*"Five years ago, few jurisdictions with less than 500,000 in population could cost-justify GIS, which required a minimum investment of $500,000. Today, nearly any city or county can afford some type of system, whether it's based on personal computers, more powerful engineering workstations or mainframe computers."*

## 2.4 Reasons to Use Geographic Information Systems

Some common reasons for municipalities to adopt a GIS include the reduction of duplicated information, greater availability of information, and better quality of information for decision-making process. These issues were addressed by Rebecca Somers (1987) in a paper on GIS in local governments in which she wrote:

*"A major goal of most local government GIS efforts is to implement a multipurpose, integrated system that will serve the needs of a variety of users. The objectives include reducing duplication of effort in order to reduce costs, centralizing common data to eliminate discrepancies and unnecessary effort involved in maintaining multiple copies of the same information, increasing efficiency in daily operations, increasing management control, and providing information for decision support and policy formation."*

GISs are used to facilitate research, management, and planning by a variety of businesses and units of government at all levels. The users come from a variety of fields, including transportation, geography, soil science, forestry, utility company, government, engineering, geology environmental organizations, demography, and planning. Many GISs have more than one application, with numerous users.

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# CHAPTER 3

# ELEMENTS OF A GIS

Vast amounts of information are managed and maintained by government. This information is divided into spatial and non-spatial information.

Spatial or locational information answers questions like "where is it located"? Location is specified in different ways on a map. The location of an object can be determined by latitude and longitude, but this method is usually considered to be inappropriate for most users. The most common form of displaying spatial information in municipalities are legal descriptions, street addresses, and metes and bounds descriptions of land parcels.

Non-spatial information is known as attribute (or descriptive) information. Non-spatial information describes the characteristics of the spatial feature. Non-spatial information for a land parcel includes the property owner's name, the value of the property, the amount of property tax, the age of the structure (if one is present), and the number of occupants.

## 3.1 Spatial Data Model

A GIS is a computer system in which all the data are represented in digital instead of analog form. Spatial geographic data are those which represent spatial objects in three forms: points, lines, and polygons or areas. All features of the landscape can be reduced to one of these three spatial data categories.

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To use computers for handling spatial data, data must be reduced to the computer's level of comprehension. According to Parker, (1988; 1990) three things have to be specified for the computer:

**location -** Where each feature is in geographic space.

**attribute -** What each geographical feature is. And,

**topology -** What spatial/ relationship does each geographical feature have to other geographical features.

Geographical data can be represented in a number of ways; as simple lists, as ordered sequential files; or as indexed files. When organized into a database, there are three different data models, hierarchical, network, and relational data structures.

Hierarchical structures require large overhead to be maintained in the form of data redundancy, index file, and pointers. In network structure, travel within the database is facilitated but its size is enlarged by the pointers that have to be maintained and updated every time a change is made to the database. A relational database structure stores no pointers and has no hierarchy. Instead, data are stored in simple records maintained as two-dimensional tables. But considerable time is needed to search for the right records in a large database. Hence, very skillful design work is needed if these data structures are to perform adequately within a GIS database (See Burrough, 1986; Date 1981).

## 3.2   Graphic Features

The basic building blocks of graphic data in a GIS are represented by three basic features: points, lines, and areas. All of these features require descriptive (or non-spatial) information in order to be meaningful.

Points are used to locate objects when the size of an area is of no importance or when there is no definable area. A point could display the location where a traffic accident occurred (where no precise area can be identified) or show the location of a fire hydrant.

Lines are a group of points connected together, with no significant width. Lines represent things like natural features, pipes, roadway centerlines, property lines, and political boundaries.

Areas are created by a sequence of connected lines. Areas can display outlines of soil types, land parcels, political boundaries, or anything else in which area is of importance.

## 3.3 Fundamental Data Representation Schemes

As humans, we can read a hard-copy map to obtain information. However, computers cannot deal with the analog hard-copy map like humans. To have computers handle spatial data from a map, data must be reduced to the computer's level of comprehension, and such a reduction process in GIS is called digitizing. The digitizing process converts shapes in a map to numeric values. Spatial data structures are used to store the information in the computers.

The representation of shapes and forms in a computer may be done in one of several ways, that is, in raster, vector, or combined mode. Raster is an array of points or cells arranged in horizontal rows, and vertical columns, like the pattern of a checkerboard. A TV picture is a good example of raster mode representation except that it is analog instead of digital. Raster mode can cause a very large database to accumulate if no compression techniques are implemented. Burrough (1986) discusses four such compression alternatives: chain codes, run-length codes, block codes, and quadtrees. Raster mode's main advantage is its simple structures.

When vector data structures are used, there are no cells and all the polygon and line data are composed of short lines or "vectors" strung together. In vector mode, exact representation of objects is

possible. Moreover, entire geometrical relationships between map features (topology) are built up. Two

main advantages of the vector mode is that there are no limits on resolution capability or location for a

point. Table 2.1 shows comparisons between the raster and the vector data representations.

### 3.3.1 Raster Data Structures

The raster data structure uses a system of cells, or a grid, to store and process data in the

computer. A raster data structure is closely associated with remote sensing imagery. The raster cells can

take many different geometric shapes. The different shapes have certain advantages and disadvantages.

The rectangular cells are the most commonly used shape of the raster data structures. The square

or rectangular cells are very useful if the cells are to be divided into smaller cells or added together to make

larger cells. Rectangular cells determine the distance between neighboring cells. A rectangular raster data

structure can be displayed as a simple two-dimensional array.

Raster

Vector
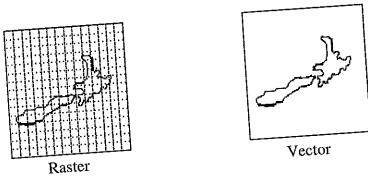
Figure 3.1. Representation of two forms of data storage.

### 3.3.2 Vector Data Structures

The building blocks of the vector data structures are referred to as nodes and arcs. A node is a

point at the beginning or end of a line or at the intersection of multiple lines. An arc is created by joining

nodes together to form a line.

Vector data structures are compact in size and produce more accurate maps than do raster data structures. Vector data structures require the use of sophisticated algorithms and significant computer processing power to efficiently manage the data. Therefore, more expensive hardware and software are required when using vector data structures.

Table 3.1. The Comparison of Vector and Raster Data Structure

| Dimension | Vector System | Raster System |
|---|---|---|
| Advantages | 1. Compact data structure<br>2. Accurate Graphics<br>3. Exact description of topology with network linkages<br>4. Possible retrieval, updating and generalization of the graphics and attributes<br>5. Good representation of the phenomenological data | 1. Simple data structure<br>2. Ease of spatial analysis<br>3. Ease of overlay and combination of mapped data with remotely sensed data<br>4. Ease of simulation due to the similarity of size and shape<br>5. Low cost of technology |
| Disadvantages | 1. Complex data structure<br>2. Overlay difficulties<br>3. Difficult to do simulation due to different topological forms<br>4. High cost of display and plotting for high quality color<br>5. High cost of technology | 1. Large Volume of data<br>2. Difficult to establish network linkages<br>3. Crudeness of graphics<br>4. Loss of information with use of large cell data<br>5. Hard to change projection without special algorithms or hardware |
| Usage | 1. Linear network studies (Minimum time path finding, Center finding in a network)<br>2. Property ownership and utility mapping and analysis<br>3. Most urban types of data and problems(Urban network analysis) | 1. Many types of numeric modeling<br>2. Good when remote sensing data are available<br>3. Multiple map combination or generation<br>4. Most rural types of data and problems(Natural resources) |

All vector-based systems directly represent the map topology. The topology refers to the relationships between different spatial objects, such as which polygons share a boundary, which points fall along the edge of a particular polygon, and so forth (Star and Estes, 1990). The topology describes the linkage between spatial features.

Major characteristics of vector and raster systems are summarized in Table 2.1. For more software description, see Gould (1990); GIS World IDC. (1990); Parker (1989); USA CERL (1989); Westervelt, Goran, and Shapiro (1986).

## 3.4 Topology and Topological Data Structures

As mentioned in the above section, the vector GIS maintains a topology in managing geographical features. Topology is a branch of mathematics dealing with two types of object-points (nodes), lines (edges), and one type of basic relation between them (Frank, 1984).

Even though there are a wide variety of computer graphics systems today, including CAD and CAM, the treatment of topology, or lack of it, constitutes a fundamental difference between modern GISs and old ones, and between GISs and other graphics systems.

In most existing GISs, the topology and geometry of spatial objects are not well differentiated. Instead, the systems often try to derive topological relationships from the geometric properties of the entities. During the topology construction, certain GISs normally place a node (representing an intersection) at any point where lines cross, ignoring the fact that a cross on a two-dimensional map does not necessarily mean intersecting the three-dimensional world (Bernstein and Eberlein, 1992).

### 3.4.1 Topological versus Cartographic Databases

The choice of a particular spatial data structure is one of the important early decisions in designing a geographic information system. A spatial database is called a topological database once the spatial

relationships such as connectivity, adjacency and area definition are computed and stored. In other words, a topological data model keeps spatial relationships for various kinds of spatial analysis.

A cartographic database, by contrast, does not contain the spatial relationships and it manipulates spatial objects individually. Therefore, cartographic databases are less useful for analysis of spatial data. However, they are satisfactory for simple mapping of data.

In practice, many packages designed for mapping only use cartographic database models. A cartographic database can usually be converted to a topological database by computing relationships-the process of building topology by planar enforcement.
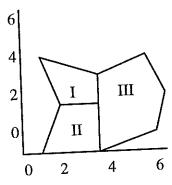
Since topology is explicitly represented in a vector data structure, several forms of vector data structures will be reviewed in this section. Star and Estes (1990) describe the following typical vector data structures:

- Whole polygon structure;
- Dual Independent Map Encoding (DIME) structure;
- Arc-node structure;
- Relational structure; and
- Digital Line Graphs (DLG) structure.

### 3.4.2 Whole Polygon Structure

In a whole polygon structure, each layer in the database is divided into a set of polygons as shown in Figure 3.2. Each polygon is encoded in the database as a sequence of locations that define the boundaries of each closed area in a specified coordinate system, and each polygon is then stored as an independent feature.

| Polygon I: | Polygon II: | Polygon III: |
|---|---|---|
| 1,4 | 2,2 | 6,4 |
| 4,3 | 4,2 | 7,2 |
| 4,2 | 4,0 | 6,1 |
| 2,2 | 1,0 | 4,0 |
| | | 4,2 |
| | | 4,3 |
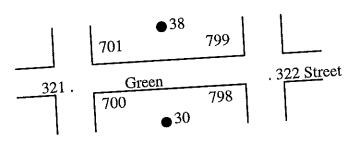
Figure 3.2. Whole Polygon Structure

There is no explicit means of referencing areas that are adjacent in this system. By maintaining each polygon as a separate entity in this way, the topological organization of the polygons is not maintained. Therefore, in a whole polygon structure, line segments that define the edges of polygons are recorded twice. Similarly, points that are shared by several polygons also can be represented several times in the database. With this organization, editing and updating the database without redefining the data structure can be difficult.

### 3.4.3 Dual Independent Map Encoding(DIME) Structure

The DIME structure, developed for use by the U.S. Bureau of the Census, was designed to incorporate topological information about urban areas for use in demographic analyses (Coolce, 1987). The basic element of the DIME file structure is a line segment defined by two end points or nodes. Figure 3.3 illustrates the structure of the DIME file in a simplified way, showing segment codes for line segment and nodes' metric location as easting and northing.

An advantage of using the DIME structure for certain applications is its ability to match addresses of spatial objects in multiple files, since the addresses are explicitly stored in the DIME files. A major disadvantage of the DIME structure lies in the difficulty of manipulating complex lines, for example in functions that require a search along streets. This is because streets are generally broken into discrete street segments by the cross streets, so it is a significant computational effort to follow the segments in sequence.

Street Name:  Green
Street Type:  Street
Left Addresses:  701-799
Right Addresses:  700-798
Left Block:  38, Left Tract:  12
Right Block:  31, Right Tract:  12
Low Node:  321
X-Y Coordinate:  155 000 - 232 000
High Node:  322
X-Y Coordinate: 156 000 - 234 000

Figure 3.3. Contents of A DIME File
(Totschek, Almendinger, and Needham, 1969)

### 3.4.4   Arc-node Structure
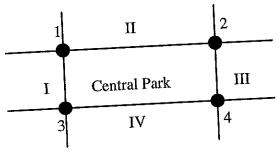
In an arc-node data structure, objects in the database are structured hierarchically. In this system, points are the elemental basic components. Arcs are the individual line segments that are defined by a series of x-y coordinate pairs. Nodes are at the ends of arcs and form the points of intersection between arcs. Polygons are areas that are completely bounded by a set of arcs. Thus, nodes are shared by both arcs and contiguous polygons (Peucker and Chrisman, 1975). Several commercial geographic information systems use forms of this arc-node data structure.

Arc-node structures, as shown in Figure 3.4, permit the encoding of the geometry of the data with no redundancy. In an arc-node database, attribute data of arcs or nodes are explicitly linked to geometry. For example, traffic control device descriptions are stored with the relevant nodes, and roadway length and pavement condition are stored with the appropriate arcs.

## 3.4.5   Relational Structure

The relational data structure is another form of arc-node vector data organization. In the last arc-node example, data attribute values were stored together with topological information. In a relational data structure, attribute information is kept separately. The topological data in a relational structure is organized in the same fashion as in an arc-node organization. The principal difference is in the attribute values. These are stored in relational tables which are straightforward. For example, a row in a table represents a single data record, and the columns represent the different fields or attributes. One of the relational tables keeps track of the attributes of points or nodes in the spatial database.

Notice that this manner of storing data is directly comparable to that of the arc-node format in the previous section. The main difference is that, in the relational structure, the attribute data are maintained separately from the topological information. Thus, there are more separate files and pointers to maintain. General-purpose database management software is available for the relational model. Geographic information systems that take advantage of this software may cost less to develop and may provide added flexibility, by relying on a commercial database management system.

| Node No. | X | Y | ... | Traffic Control |
|---|---|---|---|---|
| 1 | 126.5 | 578.2 | ... | Signal |
| 2 | 218.6 | 581.9 | ... | Sign |
| 3 | 224.2 | 470.4 | ... | None |
| 4 | 129.1 | 471.9 | ... | Sign |

| Arc No. | F-Node | T-Node | Length | ... | # of Lanes |
|---|---|---|---|---|---|
| I | 3 | 1 | 106.3 | ... | 4 |
| II | 1 | 2 | 92.2 | ... | 4 |
| III | 2 | 4 | 116.6 | ... | 2 |
| IV | 3 | 4 | 95.1 | ... | 2 |

| Polygon | Arcs | Perimeter | Area | ... | Zoning |
|---|---|---|---|---|---|
| Central Park | I,II,III,IV | 405.2 | 10203 | ... | 34 |

Figure 3.4. Arc-Node Data Structure
(Adapted from Star and Estes, 1990)

## 3.4.6 Digital Line Graph Structure

The United States Geological Survey (USGS) has developed a digital cartographic data set called Digital Line Graph (DLG) data. The data are topological structured and supplied in DLG version 3 format, supporting both spatial and non-spatial attribute data. The DLG-3 structure has three major components (nodes, lines, and areas) which are analogous to the 0-cell, 1-cell, and 2-cell. The line is the basic element of the DLG-3 structure and any user of the DLG-3 data must start by processing line records. As shown in Figure 3.5, the line records contain one-way pointers to the nodes at each end of the line and to the areas on

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each side of the line. These pointers provide the minimal information needed for a topological structure

(Marx, 1986).
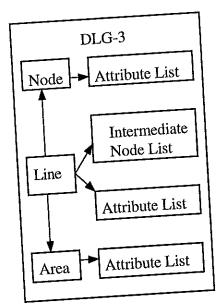


Figure 3.5. The Structure of Digital Line Graph
(Marx, 1986)

The DLG-3 format is an open structure in the sense that users can easily add data to the structure with minimal disturbance to the other elements. However, to use this data for purposes other than mapping, requires significant processing is required to create additional pointers that allow referencing a line from its nodes. Furthermore, there are no provisions for connecting areas which have the same attributes. Therefore, the DLG-3 file structure is generally regarded as a data exchange format and not as an application format.

## 3.5   Map Features and Topology

Maps are fundamental requirements for GIS and transportation. A transportation network is drawn from a street map, and a land-use map is necessary for delineating a traffic analysis zone scheme. The two basic types of map information are spatial and descriptive information. The spatial information describes

the location and shape of geographic features and their relationships. The descriptive information tells a map reader attributes of particular map features (Environmental Systems Research Institute, 1990).

Spatial information in a map is represented graphically as a set of map components. Objects like a well or a manhole can be represented by points. Roads and streams can be represented by a series of lines. Finally, areas in space such as lakes or political boundaries can be represented as a closed polygon connected by lines.

In other words, points, lines, and polygons are the basic map definition elements for representing spatial objects. In the topological approach, a map may be regarded as a combination of fundamental building blocks called cells. The term n-cell is a building block of dimension n and entities involved in a map are O-cell (a point; vertex, node), 1-cell (an arc; line segment), and 2-cell (a region; block, parcel, tract, area)(Hollingshead, 1992). Table 3.2 shows the minimum elements required for a definition of a map, and the incidence relations between the n-cells required to capture the topology of the map.

Table 3.2. Basic Map Definition Elements

| Spatial Entities | Relationship | Metric |
|---|---|---|
| 0-cell | } 0-1 Incidence | Coordinates |
| 1-cell | | Shape |

Questions that characterize the spatial relationship are divided into two categories. First, the topological questions deal with the relationships of the elements. Second, the metrical questions deal with shape and location (Hollingshead, 1992).

## 3.5.1 Topological Issues
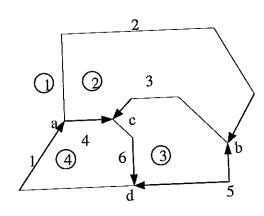
1. What 0-cell, 1-cells, and 2-cells are involved?

2. For a 1-cell, which 2-cells are adjacent? (left-right polygon topology; adjacency or contiguity)

3. For a 0-cell, which 1-cells are terminated? (arc-node topology; connectivity)

4. For a 2-cell, which 1-cells are bounding? (polygon-arc topology; area definition)

5. For a 1-cell, which 0-cells are end points? (arc-node topology)

### 3.5.2  Metrical issues

1. What is the location of a 0-cell?

2. What is the shape of a 1-cell?

The above five topological questions are directly related with notions of contiguity, connectivity, and area definition. Contiguity allows the computer to recognize, for example, that forest land is adjacent to a lake. In Figure 3.6, polygon 2 is on the left of arc 4, and polygon 4 is on the right. Therefore, it's know that polygons 2 and 4 are adjacent.



| ARC | L-poly | R-poly |
|-----|--------|--------|
| 1   | 1      | 4      |
| 2   | 1      | 2      |
| 3   | 3      | 2      |
| 4   | 2      | 4      |
| 5   | 1      | 3      |
| 6   | 3      | 4      |

Left Right Polygon List

| ARC | X, Y list        |
|-----|------------------|
| 1   | 5,3 0,3 2,5      |
| 2   | 2,5 2,9 6,9 8,6  |
| 3   | 7,4 6,6 4,5      |
| 4   | 2,5 4,5          |
| 5   | 7,4 7,3 5,3      |
| 6   | 4,5 5,4 5,3      |

Arc location

Figure 3.6. Left-Right Polygon Topology for Identifying Adjacency
(Figure 2.10, Figure 2.11, and Figure 2.12 are adapted from ESRI
(1990))



| ARC | F-node | T-node |
|-----|--------|--------|
| 1 | d | a |
| 2 | a | b |
| 3 | b | c |
| 4 | a | c |
| 5 | b | d |
| 6 | d | c |

Left Right Polygon List

| ARC | X, Y list |
|-----|-----------|
| 1 | 5,3 0,3 2,5 |
| 2 | 2,5 2,9 6,9 8,6 |
| 3 | 7,4 6,6 4,5 |
| 4 | 2,5 4,5 |
| 5 | 7,4 7,3 5,3 |
| 6 | 4,5 5,4 5,3 |

Arc location
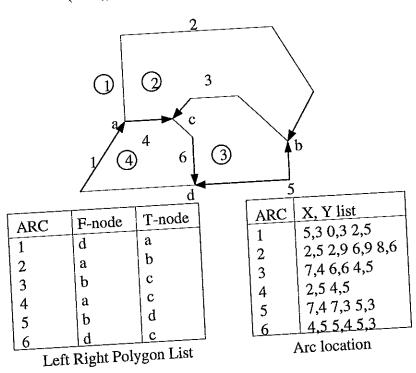
Figure 3.7. Arc-node Topology for Identifying Connectivity

Connectivity involves the connected line-node relationships and is often used to model

utility and other networks, and to trace through these network for analysis of flows. In the

illustration in Figure 3.7, arcs 3, 4, and 6 all join at node c. Therefore, the computer knows that it

is possible to travel along arc 3 and turn onto arc 6 since they share a common node c, but it is

not possible to turn from arc 3 onto arc 1 because both arcs do not share a common node.

In GIS topology, closure or area definition relates arcs that make up each polygon. Figure

3.8 tells that arcs 2, 3, and 4 comprise polygon 2 and arcs 3, 5, and 6 polygon 3 and so on.

| POLY | ARC list |
|------|----------|
| 1 | -1, -2, -5 |
| 2 | 2, 3, 4 |
| 3 | 3, 5, 6 |
| 4 | 1,4,6 |

Left Right Polygon List

| ARC | X, Y list |
|-----|-----------|
| 1 | 5,3 0,3 2,5 |
| 2 | 2,5 2,9 6,9 8,6 |
| 3 | 7,4 6,6 4,5 |
| 4 | 2,5 4,5 |
| 5 | 7,4 7,3 5,3 |
| 6 | 4,5 5,4 5,3 |

Arc location
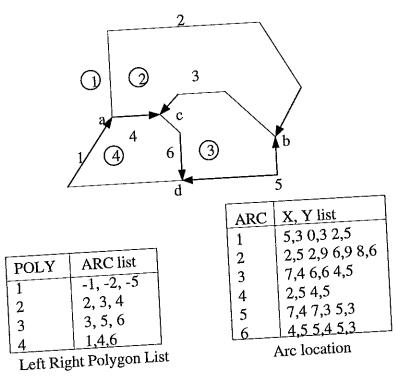
Figure 3.8. Polygon-arc Topology for -defining Area

## 3.6 Trade-offs in a Topological Data Model

One of the advantages of using a topological data model is that spatial analyses can be done without using the coordinate data (Aronoff, 1989). This avoids the time-consuming calculations needed to derive spatial relationships from the geographic coordinates. As a result, many spatial operations are performed much more efficiently by a topologically structured database.
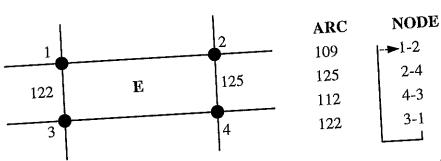
Creating a topology between map features, however, imposes a cost. When new features have been added or some existing features have been deleted or modified, the topology should be updated to provide accurate information. This updating procedure can be relatively time-consuming depending on the size of the map, efficiency of the software, and speed of the hardware platform. In the TranDASS case study, it takes about a minute to update a topology of the Korean highway network that contains 220 nodes and 290 arcs (Choi, 1993).

## 3.7    Uses of Topology
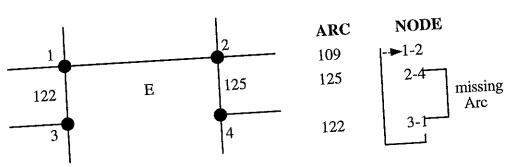
Topological information is not only used in editing and quality control but also used to perform spatial analysis such as connectivity, contiguity (adjacency), and proximity.

### 3.7.1    Data Editing and Quality Control

As can be seen in Figure 3.9, by applying logical tests to topological data, the system can identify errors such as missing or extraneous lines.



Figure 3.9. Logical Tests of Connectivity to Test Topological Integrity
(Antenucci et al., 1989)

Undershoots and overshoots can also be identified using the topology. For example, A simple rule can be imposed on computers that a very short 1-cell terminating in a 1-valent 0-cell indicates an

overshoot, or a long 1-cell terminating in a 1-valent O-cell very close to another 1-cell indicates an

undershoot.
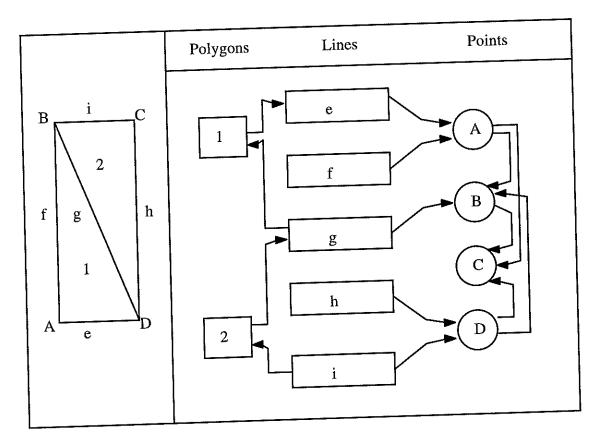


Figure 3.10. Topological Data Structure
(Caliper Co., 1990)

## 3.7.2  Connectivity and Adjacency Representation

Other uses of topological information include analytical functions such as connectivity analysis

that can be used to model urban utility networks-sewage, telephone, and transit line-and to trace analysis of

flows. In addition, routing, districting, and other algorithms use topological information to select or

evaluate routes and to allocate and evaluate proximity to resources.

As shown in Figure 3.10, connectivity and adjacency relationships can be identified clearly through

the relation diagram. Since line g is a constituent of both polygons 1 and 2, it can be said that both

polygons are adjacent with arc g in common. In addition, whenever points are connected directly by arrows, two points are connected by an arc. For example, arc g's beginning node is B in diagram on the light-hand-side and B is connected to C. Therefore both points B and C are connected directly. Furthermore, since points C and D, and C and A are connected, the set of points B-C-D and B-C-A comprise a path that can be traversed.

In sum up, topological information can be used in the following aspects:
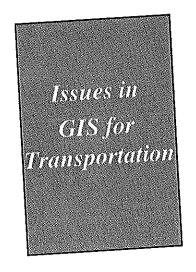
- It provides connectivity and adjacency information for spatial analysis. For example, line and node connectivity relationships are used to model utility and other networks and to trace through these networks for analysis of flows. It can also be used for routing, districting and other algorithms to select or evaluate routes and to allocate, and evaluate proximity to resources. Additionally, topological information supports efficient polygon overlaying procedures.

- It may be used in editing and quality control. By applying logical tests to topological data, the system can identify errors such as missing or extraneous lines.

Arc-node topology (connectivity) can be used for easy and interactive generation of transportation networks. That is, arc-node topology is best for converting to link-node based transportation networks. In addition, adjacency information in topology will be used for generating traffic analysis zones since it will be a valuable constraint that guarantees the contiguity of agglomerated spatial basic units (parcels), which will, in turn, constitute geographical units (zones) for the transportation modeling (trip generation and trip distribution).

## 3.8 Database Organization

The Arc/Node method stores the descriptive information along with the spatial information in the same database. This method reduces the amount of redundancy between the descriptive and the spatial information. The disadvantage of this method is the difficulty involved in changing one element without affecting the other element.

The relational method essentially uses two databases. One database stores the spatial information, and the second database stores the associated descriptive information. The advantage of the relational method is the ease of access to change information in either database without having to process the other information at the same time. The disadvantage of the relational method lies in the redundancy created between the spatial and non-spatial information. The relational method also makes it easier to use information originating from other databases.

# CHAPTER 4

# GIS TOOLS

The tools within a GISs can be classified into five areas: data entry, data analysis functions, data manipulation, querying of information, and display of information. The different functions are shown in Figure 4.1.
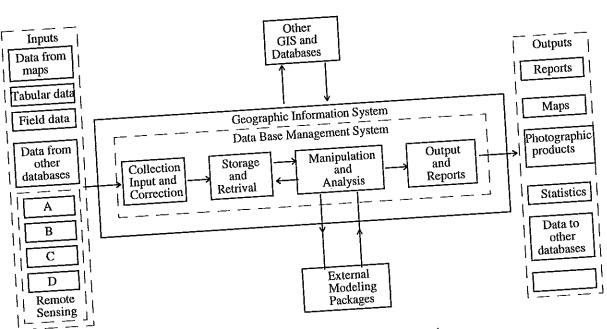


Figure 4.1. Illustration of GIS Functions

## 4.1 Data Entry

In this section we discuss issues that relate to entering data into a GIS. The user needs to know what forms of data can be used by the computer and to understand how the data is entered.

### 4.1.1 Methods of Entering Graphic Data

The method of data entry is an important factor in the integrity of the information produced. There are four ways of entering graphic data into a GIS usable format. These methods include manual digitizing, automatic scanning, Coordinate Geometry (COGO), and conversion of information from a different digital format.

Manual digitizing is the most often used method of data entry. The reason for its popularity is that, when compared to other methods of data entry, it supplies a reasonable degree of accuracy for a low cost.

Scanning has higher capital and operating costs than does manual digitizing. It also lacks the flexibility of manual digitizing. Scanners excel at recording data such as soil types or contour line maps. "Clean" maps, with little or no extraneous data, make the scanning process go much faster, because a "clean" map reduces the amount of post-scanning editing that needs to be done.

Coordinate geometry is designed primarily for capturing and entering the survey data. This is the most accurate method of data entry. It is also a very costly method of data entry. "A city with 100,000 parcels may spend $1.50 per parcel for digitizing or ($150,000 total), but anywhere from five to ten times that amount if entering in the information using coordinate geometry" (Dangermond, 1983). It is also very difficult to enter irregular lines and odd-shaped polygons using COGO.

The final method of entering data is by the conversion of available files. These files can come from already digitized files from CADD programs, or files can be purchased from private businesses and government agencies.

## 4.1.2 Computer-Usable Forms of Data

The form in which the data are recorded is a very important consideration of the data entry process. Data can be entered into a computerized GIS in six forms: computer drawings, vector data, raster data, tabular data, text, and images.

One form of data used by a GIS is computer graphics which are produced by CADD programs. Most data entered from a CADD program must have the format changed to the GIS readable format.

A second form of data is created through digitizing. Digitizing is similar to using a CADD program, the difference being that a digitizing package is especially designed for a GIS.

Another form of data is raster data, which is usually associated with remotely-sensed images. Raster data has a grid structure with many individual cells. Raster data are also used for scanned data and some processed vector data.

A fourth form of data is tabular, or an array of values. Most tabular data are developed in a DBMS. The data can be anything from a simple table to a complicated spreadsheet.

Text is the fifth form of data which can be used in a GIS. Text data usually come from a word processing program. The text used in GISs is often from letters, office memos, and lists of names.

The last form of data is pictures and video tape. The use of pictures and video tape is one of the latest developments to be incorporated in the GIS. A picture or video tape is recorded on a video display or laser disc system. The GIS user can select which picture or tape to view on the computer screen. Pictures and video images are usually available only on workstation, minicomputer, and mainframe platforms, because a large amount of computer memory and processing power are required to manipulate and display these pictures and video images.

The effectiveness of a GIS is related to the availability of up-to-date and reliable data. Most GISs should have several of the methods of data entry available. Manual digitizing is the most frequently used method of data entry because of its relatively low cost and its high degree of accuracy. Scanning is an

efficient method of data entry if the maps are well prepared or "clean." Coordinate geometry (COGO) traditionally has only been found on most high end GISs, but COGO is becoming more readily available on less expensive systems. Probably one of the most important features of data entry is the ability to import and export digital files of different formats. This feature allows the user to have access to a large amount of existing data, such as Dual Independent Map Encoding (DIME), Topologically Integrated Geographic Encoding and Referencing (TIGER), Digital Line Graph (DLG), and Digital Exchange File (DXF).

## 4.2    Data Analysis Functions

Data analysis functions of a GIS should include operations, such as interpolation, measurements, network tracing, proximity analysis, buffering, and map overlaying.

### 4.2.1   Interpolation

Interpolation allows the user to develop additional isometric lines between existing isolines mathematically. Interpolation is an extremely useful function in the development of topographic models. An example application is an engineering department which uses this function to create additional isolines to aid in the design of rain water catch basins with existing survey data.

### 4.2.2   Measurements

The measurement functions of most GISs includes simple tasks, such as finding the perimeter of an area of a polygon, or finding the distance between two objects.

For example, an assessor's office might calculate the acreage of a large irregular shaped lot for the purpose of determining the property tax. The task can be accomplished using manual techniques, but this usually takes a substantial amount of time to complete and the accuracy is usually questionable. A GIS

assigned the same task could complete it within seconds along with a high degree of accuracy, assuming the lot has already been entered into the system. The savings in time makes the assessor's job much more efficient and the improved accuracy makes the property tax more equitable.

### 4.2.3 Network Tracing

Network tracing allows the user to assign vehicles to the shortest or most efficient route. This function can be used to find the most efficient route for school buses and garbage trucks. It can also be used by the Police and Fire Departments to route emergency vehicles to the scene of an accident in the least amount of time. Also, it can aid engineers in designing alternative traffic routes during the construction season.

### 4.2.4 Proximity Analysis

Proximity analysis allows the user to determine how many like or unlike objects are within a user defined area or in a radius from a selected point. For example, proximity analysis might support a query of the number of properties within one mile of the intersection of Elm Street and 12th Avenue with a taxable value of greater than $80,000.

### 4.2.5 Buffering

The buffering function is designed to create an area around a point, line, or area. This function is often used in association with Boolean overlays to exclude areas on a map during a site selection process.

For example, consider a county which is looking for new sites for a new airport. Federal regulations require that no solid waste landfills can be located within one mile of an airport. By using the buffering function of a GIS, the areas within one mile of all the landfills in the county are excluded from the site selection process.

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### 4.2.6 Map Overlaying

Overlaying is perhaps the most powerful feature of a GIS. Overlaying allows the user to combine many maps into one composite map. The overlay function can also be used in conjunction with Boolean variables to eliminate unwanted categories or features in the site selection process mentioned in the buffering section.

## 4.3 Data Manipulation

Data in a GIS can be manipulated in many different ways, including generalization, window/zoom, updating, map merging, and projection selection.

### 4.3.1 Generalization

Generalization is a method of viewing mapped information with a reduced degree of detail from the original information. Generalization reduces the amount of data the computer must handle, but it also reduces the degree of resolution. Generalization is used to look at the entire map when a high level of detail is not required.

For example, for some purposes a map displaying all of the delinquent tax parcels in the city of Chicago could be of limited use, but a map showing the city blocks which have greater than one quarter of their total area as delinquent parcels might be more useful.

### 4.3.2 Windowing (Zooming)

Windowing (or zooming) allows the user to examine smaller areas on the map in greater detail. It can also be used to zoom out from a map to provide a wider view of an area. For example, an engineer could window in on a particular intersection to locate underground utilities.

### 4.3.3 Updating

The update function allows the user to change both spatial and non-spatial image data from the keyboard. Without the update function the GIS operator would have the difficult task of opening computer files and searching the computer coded machine language to make changes to the file.

### 4.3.4 Map-Merging

In the creation of a geographic database, many maps must be entered into the computer. The process of map-merging combines two or more maps inorder to make a continuous map. For example, a county that has its soil information in a GIS, but lacks the all ability to merge the soil maps into one map, could only display one section at a time. An overview of the entire county's soil maps would be impossible.

### 4.3.5 Projection Selection

Map projections are a means of representing the curved surface of the Earth on a plane surface. The type of projection on which the map is based determines what kind of spatial distortion will be present and to what degree that distortion will affect the accuracy of the data. Maps based on projections should be used if the represented study area is larger than six square miles.

For example, a regional planning agency wants to produce a land-cover map of the entire region. The region covers several hundred square miles. A transverse mercator projection is selected because its effects on the information will be minimal.

## 4.4 Queries Information

The query function allows the user to extract information from the spatial and/or the non-spatial database. The information to be retrieved is determined by the user, who sets the different search parameters. There are two basic types of queries possible in most GISs: attribute query and spatial query.

### 4.4.1 Attribute Queries

An attribute query allows the user to extract non-spatial information from the database. For example, the user can request a list of all single family detached land parcels with more than $3,500 in special assessments outstanding within the city.

### 4.4.2 Spatial Queries

A spatial query extracts information from the database and displays it in graphic form. The results of the spatial query are usually presented on a map. A spatial query could, for example, show all the streets built prior to 1964, in the southwest quarter of the city.

## 4.5 Information Display

There are three basic ways to display information from a GIS: text/tabular, map generation, and chart display.

### 4.5.1 Text/Tabular

Most of the text and tabular information produced from a GIS includes work orders, form letters, lists of information, and tables of numbers. Virtually all text information is displayed on a computer screen, and the hardcopy is usually available through a printer.

### 4.5.2 Map Generation

Maps are the primary form of informational display in a GIS. The quality of maps generated by a GIS is dependent upon the software and hardware.

Software directly affects the quality of the map; raster-based software usually results in maps with a choppy appearance, while vector-based software usually produces smoother looking maps. In recent years, some raster software has been developed which that competes with vector software in the production of high quality maps.
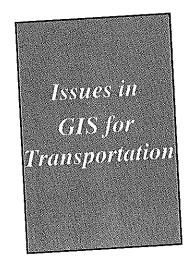
The hardware used in map production also affects the quality of the map in a dramatic way. Some basic map-making hardware includes printers, plotters, and film recorders. There are many different kinds of printers available today. Laser and ink-jet printers usually generate higher quality maps than do line and dot matrix printers. Plotters are commonly used to create hardcopy maps. Film recorders take electronic images of the map and project them onto film which is used to produce slides, overhead projections, or prints.

### 4.5.3 Chart Production

The production of charts is usually related to the statistical analysis of information. Some of the more common charts include histograms, bar charts, line graphs, and pie charts. Some GISs do not come

with the ability to chart or graph information. However, the process of downloading the information and running it through a statistical software package is usually a simple one.

# *PART II*

## GIS FOR TRANSPORTATION

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# CHAPTER 5

## INTRODUCTION TO
## GIS-T

Within transportation agencies, it is common to find large amounts of diverse information being collected and maintained to manage the highway network. Data on pavement condition, traffic, accidents, and highway geometry, to name a few, are collected regularly. In addition, ancillary information on such things as culvert locations, guardrail status, roadway postings, and bridge condition may be collected and maintained.

Depending on the applications for which the data will be used, the responsibility for collecting the required information will, in many instances, not be borne by a single entity within a highway department. Typically, various divisions within the organization will have different data requirements for carrying out their functions. Consequently, it is common to find various entities within a highway department collecting and maintaining data needed to satisfy particular objectives. This situation usually results in data being scattered around different locations within an organization. For example, pavement condition data may be collected and maintained by a Pavement Evaluation unit, accident data by a Safety unit, and traffic data by a Planning unit. However, in order to make sound decisions, the highway administration needs to have access to all the pertinent data available and be able to derive a clear picture of the overall needs of the highway and bridge network.

Geographic information systems (GIS) provide an approach for managing the large and diverse information needed to support decisions affecting the highway and bridge infrastructure, as well as other transportation issues. Through a GIS, data collected throughout a transportation agency can be integrated to support both analysis and graphics applications. This technology is rapidly gaining popularity among transportation agencies in the United States. There are many on-going projects within several agencies at the state and federal levels that are directly related to the development and implementation of a GIS. Geographic information systems are expected to play a major role in the daily operations of state transportation agencies in the near future.

## 5.1 ELEMENTS OF A GIS-T

The main elements of any GIS-T are its database models. Geographic data possesses three inherent characteristics: position, description, and variation with time. The time component can be handled by progressive updating of the geographic element's position and description as they occur, or if applicable, by time modeling algorithms. For example, how will a habitat area change due to flooding during the upcoming rainy season? The descriptive component of the geographic element is maintained in an attribute data base, while the positional component of the element, which is described by its geographic coordinates and by its topological relationship to other elements, is maintained in a geographic data base.

### 5.1.1 The Geographic Data Base

The geographic data base or map base can be structured in either grid (raster), vector, or triangulated irregular network (TIN) format. The TIN structure is better suited for topographic data analysis and is often offered as a separate option in a GIS package. The grid and vector structures are usually used in the planning analysis fields (Dueker, 1987).

The grid structure utilizes a rectangular array to define a polygon framework for storing geographic information. The grid acts as a matrix of x, y coordinates to represent changes in geography. The advantages of such a system are apparent when performing map overlays, since they can be performed without prior processing, or when using satellite digital imaging or scanned aerial photographs as means of data input. Disadvantages include a slowing in display time directly proportional with map resolution, and an inherent inability to explicitly represent feature boundaries (Stiefel, 1987).

Data in a vector format geographic data base can be structured topologically, facilitating the storage and retrieval of geographic data and the recording of spatial relationships of geographic features. Since vector-based GIS uses lines to represent geographic features, their resolution is only limited by the resolution capacity of output devices. However, this same quality also poses some disadvantages. Map overlaying involves determining areas of overlap between base and overlay map elements by comparing polygon areas and determining points of intersection. The time taken for this operation is a function of map complexity and CPU processing speed and can be quite lengthy. Also, scanned photographs and satellite images must be converted to vector format before they can be analyzed by a vector-based system. This is usually performed manually with a digitizing tablet and is a labor-intensive and time consuming process.

## 5.1.2 The Attribute Data Base

Attribute data refers to all descriptive non-geographic information (variables, names, and characteristics) that identify a geographic feature. For instance, an artificial lake can be identified by such things as name, water level, water quality, chemical composition, salinity, water temperature, alligator population, bottom soil type and ownership.

All GIS's use some kind of data base management system (DBMS) to facilitate the handling of attribute data. DBMS's integrate tools for formatted data entry, data editing, data processing and manipulation, data query, and report generation.

DBMS's can be hierarchical or relational depending on the data base model used. In a hierarchical DBMS, attribute data is organized using a hierarchical data structure where all information related to a geographic feature is linked together by pointers stored in the data record (Stiefel, 1987). This structure allows for fast information retrieval and is useful in applications where a rigid data structure is desirable. In a relational structured DBMS all feature information is kept in tables where the relationships between entities is maintained by indexes that point to data fields. Related data associations are formed according to specific data interrelationships. The relational approach, although slower in information retrieval than its hierarchical counterpart, offers a more flexible data structure. This quality is important in applications were the user needs to define new relationships between data fields which in turn will result in the creation of a new attribute.

## 5.1.3 The Georelational Data Structure

One of the main functions of a GIS is to establish the relationship between the location of features in the geographic data base and their corresponding descriptions in the attribute data base. A GIS performs the linkage between locational and attribute data by means of a georelational data structure. A georelational data structure is a hybrid data model that represents locational data in a topological model and represents attribute data in a relational model (Morehouse, 1985). In order to establish a georelational structure, a one-to-one relationship must exist between the record of an entity in the locational data base and the record of that entity's descriptive data in the attribute data base. It is this link between geographic and attribute data that allows a user, for example, to map all roadway sections with serviceability indices greater than 3.5 (Further information see Dueker, 1987).

## 5.2 ROLE OF GIS-T IN TRANSPORTATION AGENCIES

The major significance of GIS-T for DOTs is in its role as a data integrator. Many types of data can be integrated in GIS-T: highway and bridge inventories; photo logs; alignments and other design detail; signage, accident records and other safety data; traffic volumes, flows, and other operational data; and right of way and other ownership data other, more disparate data, can also be integrated such as administrative, land use, demographic, environmental, resource, terrain, and subsurface data. GIS-T does not create a single integrated database, rather it creates a mechanism for integration at will to assist in solving whatever problem is at hand.

GIS-T also serves as a systems and process integrator. As depicted in Figure 5.1, the components of the infrastructure life cycle management process (also the functional areas of a transportation agency) can be viewed as contributing to and extracting from a common spatial data store. Although the various components might require data at varying levels of abstraction and over varying geographic extents, GIS-T provides mechanisms for data conflation and data aggregation. In this view, the major functional areas of DOTs are more closely bound than in earlier views of infrastructure management as a series of linearly related processes. Potential GIS-T applications span all functional areas and include the following:

1. At the planning stage, including transportation planning, pavement management, bridge management, capacity management and air quality analysis.

2. At the preliminary design stage, including corridor investigation, environmental investigation and right of-way acquisition.

3. At the construction stage, including construction planning, detour routing and site management.

4. At the operations and maintenance stages, including highway inventory, accident analysis, winter storm management, traffic monitoring, hazardous waste routing, oversize and overweight permitting.
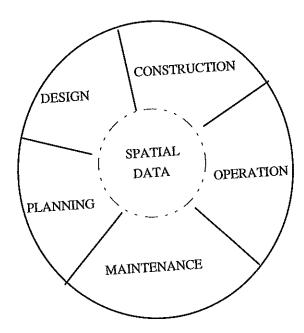


Figure 5.1. Centrality of Spatial Data in Transportation Infrastruaure.
(Adams et al., 1992)

Process integration also appears in Huxhold's (1991) holistic model of information needs and the business of government (see Figure 5.2). Here, basic data are created at the operations level, are summarized for decision making at the management level, and are aggregated even further for policy making. In turn, top-level or policy decision making addresses organization-wide issues during extended time periods, management translates policy into actions, and services to the public are delivered at the operations level. Most of the data at all three levels are geographically referenced. This view of the relationship between information flow and program delivery leads to comprehensive information systems design that supports the organization as a whole.

Program Development →

I
n
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a
t
i
o
n

Program
Delivery

**Policy**

**Management**

**Operations**
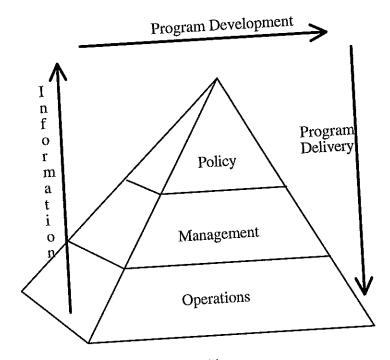
Figure 5.2. Transportation Business pyramid.
(Huxhold, 1991)

Document Scanning System

Image Processing System

Raster GIS

Vector GIS

DBMS

CADD System

Video Media Syatem

Surface Modeling System

Visual

Overlay

Index

Data

Conversions
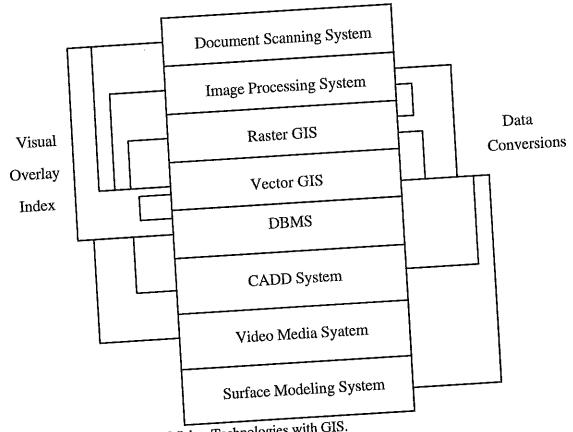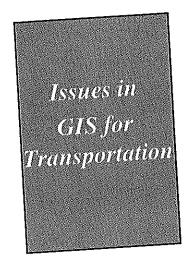
Figure 5.3. Integration of Other Technologies with GIS.
(ESRI, 1989)

GIS-T concepts are also at the heart of technology integration. The technologies depicted in Figure 5.3 are integratable, along the indicated linkages, at either (1) the visual level through display-time overlays or (2) the data model level through conversion mechanisms (ESRI, 1989). All of the technologies in Figure 4.3 are used to capture, manipulate, analyze, or present spatial data and spatially referenced data.

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

**Issues in GIS for Transportation**

# CHAPTER 6

## GIS-T APPLICATIONS

GIS-T is the adaptation and adoption of GIS for transportation purposes, particularly in areas of the development of methods for data storage and the provision of appropriate analytical abilities (Lewis, 1990). It is an environment or framework for managing and analyzing spatial data related to transportation. For example, it can do the following tasks (Lewis and Fletcher, 1992):

- managing and manipulating network
- updating and displaying network attribute
- spatial analyses
- routing analyses
- georeferencing
- linking to other applications

Thus far, examples of GIS-T databases include pavement management, accident management, traffic management, inventory, sign and signal maintenance, photo logging, and transportation networks, as shown in Figure 6.1 (Examples of applications in each area can be found in AASHTO, 1989, AASHTO, 1990, AASHTO, 1991, and AASHTO, 1992). Since transportation data basically deals with linear

transportation networks, GIS-T puts more emphasis on networks which are linear-based arc systems rather than area-based polygons.

However, existing GIS packages have not been well developed to deal with linear data as most transportation agencies require (as compared to polygon data (Lewis and Fletcher, 1992)). Therefore, it has been difficult to facilitate more efficient data storage of multiple representations of a road network. Eberlein (1992) pointed out a set of problems which are obstacles to address many transportation data management and visualization problems using currently available GIS packages. With these problems it is difficult to add the necessary transportation semantics such as routes and sections of arcs.
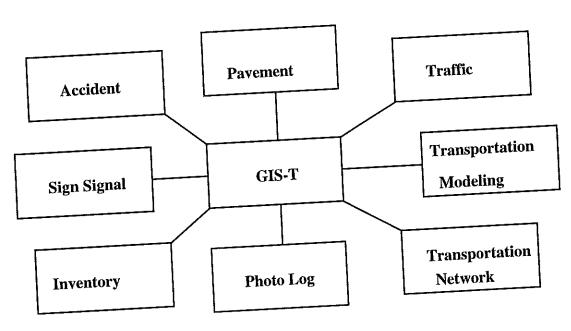


Figure 6.1. Application Area of GIS-T
(Adapted from Fletcher and Lewis, 1989)

Dynamic segmentation within a GIS framework refer to methods for referencing road attribute data of a variable segmentation of the road network. It allows multiple overlapping attributes to be stored without duplicating route geometry. Further, it allows sizable data storage gain and efficient manipulation of transportation entities (such as routes-a combination of arcs, section-a portion of arc, and event-node) by

establishing those databases. It can resolve some problems articulated by Eberlein (1992) such as the entity recognition problem and the reference system problem.

## 6.1 GIS-T Applications

In spite of the problems of currently available GIS software, many applications have appeared in transportation data management (AASHTO, 1989; 1990; 1991; 1992). Broad uses of the GIS-T application framework in planning and engineering can be found in Lewis and Petzold (1990). They are as follows:

**Highway**

- planning of urban and regional roads

- inventory of roads (bridges, signals, lights, sign, etc.)

- pavement management system

- bridge maintenance application

- highway planning

- traffic engineering

    1. accident analysis

    2. highway safety program development

    3. customized traffic ordinance management

    4. state-wide traffic signal system management

    5. traffic requests and investigation

    6. policy and standards development

    7. special traffic engineering system studies

    8. traffic demand forecasting

- corridor selection

- winter storm management

- environmental impact of transportation facilities

## Public Works

- facility mapping and management (manholes or sewers, etc.)

- solid waste planning

    1. landfill planning and management

    2. collection route planning and management

    3. meter reading route planning and management

## Transit and School Bus

- ridership corridor analysis

- route planning

- school redistricting

- school bus routing and scheduling
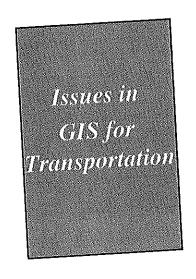
## Others

- airport noise abatement, facility mapping and management

- medical and police emergency responses

- hazardous material routing

- rail management

- port management

- disaster management.

All of the above listed problems are descriptive and static tasks. GIS applications to more dynamic transportation analyses are beginning to appear. Lee presented a simple model of dynamic vehicle routing with emphasis on its system configuration and data organization (Lee, 1990) and Insignares and Terry (1991) applied GIS to traffic control. They refer to several benefits of GIS to Advanced Traffic Management Systems (ATMS) :

1. A user may perform queries of the ATMS in a spatial manner.

2. Geographical organized information can be shared between agencies aiding inter-agency analysis of transportation.

3. Facilities management, incorporated with a GIS, can facilitate the management of remote ATMS component.

Research is being performed to investigate the role of GIS in resolving the temporal data problem associated with the ATMS requirement to predict traffic flow (Al-Thah and Barrera, 1990). In the area of the intelligent vehicle and highway system (IVHS), a GIS based ATMS serves as an ideal model since many of the core functions required for an IVHS will be available through a GIS base ATMS. The spatially referenced structure of the GIS provides a data foundation for real-time analysis of IVHS remote monitoring and control device, including in-car navigation equipment (Wheatley, 1992).

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# CHAPTER 7

# REVIEW OF GIS-RELATED ACTIVITIES IN TRANSPORTATION

Although many applications of GIS have traditionally been outside the transportation area, the technology is rapidly emerging as the information management tool of the future for transportation agencies. There are numerous on-going projects within several agencies that are directly related to the development and implementation of geographic information systems. In this section, a review of GIS-related activities within several transportation agencies in the United States is presented. The review is indicative of activities, but is not intended to be fully comprehensive.

## 7.1    GIS-Related Activities at the Federal Level

In addition to the preceding GIS activities at the state level, there are similar activities on-going at the Federal level. This section presents the Federal Highway Administration's (FHWA) and the American Association of State Highway and Transportation Officials' ( AASHTO) ongoing efforts aimed at developing applications of GIS technology in the transportation realm.

### 7.1.1 Federal Highway Administration

The FHWA sponsored the development of a software package called GRIDS and is actively disseminating it throughout the 50 state DOT's. GRIDS, an acronym for Geographic Roadway Information Display System, is a microcomputer-based software package that allows its user to access and display data pertaining to the U.S. Interstate Highway System. GRIDS was developed by the Caliper Corporation of Newton, Massachusetts under the sponsorship of the Federal Highway Administration's Office of Planning and Pennsylvania State University.

GRIDS displays a map of a state (maps for the forty-eight contiguous states are available) from data associated with state and county borders, geographic location and population of major cities, and interstate highway road sections. A user, by means of an interactive type interface, can request GRIDS to zoom-in to a particular area of the state and to display information concerning the interstate highways within the area of question.

GRIDS integrates many analytical and data query capabilities that are used with its attribute data base (a subset of the Highway Performance Monitoring System data) to produce statistical summaries and pie and bar graphs of selected data. The data query capability is also used to select specific sections of interstate highways that meet certain criteria. Then, the selected sections can be highlighted in distinctive colors directly on the map display. Also, the system can be asked to display the value of any attribute (AADT, serviceability index, skid) on the map, next to its corresponding section. Section traffic volumes can be displayed over the highway map by proportionally varying band widths.

The land base map used for GRIDS is based on the Oak Ridge National Laboratories (ORNL) 1:2,000,000 scale National Highway Network. In order to simplify manipulation, the network has been divided into state sub-networks. Each sub-network is made of various files containing both geographic and attribute information. The attribute data base used in GRIDs is a subset of the data contained in the Highway Performance Monitoring System (HPMS) data base (Simkowitz, 1989). This is maintained and

updated by the FHWA on a yearly basis, and is made from data submitted by each of the 48 contiguous states. In this detailed and extensive data base, interstate highways are divided into sections. Section lengths vary widely from state to state. Each section, together with its associated attribute data, constitutes a record in the data base. Sections are classified into universe and sample. Universe sections contain only vital information such as road number, average daily traffic, etc., while sample sections contain more detailed information such as road curvature and grade data (Peterson and Smyre, 1984).

The GRIDs package was primarily developed to display roadway information for interstate highways found in the HPMS data base. It is useful for graphically displaying information accessed within the boundaries of its data base. However, program modifications are necessary to enable a transportation agency to use its own data base and to display roadway information on non-interstate highways.

In addition to the above limitation, the current version of the GRID program does not have any capability for editing the data base. The Pavement Management Systems (PMS) data base files are centrally managed by the FHWA which provides state transportation agencies with copies of the GRIDs package, including the HPMS files applicable to a particular state. Thus, further program modifications are needed to add editing capability to the program. Ideally, these modifications and other revisions to the program should be carried out by the transportation agencies themselves, as an in-house effort. However, all program modifications will most likely be made by Caliper Corporation since they own the copyright to the software.

The FHWA Office of Planning has also joined forces with the Bureau of Census, the U.S. Geological Survey, the city of Columbia, Missouri, and the Caliper Corporation to evaluate the suitability of the Bureau of Census TIGER/Line files to transportation applications. The TransCAD GIS package developed by Caliper Corporation, was used for the study together with the following sources of data: TIGER/Line file for Boone county (Missouri); the Urban Transportation Planning Package (UTPP); 1980

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Census Data; and accident records and sign inventory provided by the Columbia Department of Public Works. Several GIS applications to transportation were demonstrated:

- The ability to build connected transportation networks from TIGER/Line files
- Routing and traffic assignment performed on the transportation network
- Demographics studies within census tracts and traffic analysis zones
- Accident analysis studies based on spatial relationships between accident locations and traffic signs.

These applications demonstrated the usefulness of the TIGER/Line file for solving transportation problems within a GIS environment (Simkowitz, 1989).

## 7.1.2 American Association of State Highway and Transportation Officials

The American Association of State Highway and Transportation Officials (AASHTO) has recently sponsored a symposium on Geographic Information Systems for Transportation. The symposium was organized for the following purposes (Bacon and Moyer, 1989):

1. To share information on current operational Geographic Information Systems in several transportation agencies in the United States and Canada.

2. To identify specific GIS applications in transportation.

3. To provide technical material on GIS to better the understanding of this technology within the transportation community.

4. To determine the perceived needs and expectations of high-level transportation executives on GIS.

5. To develop an action plan to guide further activities on GIS in the transportation area.

Numerous applications of GIS to transportation were identified during the symposium including:

1. Infrastructure management

2. Scheduling of projects

3. Improvement of highway safety

4. Environmental impact assessment of existing and new facilities

5. Travel demand modeling

6. Vehicle routing.

An important conclusion reached during the conference is that the technology already exists to allow transportation agencies to begin implementing geographic information systems. The key question to answer is HOW to implement a GIS. In this regard, a number of issues were identified in the areas of Applications, Management, Data Needs and Acquisition, and Technology which the symposium attendees felt were critical to the successful implementation of a GIS.

The issues raised also formed the basis for the development of an action plan to guide GIS activities in the field of transportation. This plan consisted of five major items:

1. Education - A strong case was made for educating and training the transportation community on GIS.

2. Standards - There is a need to develop standards in several areas to facilitate data sharing.

3. Institutional impacts - As with the implementation of any new technology, the potential impacts of GIS to transportation agencies need to be defined.

4. Networking - Information on GIS activities should be made available through some kind of a network.

5. User requirements - Certain transportation applications of GIS may be unique and significantly different from traditional GIS applications (e.g., natural resources management, automated mapping, facilities management). Thus, there is a need to identify specific user requirements

within the transportation community and to communicate these to vendors of GIS products so
that transportation requirements can be better met.

## 7.2 State Departments of Transportation

### 7.2.1 North Carolina Department of Transportation

A GIS feasibility study was completed by the Division of Highways of the North Carolina DOT (Dildine et al., 1988). Three major areas of application of a GIS were identified:

1. Map publishing - a GIS provides a way of automating the production of a variety of maps used within the Department. These include county maintenance maps, straight line maps, urban planning maps, and Transportation Improvement Program (TIP) maps.

2. Management/modeling activities - a GIS can function as a data analysis tool to support the programming of roadway projects (e.g. maintenance, rehabilitation, and safety improvement projects), and the justification of funding requests.

3. Ad-hoc queries - a GIS can be used to perform "what if" analyses on the highway network and can show the effects of different "what if" scenarios in a way that the user can readily grasp and comprehend, i.e., through pictures.

The feasibility study was conducted by a GIS Task Force within the Division of Highways who has determined that a GIS is feasible and should be actively pursued by the Department. The Task Force has developed a plan for implementing a GIS that calls for the creation of an Implementation Committee and a staged approach to GIS implementation. Initial efforts will be to develop a GIS for users in the major areas of pavement management, traffic engineering, planning, bridge maintenance, map publishing, and

field office support. The initial cartographic data base will be developed from 1:100,000-scale USGS DLG's to allow the GIS to be operational within a reasonable length of time. However, the implementation plan also calls for the development of a 1:24,000-scale digital cartographic data base that will serve a broader range of users. The informational data base design is also going to be established in the initial phase of the implementation plan. IBM's relational data base, DB2, has been recommended by the GIS Task Force as the informational data base management system to use with the GIS.

In addition, the development of user interfaces and application programs will be accomplished in the initial stage. As these programs are developed and brought on-line, the Implementation Committee will provide support to users in the initially targeted application areas to help them start using the GIS. This will be accomplished in Phase 2 of the implementation plan.

In Phase 3, expansion of the GIS to serve other users within the Department is planned. The Task Force anticipates that as the GIS becomes fully functional, personnel from other branches of the Department (e.g., Policy and Programs, Maintenance, Construction, and Design) will become heavy users of the technology. At this point, the Task Force realizes that a careful evaluation of user needs in these other areas will be necessary so that application programs can be developed accordingly.

Development of the 1:24,000-scale digital land base is also scheduled to begin in Phase 3 of the implementation plan. Currently, 1:24,000-scale DLG's are not available for the entire State so the implementation plan also calls for the study of methods for developing and updating the digitized land base in a GIS. In addition, the plan calls for evaluating the application of photo-logging and laser disc technology within a GIS.

## 7.2.2  Ohio Department of Transportation

The Ohio DOT began developing a GIS in 1980 with initial funding from the National Highway and Traffic Safety Institute. Consequently, the primary application of GIS has been in the analysis and

reporting of accident data. The GIS is based on INTERGRAPH hardware and software. Data is stored in the Department's IBM mainframe computer and an interface allows access of the data by the GIS. INTERGRAPH's Data Management and Retrieval System (DMRS) is used for data base management, and its Spatial Analyst software is used to query, analyze, and display the geographic data base. This data base includes 112,000 miles of roadways and was developed by manual digitization (Bacon and Moyer, 1989).

Ohio has made considerable use of GIS in planning and operations, and sees its greatest potential as being in the support of the decision-making process.

### 7.2.3  New Mexico Department of Transportation

The New Mexico department of Transportation is developing a statewide network of geodetic monuments which will be used to locate positions within the State using Global Positioning System (GPS) technology. The Department views GPS as being necessary to support the long-term implementation of a GIS. Although initial GIS implementation will be based on the 1:100,000-scale Census TIGER files, the ultimate goal of the Department is to have a highly accurate, large-scale land base for its GIS. This land base will be developed and maintained through GPS.

GIS implementation is currently underway with two immediate objectives. The first is to define the system requirements and the second is to subsequently develop a request for proposals to commercial vendors. With respect to issues on GIS implementation, the following were identified by the Department as being crucial to the successful implementation of a GIS:

1.  Location referencing scheme - Although the Department has already developed a common referencing scheme for its GIS, the process was not without difficulties. Consequently, the New Mexico DOT sees the development and implementation of a unified location referencing scheme as being an important issue to address. Guidelines are needed which will help make this task easier.

2. Data standards - the Department believes in encouraging the use of data standards to facilitate information exchange. In particular, standards for digital cartographic data are important.

### 7.2.4 Pennsylvania Department of Transportation

Pennsylvania spent $ 51.7 million for GIS implementation by 1989 (Bacon and Moyer, 1989). The state DOT has digitized 42,000 miles of highways, with another 3 to 5 more years estimated before the digitization efforts are completed. High on the list of Department priorities is the restructuring of position-related data. With so many data bases, Pennsylvania DOT relies heavily on a fully functional, network-structured data base design. It is expected that the combination of graphic and tabular data to support planning and decision-making activities will push the technology rapidly forward in the near future.

### 7.2.5 Colorado Department of Highways

The Colorado Department of Highways (CDOH) is in the third year of its initial GIS plan which covers three major areas (CDOH, 1989):

1. System acquisition

2. Data base development

3. GIS accessibility

The system acquisition phase was completed with the purchase, in 1986, of the ARC/INFO software from Environmental System's Research Institute (ESRI). Data base development is currently on-going and was scheduled for completion in 1992. In order to facilitate the development of the geographic data base, existing USGS 7.5-minute quadrangle maps for the entire State were purchased by the Department from the Petroleum Information Corporation. Considerable enhancement to the highway layers of the digitized maps is currently being done by the Colorado DOH.

To date, 7 of the 56 counties in the State have been digitized and linked to the Department's statistical data bases. A route-milepost reference system is used to link the geographic data base to the CDOH data bases, the main one being the Colorado Roadway Information System (CORIS). Data base development efforts are expected to lead to an integrated data base with over 100 attributes per roadway segment. The geographic data base will contain approximately 160,000 separate line segments, representing 9200 miles of state highways, and 67,600 miles of county roads and streets.

Already, certain benefits have been realized in the implementation of the GIS. The most noticeable benefits are in the reduction of the time required to produce map overlays and update existing maps, and in the elimination of redundant base maps. In particular, the map overlay function was very useful in the designation of routes for the Hazardous Material Route Designation program. In this application, census data were overlaid with the highway network in order to produce population estimates for the routing model.

Other on-going GIS activities within the Colorado DOH include:

1. Implementation of the Department's computer network which will provide users access to the GIS and to any other data in the Department.

2. Evaluation of GPS to increase network of survey control points and produce more accurate maps.

3. Evaluation of the needs of CDOH engineers to determine if a project level GIS component is feasible.

4. Acquisition of new non-highway related information such as demographics, political district boundaries, soil types, land use classifications, and contours to increase modeling capabilities.

The Department plans to undertake an intensive effort during the next three years to complete the geographic data base. This will be accomplished using commercial vendors to help in the digitizing efforts. The Department also intends to continue actively promoting cooperation with Federal, State, and local agencies by sharing information and thus avoid duplication of efforts.

### 7.2.6 Wisconsin

The Wisconsin DOT has a long history of automation development. As is true of pioneering efforts, this has its positive and negative aspects. The negative aspects are related to the propagation of numerous systems developed at different times using different technologies which are not compatible with one another. Like other states, their accident system is not compatible with the roadway inventory which is not compatible with pavement condition and so on. However, with the development of a completely digital state highway map for their 12,000 mile road network, the Wisconsin DOT views GIS as a possible data base integrator. They are using ARC/INFO software to systematically examine GIS applications into:

a) The integration of photolog data into GIS (Fletcher, 1988) and

b) The integration of other highway attribute data into a GIS using a line overlay approach. Separate files will continue to be maintained by different units within the DOT. It is the job of GIS to use topologically structured cartographic chains to perform the integration.

### 7.2.7 Kansas

The Kansas DOT is actively trying to expand the capability of the FHWA sponsored GRIDS system. As originally configured, the GRIDS package was optimized to analyze the HPMS data for each state. Efforts in Kansas are focused on adding bridges to the system so that information stored in the Federal ridge Management System can be graphically displayed. The Kansas effort should permit graphical displays of deficient bridges to supplement the deficient highway identification routes available with the original GRIDS package.

## 7.2.8 California

Like Kansas, the California DOT was equally impressed with the potential of the GRIDS package. The California efforts have focused on expanding the network. The original GRIDS package only contained routes on the primary network. However, the HPMS package contains information on secondary systems such as minor arterials and collectors. California has digitized its entire highway network and now can graphically display, via the GRIDS software, every highway for which it is responsible.

## 7.2.9 Alaska
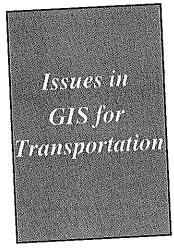
The Alaska DOT is currently integrating its highway related data bases (inventory, condition, traffic, accidents and project history) into a Highway Analysis System (HAS) (Nyerges, 1988). This system contains a topological segment/node representation of the physical roadway network. Attribute data is referenced according to a relative distance from the beginning node. Maps are being digitized and digital data is being acquired from USGS to provide coordinates for highway geometry.

This work is being performed under contract with Boeing Computer Services.

# *PART III*

## GIS IMPLEMENTATION STRATEGIES
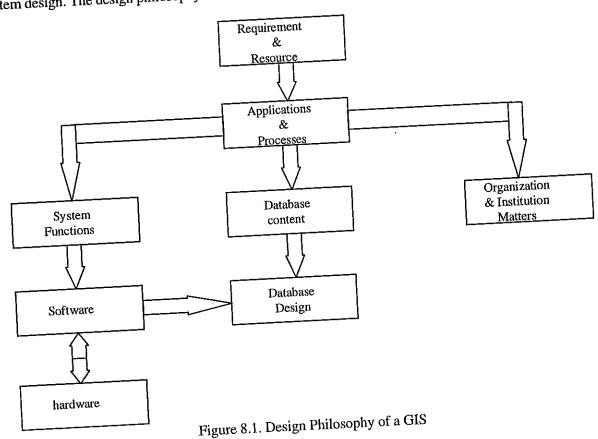
# CHAPTER 8

*Issues in GIS for Transportation*

# DESIGN AND IMPLENTATION OF GIS

Organizational inertia often poses a challenge to the introduction of GIS, and its successful implementation depends on sufficient institutional support. The best way to generate that support is to formulate and present a clear vision of the role of the GIS within the organization. A consistent philosophy will lead to a clear vision of GIS utility. That philosophy may be simply stated: Applications must drive system design. The design philosophy is shown in the Figure 8.1.

Figure 8.1. Design Philosophy of a GIS

The term *system* entails more than hardware and software components, although it certainly incorporates those elements. A system also embodies data base content and structure, personnel, organizational structure, and financial resources. System function, data base content, institutional structure, and procedures all are based on a clear statement of the system's requirements. Too often, hardware and software become the dominant or exclusive focus of GIS decisions.

Requirements of a GIS should be defined in terms of the applications the system is expected to support. As noted above, the technology offers a diversity of potential, not all of which may be purchased from a single vendor. By thoroughly investigating the applications that the user organization(s) must support, and by establishing the relative priorities of each, the definition of a system uniquely appropriate to the organization will emerge.

The design process is iterative, moving from the abstract, to a concept, to a preliminary design, to detailed design, and then to specification. A data base is the foundation needed to perform any application. Whether the data base is built transactionally, over a period of time, or, as is more often the case, is the result of a substantial preliminary effort, its content and accuracy are essential to the success of GIS. The cost of data base development and maintenance will exceed the costs of all other GIS components by several fold. Defining data base content and accuracy, while maintaining applications priorities, is one of the important first steps in system design.

Later in the process, a detailed data base design becomes critically important to system implementation but is not essential early on. Furthermore, the detailed data base design depends on software considerations usually addressed later in the process, and on the institutional procedures that support data maintenance.

The functions of the system can be determined without focusing on specific software and hardware products. Graphic and data base manipulations, analytical functions, and the system's configuration are examples of system functions. By defining these elements, the character of the system takes form and cost

estimates become possible. Within the context of the chosen applications, the relative importance of various system functions must be determined:

- Should the system be optimized for the entry of drawings or maps?
- Will the manipulation of graphic data more likely involve the combination of various themes best represented by polygons or the movement and placement of lines and dimensions?
- Will the linear features be schematic representations or accurately depict placement?
- Will linear features be used in a manner that makes their connectivity essential and desirable, or unimportant?
- Should more than one individual have immediate access to graphic representations of the data base?
- Will a centralized or distributed processing equipment configuration best serve the user community?
- Will the equipment support other processing functions that are non-spatial?

The answers to these and other questions form the basis of conceptual system configurations accommodated by multiple vendors. Specific decisions on software and hardware are premature at this stage. In fact, early commitments to vendors can shift the design focus away from solutions that best respond to system requirements.

Computer hardware should be viewed as subordinate to software. Once it becomes clear that one or more software packages support the application requirements, compatible computer processors and operating systems can be chosen. With the increased availability of UNIX and associated technology, software is more easily transferred between computer processors of various makes. Processors and other

computer hardware must be measured by price considerations as well as their ability to meet specific user needs.

In some situations, the processor and operating system influence, even control, the selection of GIS software. An organization that has accepted a particular vendor as its supplier sometimes limits its software choices. In other instances, the availability of existing processing resources and the need to avoid additional costs governs the choice of a hardware platform.

To realize the full benefits of GIS, institutions must adapt to the technology. Although it is possible to introduce GIS technology as a tool to replace or enhance what is done manually or not at all, its integration into decision making and work flow is likely to require changes in procedures and, perhaps, in the structure of the organization itself. Identifying potential changes in structure and procedures is another preliminary task.

Structural changes are threatening to any organization. When a system is implemented to increase the productivity or capability of an individual operating unit, structural changes are modest or nonexistent. Perhaps the drafting work force is divided into an automated group and a manual drafting group, resulting in two lead drafters. When GIS is introduced to support an entire agency or company, or multiple government agencies and jurisdictions, the situation usually demands new formal and informal agreements, interactions, user committees, policy or management committees, cost allocation, joint budget procedures, and so on. New lines of communication and assigned responsibilities require structural changes, both subtle and dramatic.

The way a task is accomplished can change. The availability of a single and consistent data base eliminates steps previously taken to process and validate zoning requests, work orders, and information queries. The physical movement of hard-copy data is rendered obsolete. Storage and archival functions change or are eliminated, and a range of simple and complex procedures are modified. The extent to which

an organization succeeds in altering its procedures and work flow has a direct bearing on whether the technology will be integrated whether the organization will reap its benefits.

## 8.1 Gaining and Maintaining Support

The decision to proceed with the implementation of a GIS hinges on technical, institutional, and financial factors. This decision represents a major commitment for most organizations and requires support at all levels of the organization. Further, that support must be sustained through the tedious and sometimes lengthy process of system implementation.

Three general approaches--technological, political, and educational--can build and maintain organizational support.

The *technological* approach calls for a specific and logical sequence of activities. It requires the definition of user requirements, addresses fundamental hardware and software issues, and defines databases and applications in detail. The results are framed in a cost-benefit analysis. Typically, the technological approach is launched by operational units, such as the comprehensive planning division within the planning and development department in a municipal government or the drafting section within the distribution engineering branch of a utility organization. The technological approach generally is used by individuals and organizational units who are promoting the concept to higher authority levels in the organization.

Senior and mid-level managers usually garner support for GIS with a *political* approach. The aim of this top-down approach is to inspire enthusiasm about the technology and to surmount insecurities associated with change or risk of failure. Senior managers also are in a position to overcome institutional and personal barriers. The political approach employed by senior management typically lacks technological definition. Their interest in the concept more often relates to a desire to enhance efficiency, effectiveness, profit, and state-of-the-art profile. Mid-level managers may find themselves straddling the fence; they might

rely on a political approach to win sponsorship from senior management and on a technological approach to gain acceptance of GIS by operational staff.

An *educational* approach most frequently plays a supporting role and varies somewhat given the target group. Senior management needs an overview of the technology that addresses who is using it, with what success, and its costs and benefits. Senior management cares about how the bottom line performs and the essential factors that influence it, such as cost schedules, labor, and impact on other priorities.

Mid-level managers require a higher level of understanding of the technology; they are less likely to be persuaded by broad-brush overviews. Labor requirements expressed in terms of quantity, experience, and availability within the organization and other logistical issues are likely to be of interest. Financial considerations usually are expressed in terms of fiscal-year budgets and cost per parcel, utility service, or other relevant unit of measure.

At the operational level, the educational requirements--diverse, technical, and interdisciplinary-- may add to the marketability of individuals within and beyond the organization. These trained individuals are more likely to seek out additional educational opportunities, such as conferences, workshops, and professional journals. Moreover, they frequently are asked to survey industry offerings and to host demonstrations and sales discussions led by vendors of GIS products and services. The education that operational staff amasses, however, may be fragmented, requiring substantial thought and effort to establish a context relevant to the operational requirements of the organization as a whole.

## 8.2    Implementation Methodologies

Organizations quickly become enamored with color screen displays, computer processors, and potential applications. The temptation is to buy a system, built a data base on the fly, and get started. Many systems are launched with little planning, little design, and great expectations.

Such an implementation strategy may succeed. However, more thoughtful ways of approaching implementation minimize the risks and match the direction and pace with available resources.

Implementation of a full-scale GIS is a long, complex process. It generally involves multiple organizations and often costs hundreds of thousands, if not millions, of dollars. The full process, from the decision to implement a GIS to its completion, requires subdivision into logically related steps to aid understanding. Seventeen such steps are listed here.

The five broad stages and seventeen steps to successful implementation are as follows:

## I   Concept

Step 1: Requirements analysis

Step 2: Feasibility evaluation

## II   Design

Step 3: Implementation plan

Step 4: System design

Step 5: Data base design

## III   Development

Step 6: System acquisition

Step 7: Data base acquisition

Step 8: Organization, staffing, and training

Step 9: Operating procedure preparation

Step 10: Site preparation

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## IV  Operation

Step 11: System installation

Step 12: Pilot project

Step 13: Data conversion
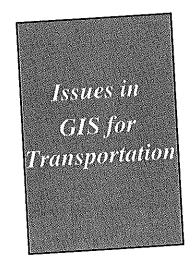
Step 14: Applications development

Step 15: Conversion to automated operations

## V  Audit

Step 16: System review

Step 17: System expansion

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# CHAPTER 9

# GIS IMPLENTATION STAGES AND STEPS

The five stages and seventeen steps described here are very important. For an actual implementation project these steps can be further subdivided into many work units. The sequence of the specific actions will vary from project to project, depending on strategy, priorities, and the local environment. Some steps will be accomplished in sequence, others will occur in parallel, while still others will overlap. The implementation stages are shown in Figure 9.1
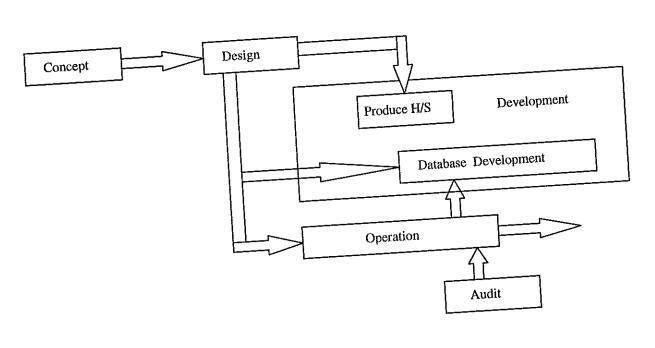
Figure 9.1. Implementation Stages

## 9.1 Concept

During the concept stage of implementation, the project is defined based on an evaluation of user needs and available resources, and feasibility is assessed. The two steps in the concept design stage are shown in Figure 9.2
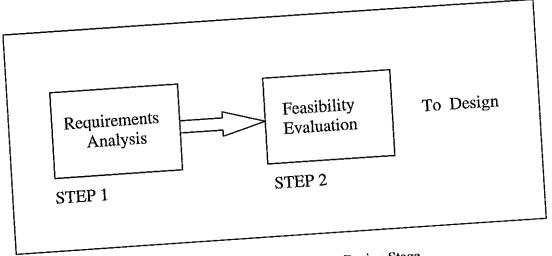


Figure 9.2. Two Steps in Concept Design Stage

### 9.1.1 Step 1--Requirements Analysis

Requirements analysis is the foundation of a successful GIS implementation. The analysis includes the identification of activities relying on map and geographic information throughout the organization, with attention to both graphic elements and non-graphic attributes of the graphic information. In many cases, it is the attribute or geographically related data that is of central interest to the professional and administrative work force. Furthermore, an inventory of current map data files leads to an assessment of redundancy in the collection and handling of data, the identification of information that is desired or needed but not available, and an appreciation of potential data base maintenance procedures. This final component of the analysis stems from the characterization of how information flows through the organization. In many cases, benefits can be derived by simplifying this information flow and eliminating inefficiencies in handling, storage, and manipulation of geographic data among various organizations or units.

Important GIS design considerations related to function, data content, and capacity depend on a clear understanding of the needs of the various units involved. The organization's requirements are identified from a structured analysis of its operations and projections of future conditions. The evaluation of needs should be done rigorously and methodically.

At least the following seven types of requirements are assessed in the analysis:

- Processing functions and data contents

- Data standards and characteristics

- System applications and products

- Software functionality

- Hardware devices and capacities

- Communications facilities

The requirements analysis may use several techniques, including interviews, workshops, questionnaires, and modeling. The purpose of the analysis is to describe the present and future requirements of the GIS based on the perceptions and information supplied by current staff. However, since those persons typically are not familiar with GIS technology, it may be necessary to ensure a common basic level of understanding through training sessions, workshops, conference attendance, publications, or other educational techniques.

The requirements definition process involves identifying those organizations or groups within an organization that may benefit from the GIS and dividing them into functional areas and levels of significance. Individual representatives with extensive knowledge of the organizations and their operations should participate in the analysis.

Interviews are a primary method to obtain required information. They may be structured with specific questions or unstructured, allowing the unique conditions of the organization and the interviewer to guide the discussion. One or more analysts with a thorough understanding of GIS technology should carry

out the interviews. If practical, the analyst(s) also should have some knowledge of the organization and its operational function. The persons being interviewed should understand the purposes, management issues, and technical aspects of each function discussed. Conducted with individuals or small groups, interviews cover descriptions of the organization's mission, current operations, and problem areas. During the course of the interviews, sample maps and other supporting materials are collected and reviewed, and the organization's resources and operating environment are defined.

Interviews are relatively time-consuming and labor-intensive. The time is well spent with organizations that will play a key role in the GIS development and use. With other organizations, the effort can be minimized by conducting group interviews or workshops. With this approach, several representatives of multiple organizations meet with an interviewer or moderator to describe and record the needs of the various organizations.

To gather information on maps, data, and application needs, questionnaires may be used. The map features, current map descriptions, scales, data volume, and other information are easily recorded by the participants on properly designed questionnaires. Similarly, information about current costs and resource commitments often can be acquired through questionnaires.

Models or checklists of standard functions and requirements can verify and analyze the information collected. The models are used to analyze a variety of tasks, including data and map features, required relationships among data, processing and display functions, and hardware devices and capacities. The requirements information is documented for use in subsequent steps. This initial step supplies virtually all of the other steps with information for design, application development, and operation. The documentation describes the scope of participation: the objectives of the system; the data entry, processing, retrieval, and display functions required; the graphic map features and non-graphic data required; and the functional requirements and capacities of hardware devices. The findings are then reviewed with the participants to

identify shortcomings, confirm requirements, and clarify ambiguities. Following participant review, comments and corrections are incorporated into the final requirements document.

Internal staff, outside GIS consulting experts, or a combination of both perform the requirements analysis. As mentioned earlier, typically there is a knowledge gap between the GIS experts and the potential users. The persons conducting the requirements analysis must bridge that gap by understanding both the GIS technology as well as its potential for application in the organization, and the functions and operations of the users. The analyst must draw needed information from participants, who, because of unfamiliarity, may have difficulty stating their requirements specifically in terms of GIS. The number of analysts required depends on the size of the organization, the number of organizations involved, and the complexity of the potential GIS.

A requirements analysis conducted by a skilled team also serves an important educational role if representatives from the participating organizations are sufficiently involved in the process. Sometimes it is difficult to involve users in the analysis and to elicit the specific information needed due to their lack of time, interest, or understanding of the technology's potential.

Four to six months is a reasonable time-frame for the requirements analysis.

## 9.1.2  Step 2--Feasibility Evaluation

Most organizations must evaluate the feasibility of implementing a GIS before making a major investment. The feasibility evaluation generally involves identifying the extent to which the GIS is practical and estimating its costs and benefits. The scope of the feasibility study depends on the size and complexity of the organization and the diversity of potential GIS applications. A large, multi-organizational GIS often requires an extensive analysis, while a single organization, in which a PC-based GIS is the logical solution, may require only a few hours of investigation to prepare a memo on its value.

The feasibility study is based on the requirements analysis. The information on current operations is used to project a baseline condition, assuming that current information management methods will continue. The requirements are used to propose one or more alternative GIS configurations and databases for the organization. These conceptual designs provide the basis for estimating costs and benefits, and may address options such as central and distributed configurations of processing power and databases, extensive or minimal configurations, or other variations.

The costs of acquiring hardware and software, developing the data base, and maintaining and operating the system over a reasonable period are estimated for each alternative. The cost estimates should present a range based on estimates from a number of vendors who can deliver systems and databases that meet the organization's requirements. Operating costs include a core staff to manage and support the system and its data base, and to develop and maintain application programs.

Using the techniques described in Chapter 4, a benefit-cost analysis serves as the focal point for the feasibility analysis. First, the operation of the GIS and its impacts on the organization are delineated so that the benefits from implementation can be identified. Where practical, benefits are quantified. Efficiency gained in various functions represents a direct benefit. Most organizations also realize indirect savings in numerous areas. The estimates of these cost savings include both actual labor saved and savings resulting from improved decisions.

The costs and benefits of the alternative GIS configurations are calculated and then compared to current operations costs. The comparison should extend over time to full implementation of the GIS and its data base, and to full operation. Typically, a major GIS requires two to five years for full implementation before all non-recurring costs and benefits are realized. The feasibility analysis, therefore, should include a seven to ten year life cycle period.

Objectivity and credibility are significant issues in the feasibility analysis. In some cases, a feasibility study is conducted by a person or organization wishing merely to justify acquisition of a system.

In other cases, the study is conducted by one who wishes to block acquisition. Neither of these approaches is particularly effective. To ensure credible results, an objective party who will not benefit from a system internally or through subsequent sale of a system or data base services should conduct the study.

Conceptualization of an appropriate GIS design and estimation of costs and benefits requires a high level of expertise and access to information on system and data base costs that may not be available within the organization. Consequently, a consulting expert is often necessary. The consultant also can lend credibility to the findings.

As noted above, the scope of the feasibility study may vary widely depending on the organization and its requirements. A thorough, in-depth analysis of a GIS for a large or multi-organizational implementation may take six to nine months or longer. Allowing time for participant review and decision making may extend this period further.

The feasibility evaluation typically plays a persuasive role with senior management, boards, and elected officials in reaching a decision on whether to proceed and with what level of effort.

## 9.2 Design

If the feasibility study supports a decision to acquire and implement a GIS, the process moves to the design stage. In this stage, detailed plans for implementation, as well as the system and data base designs, are prepared. The three steps in detailed design stage are shown in Figure 9.3.
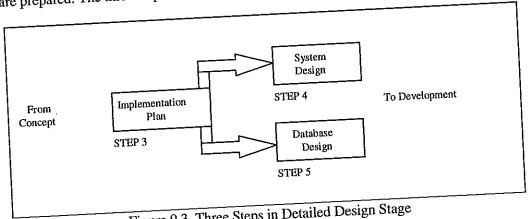


Figure 9.3. Three Steps in Detailed Design Stage

## 9.2.1 Step 3--Implementation Plan

Preparing an implementation and management plan is the next step. GIS implementation usually involves numerous tasks undertaken by multiple organizations, including system vendors and contractors. Careful planning and coordination is essential. The implementation plan provides all participants with an understanding of individual roles and responsibilities and the relationships among tasks, and it defines and controls all subsequent steps in the process as follows:

- Identifies and describes individual tasks

- Assigns responsibilities for each task

- Indicates the resources committed

- Defines relationships among tasks

- Identifies products and milestones

- Establishes a schedule.

The plan documents each factor in an easily comprehensible manner. A computer-based project management program may be used to update the plan and to monitor and report on its status. The plan is updated regularly by the project manager as tasks are accomplished or changes occur.

In addition, the plan contains a network diagram or description of the relationships among tasks and a schedule with key milestones noted. The plan defines a "critical path" through institutional and financial considerations, as well as technical efforts. The material is described at a sufficient level of detail to support management control of all tasks and resources. As described in subsequent steps, specific data base development, installation, and plans for phasing from manual to automated data management are incorporated later. A summary of the plan usually is prepared for senior managers and others with a general interest in the project.

Preparing the plan begins with identification of all tasks involved in the implementation project. A general model derived from other successful GIS projects is useful in identifying the tasks. The information

from the feasibility study on system configuration, data base contents, cost estimates, and participants is used as the basis for implementation planning.

A standard set of information is recorded for each task, including a description of the task, an identifying name and/ or number, the responsible organization and person, the funds, personnel, and other resources allocated, planned and actual beginning and ending dates, products or deliverable items, and the relationships to other tasks. Developing this information requires coordination and agreement among participants, and decisions by management to commit resources and assign responsibilities. Major decisions generally are made at the organization's highest level of management or by a policy body in a multi-organizational project. A draft of the implementation plan should be reviewed by representatives of all participating organizations to ensure its feasibility and to confirm commitments.

The plan should be prepared by someone with prior GIS implementation experience who is familiar with all tasks, and who has the skills needed to estimate the time and resource requirements for each task. A thorough implementation plan for a relatively complex project can be prepared in one to four months by an experienced planner.

Problems may occur in several areas. Adequate cooperation, coordination, and commitment among all participants may be elusive for a multi-organizational GIS. The participating organizations may have different perceptions of the tasks or effort involved, and rivalries over responsibilities may emerge. Estimates of time and resource requirements also may cause disagreements.

## 9.2.2 Step 4--System Design

Two parallel tasks are required to prepare the detailed design of the hardware/software system and the data base. GIS is implemented typically by acquiring a commercially available hardware and software system. Numerous GIS systems are available in the marketplace, each with individual strengths and weaknesses that should be assessed in light of the organization's requirements.

Selection of the system may be a formal or informal process. Most government organizations and many utilities use a formal process based on a request for proposal or similar procurement procedure. A detailed design and preparation of specifications is necessary for the acquisition procedure. Because several candidate systems typically are available, the specifications at this stage are defined as functional requirements rather than as specific devices, model numbers, or software packages.

The detailed design builds on the conceptual design of the selected alternative configuration defined in Step 2, and it is guided by the implementation plan from Step 3. The concept is augmented with detailed descriptions of hardware and software function, capabilities, and capacities.

Sometimes it is necessary to collect more detailed information on maps, data, and processing requirements than was needed for the feasibility study. More detailed analyses produce the design specifications that are used subsequently for acquisition of the system. Refinement of the conceptual design is especially important with regard to the specific workstations, plotter, and application software requirements. With the movement to distributed systems and networks, the communications requirements also should receive special attention in the design.

Preparing the detailed design requires special skills and expertise in hardware, software, networks, and communications. The designer must be familiar with the available systems and the methods of system design. The time required depends on the size and complexity of the system and the involvement of the users in the design. A relatively complex system can be designed in six to nine months with time for participant review of drafts and resolution of conflicts.

Problems are sometimes encountered in documenting generic design specifications to solicit proposals from several vendors. An organization may have a problem choosing between components that can be practically justified and those that are requested by various participants. Rapid changes in GIS technology also challenge the designer.

### 9.2.3 Step 5--Data Base Design

A detailed design of the GIS data base is produced in parallel with the system design. The detailed data base design develops specifications to create and maintain the data base. The specifications guide in the acquisition of data base development services and to encode the data base schema or other definitions necessary for the GIS.

The data base design addresses the contents, specifications, relationships, and sources of data to be incorporated into the GIS data base. A detailed design is prepared for each of the data "themes" to be included in the data base, such as planimetry, topography, ownership, jurisdictional boundaries, utility facilities, and so on.

The detailed design is a refinement and augmentation of the conceptual design developed in the feasibility study. It begins with a review of the feasibility study and conceptual design. In most cases, additional detailed information on the requirements and source materials is gathered. Each source is evaluated thoroughly to verify the availability of the required features and the accuracy, completeness, and ease of use in digitizing. The design document identifies and defines all map features and non-graphic data and their characteristics.

The relationships among the various sets of features or other data are important, especially those of connectivity and adjacency, as well as positional relationships that allow the various overlaid features to be related to each other and positionally adjusted to the control framework. The design specifies the degree of positional accuracy necessary and the hierarchy of layers and features that will achieve it.

Source materials are evaluated to identify one or more source documents or acquisition methods for each required map feature and non-graphic attribute. If no existing source can be identified, a decision is made either to delete the feature or layer from the data base or to obtain it from new aerial photographs or field measurement. Copies of the source materials are compiled by the project manager for use as a sample reference throughout the project.

The source materials are evaluated to verify the area covered by each map feature. Data entry procedures for the identified source materials are designed and evaluated to verify the practical usefulness of the source materials.

The design document is then reviewed by the potential suppliers and users of GIS data to verify the sources completeness and practicality. The design is produced by a person (or a team of two or three) skilled in GIS data base methods, cartography, and map compilation procedures. The detailed design of a complex GIS data base takes about six months to complete.

Acquiring and evaluating the source materials are the most significant potential problems. In most organizations, existing maps and data sources are scattered among multiple units and are neither complete nor uniformly standard. Significant effort is required to locate and thoroughly evaluate sources. In the event of conflicting source materials, their precedence must be resolved.

Another challenge is to determine the relationship of the data base design and the software when the software has not yet been selected. This relationship is particularly critical when the design will incorporate large volumes of non-graphic attribute data whose format must fit a particular structure while retaining their logical relationships to graphic data elements.

## 9.3   Development

In the development stage, an organization acquires GIS software, hardware, and data conversion services, and develops procedures to operate the system. The five steps in detailed design stage are shown in Figure 9.4.
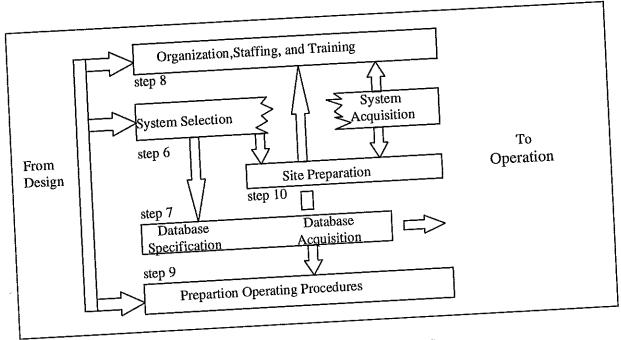
Figure 9.4. Five Steps in Development Stage

## 9.3.1 Step 6--System Acquisition

Acquisition of the GIS hardware and software often is the primary focus of the GIS project, even though several other steps are equally important. The purpose of this step is to acquire the most effective GIS hardware, software, and support at the most advantageous market price.

Systems can be acquired in various ways. An informal review and simple selection may be used, especially by private organizations. Among public and government organizations, however, a formal procurement process generally is required. The formal procurement involves specification of the system requirements, request for proposals or bids, an evaluation of proposals, and selection of the optimal system offering. The level of formality and the complexity of the selection process can vary dramatically, depending on the rules governing procurement within the organization.

Organizations sometimes choose a specific GIS early in the project for a variety of reasons, such as to establish compatibility with a related system, because a key decision maker had prior experience with

the system, or because of an effective sales approach. If no specific system has been pre-selected by this point, a selection process is carried out.

The system acquisition process uses the detailed design specifications produced in Step 4 to prepare the proposal request. Because numerous systems are available, with several viable candidates for any specific acquisition, the selection process should be designed to allow a wide range of practical offerings. First, prepare specifications that describe functional requirements rather than specific devices or software packages. The hardware specifications should describe the types of devices (e.g., workstation, processor, plotter), their functional capabilities (e.g., resolution, speed, capacity), the number of items, and their capacities (e.g., data storage, number of devices supported). The software specifications should describe the functions required for various categories of software (e.g., operating system, graphics processing, data management, applications). Specifications for communications devices and software also are included for systems that will link separate devices.

The specifications are documented in a request format that conforms to the organization's procurement rules. The request for proposals solicits details on items such as documentation, training, maintenance and other support services, and the relationship between the vendors of software and hardware if the sources are not the same. The request for proposals also describes the terms and conditions for the purchase, including insurance requirements, installation dates, payment schedule, and the organization's standard contract language. The procedures and criteria for the evaluation and selection are described, at least generally, in the request for proposals in order to clarify priorities for the vendors.

GIS vendors are invited to submit proposals offering hardware and software systems that meet or exceed the specified requirements. The response to the request for proposals becomes the core of a contract between the vendor and purchaser.

Procedures and criteria for selection are essential to an efficient and fair review and selection process. The procedures used to evaluate proposals include benchmark tests, interviews, reference

verification, and others as appropriate. The scoring and weighting criteria for each step should be defined before proposals are evaluated.

Organizations typically use a team of up to five or six evaluators with expertise in areas such as hardware, software, communications, applications, maps, operations management, and data issues. The team meets prior to procurement for orientation and any necessary training. The team reviews draft specifications and evaluation procedures before distributing the request for proposals. Once proposals are received, the team reviews and scores them, participates in interviews, verifies references, and conducts the benchmark tests. The team should meet at each stage for status reports and discussion of any problems.

Typically, the team selects a "short list" of the three or four highest scoring candidates, interviews each of the short-list vendors, conducts benchmark tests or site visits of the short-list firms, and, finally, selects the most favorable proposal. An evaluation of the technical specifications separate from the cost proposals ensures proper consideration of the technical requirements.

Proposals are ranked by assigning specific scores for each of its components. The scoring may use points on a scale (e.g., 1 to 10) or points for classes of desirability (e.g., "barely satisfactory" to "exceptionally high quality"). Groups of scores may also be assigned weights to balance the importance of each group of factors relative to the others.

Verification of references is an important selection criteria. The experiences of prior clients are particularly important in the areas of vendor support, responsiveness to problems, and the operational functioning of the system.

Interviews with selected vendors offer an open exchange of information and an opportunity to clarify at once any issues that arise. The vendor usually is given the opportunity to discuss the strengths of its proposal and the commitment of the corporation.

Two approaches--a benchmark test or a site test--are used to observe the system in operation. In a benchmark test, a specific test of system capabilities is developed and presented to the vendors. The vendor

is given a period of time to prepare for the test, perhaps one to two weeks. The evaluation team then visits the vendor and observes specific tests. Data from a pilot test or another site with similar data bases may be provided to the vendor to populate the test data base. The evaluation team observes and records functionality scores, timing, and other information about the system operations. The test is used to verify the operation of critical functions, the ease of use, and other criteria. The evaluation team should develop a test that is proportionate to the magnitude of the system to be acquired. Benchmark tests are costly, so the purchaser must be reasonable. If an extensive benchmark is necessary, the purchaser should consider partial reimbursement of the vendors for their costs.

Benchmarks traditionally have played a formal role in the selection of computer hardware and software. In the past, they have been used primarily to test basic functions of candidate systems. More recently, as basic GIS capabilities have become more reliable, the focus for benchmarks has shifted to testing a product's utility for selected applications.

The other approach to product verification is a visit to a currently operating customer site. In this case, a specific test usually is not performed. Instead, the evaluation team views actual customer operations and has the opportunity to ask questions of counterparts in a comparable organization. This approach is not as rigorous as a benchmark test, but it provides exposure to the practical realities of a candidate system and its supplier.

After the results of all evaluations are compiled, the evaluation team selects or recommends the best offering. The selected vendor then is invited to negotiate a contract for procurement of the system. The organization prepares for negotiations by identifying modifications needed in the terms of the proposal terms and conditions of the contract. Especially important are agreements for continuing support, maintenance and response to any problems that should arise, including penalty clauses for system failure. The contract should include mechanisms for dealing with any future disagreements.

The length of time for system acquisition may be as short as one month for a simple, informal procedure. Procurements with complex, rigorous procedures that involve multiple organizations may take six months to one year. A procurement process expected to take more than several months must be designed to allow incorporation of emerging changes in technology prior to contract execution.

Problems with system acquisition often arise in finding a team of persons with adequate knowledge of GIS who also represent the appropriate units of the acquiring organization. It is sometimes difficult to write specifications that are sufficiently detailed, yet still provide equitable opportunities for all appropriate candidate system vendors. Recognizing the subtle differences between systems, evaluating proposed systems, and reaching agreement on a selection may be a problem if the selection team does not have a thorough knowledge of GIS technology.

## 9.3.2 Step 7--Data Base Acquisition

Data base acquisition is a similar step to system acquisition, and occurs at the same time. Development of a GIS data base--conversion of hard-copy (analog) graphic and non-graphic data and reformatting of existing digital data--requires substantial investment of personnel, time, and financial resources. In most cases, it is impractical for the organization to acquire photogrammetric equipment and workstations and to assign sufficient staff to create the digital data base in a reasonable time. Most organizations developing a GIS today contract with a mapping or data conversion firm for the initial data base development. Conversion vendors can provide a large, skilled labor force, complemented by equipment and software tools optimized for data entry and editing.

GIS data base development generally includes four types of data entry:

1. Photogrammetric compilation and digitizing using an analytical stereo-plotter

2. Automation of existing maps using a digitizer or scanner

3. Key entry of data

4. Transfer of existing digital data.

Acquisition of a GIS data base involves contracting with one or more firms to acquire existing digital data, to digitize map data, or to enter non-graphic data. The acquisition process may be a single contract or may be divided into multiple contracts. To help keep this major effort manageable, data base development sometimes is divided into these logical components: aerial photography and analytical triangulation; compilation and digitizing of planimetric and topographic features; compilation and digitizing of parcel maps; and digitizing existing maps of other features.

The procurement process for the data base is similar to that used to purchase hardware and software described above in Step 6.

The specifications for data conversion describe all map features and non-graphic data to be entered in the data base, and the standards of accuracy to be achieved. The specifications also describe the source materials, products and their formats, and the relevant characteristics. The request for proposals includes these specifications, contract terms and conditions, evaluation procedures, and directions for submission of the proposal. In addition to commercial information, the Request For Proposals (RFP) solicits information such as conversion procedures and techniques, quality-control procedures and standards, and management and staff's experience and availability. RFP's also address equipment and software resources and availability, existing work load, outstanding proposals and potential work load increases, and delivery schedules for preliminary and final products, both hard copy and digital.

As mentioned, there may be a single request, or the overall data base development may be divided among two or more contracts. A set of procedures and criteria is established for evaluating proposals and selecting the most advantageous offer(s). The procedures address the evaluation and scoring of the various components of the proposals received. They also describe the method for conducting and scoring interviews with candidate firms, site visits to review the contractor's facilities and equipment, and the verification of references.

Proposals are reviewed to verify compliance with specifications and to evaluate the capability and capacity of the equipment and personnel that are available to do the work. Each item in the request is scored on its quality. Weighting then is applied to establish the relative importance of various factors.

Quality of service to prior clients is an important factor in selecting a mapping contractor. This can be verified by contacting references provided in the proposals. Compliance with specifications and timely delivery of products are key elements in the reference evaluations.

Once the proposals are evaluated, the number of candidates are reduced to the best qualified. Site visits to the short list of firms may be appropriate to assess the equipment, staff, and capacity of the firm to handle production in the contract time span.

Cost proposals must consider the relationship between quality and cost. The purchaser must ensure that the vendor is offering services and products of satisfactory quality before considering costs. In some cases, procurement rules require the award of contracts to the lowest bidder. In a low-bid procurement, only the opening of bids and verification of compliance with specifications is necessary. This is not the preferred approach since it does not allow recognition of differences in a firm's relative capabilities, past performance, and technical approach. In some cases, the higher-quality firms will not bid on such a request, leaving an organization with limited or lower-quality offers. Even those who bid may offer only minimal, lowest-cost services that are not as advantageous.

The specification and solicitation of services should be managed by persons experienced in GIS data base development and knowledgeable about map compilation, map digitizing, and data base development. The selection team also should include persons with an understanding of the GIS map and data requirements and the available source materials.

Solicitation of proposals, selection of the data base contractor, and negotiation of the contract usually takes five to seven months for a relatively large GIS project. Compilation of maps and conversion

to digital form may take several years for large areas or detailed databases. The main time limitation is the organization's capacity to prepare source materials and to control the quality of delivered digital products.

### 9.3.3 Step 8--Organization, Staffing, and Training

Probably the most underrated step in GIS implementation is that of organizing to implement and operate the system. Reviews on completed GIS implementation processes universally indicate that a group's personnel, and how they are organized, are key factors in success. When a GIS is managed effectively and staffed properly, its chance for success is high. One of the most serious staffing problems likely to be encountered is inadequacy, either in numbers or in skills.

While the most appropriate approach to GIS organization varies from project to project, certain issues must be addressed in almost every case. Key determinants of the GIS organization are the policies and structure of the overall organization in which it is implemented. Will the GIS be operated within a single organization or shared? If multiple organizations are involved, will the GIS require an interagency structure of some type? Will overall management be assigned to a single organization operating on behalf of all participants, or to a policy board of representatives from the participating organizations? In either case, an executive manager is needed to coordinate the activities of the participants.

The organizational structure may be centralized, with one body providing GIS services to the participants, or it may be distributed, with each participant operating independently of the others. If the participants share data or resources, standards for a compatible definition and structure of the data base and compatibility among the hardware devices and software components of the system must be established by the GIS organization.

The GIS organizational structure defines the authority, responsibility, chain of command, staffing level, and other management characteristics. Defining these clearly is sometimes difficult in a multi-organizational environment, and written agreements between the participants usually are needed to clarify

roles and responsibilities. Planning and establishing the organizational structure usually involves the highest levels of management in the participating organizations.

In a decentralized, multi-organizational project, the individual participants develop internal GIS organizations under the overall structure. Within an individual organization, the GIS responsibility may be assigned to an existing unit, a new GIS unit may be created and placed in an existing department, or an independent GIS department or major unit may be created.

Personnel are designated to perform several specific jobs or functions, including implementation project manager, system manager, and data base administrator. In addition, a GIS organization needs system analysts, programmers, and operators.

Whether shared or operated by a single organization, the GIS requires an implementation project manager responsible for all aspects of the implementation. This person manages the acquisition of the system, development of the data base, assignment and training of staff, development of application programs, and preparation for use of the system.

The system manager is responsible for day-to-day management of all system components and operations, and needs experience and knowledge in all aspects of GIS technology and operation. The system manager supervises the core GIS staff, assists with and coordinates use of the system, and serves as the liaison with the system vendor. The tasks of system manager and implementation project manager may be divided between one or two persons, depending on the scope and magnitude of the project and the operating environment.

The data base administrator manages the resources, quality, maintenance, and use of the data base. This person defines the data base and its component elements, oversees its creation, establishes and monitors quality standards, authorizes and monitors access rights to the data base, and develops procedures for continual updates.

The skills of a system analyst and programmer are required for development and maintenance of application programs, system support, and problem resolution. The complexity of the system, number of users, and sophistication of the applications dictate the number and level of skills of analysts and programmers needed for a specific GIS. The person(s) (including the data base manager) must have knowledge of the appropriate programming skills, macro or procedure language, and FORTRAN or another higher-order language provided with the GIS. Experience with the specific GIS software is desirable, but experienced persons are difficult to recruit. It may be necessary to train a person who has the basic skills.

Operators of the system--those who digitize and produce maps, retrieve data, and perform analyses--are spread throughout the user organizations, in most cases. System operators are drafters, engineers, planners, and other employees trained to use the system as it relates to their jobs.

GIS training takes place at multiple levels. The GIS manager and key support staff receive the most intense training, but a wide range of representatives from user organizations also are trained in the system's use and operation. The most basic training is provided by the system vendor to those who operate workstations. Since the GIS requires special skills typically not available in an organization, additional training for selected persons is necessary. The types of training generally include GIS system management, system software programming, and general GIS concepts. Managers throughout the organization receive training in the applications of GIS technology and its management effects and opportunities. This training may be provided by the system vendor or others, such as a GIS consulting organization, or a combination of both. In addition, the staff should be encouraged to attend GIS workshops, courses, conferences, and other events sponsored by professional societies, universities, or commercial firms.

One of the most common problems is lack of adequate staffing. Too often, organizations focus on the potential staff efficiencies that will follow implementation and fail to recognize the need for continued staffing of current manual operations and the additional requirements of GIS implementation. In most

cases, additional staff are required for a period of time to support the implementation. System operation requires assigned staff resources.

### 9.3.4 Step 9--Operating Procedures and Preparation

The usefulness of GIS to an organization depends on effective operating procedures that are carefully designed and embedded in the activities of the organization. Procedures cover the operation and management of the system, maintenance, update, and administration of the data base, application and use in each participating organization, and production of the standard and special products of the system.

Agreement of all user organizations on an overall structure for system operations is necessary. This structure ensures compatibility among the procedures of the individual units and minimizes redundant activities. The structure guides the flow of initially captured data to the GIS and its data base. It also governs the basic methods by which units use the system to retrieve and manipulate data and produce displays, maps, and reports. It defines the relationships between the system and the end users of its products and capabilities.

Based on this overall structure, the individual operating units design their respective procedures. These procedures describe how to acquire or route data, access and operate the GIS, display or generate maps and reports, deliver products to end users, and use the products in specific operations.

Procedures for use of GIS in functional activities focus on the effectiveness of those activities rather than on the GIS itself. To be effective, the GIS should be an integral part of the operating activities of each unit rather than an appendage that must be dealt with separately.

Significant major operations may need to be designed and documented, while other activities will require less formality. For data-updates, the procedures facilitates interaction with clients, citizens, or field measurement, data to be acquired, format and characteristics of the data, verification techniques, recording

methods, movement of source data to the GIS, entry and quality control, final posting, modification of existing data, and archiving.

Before installation and operation (Step 11) of the system, the organization designs and establishes system management procedures. These procedures govern all aspects of the system's operation. The system management procedures cover activities such as:

- Day-to-day operation of the system components

- Maintenance of the hardware devices and software

- Monitoring of system utilization

- Problem resolution

- Backup of data base and software

- Allocating and authorizing use of system devices and system access

- Management of hardware and software maintenance contracts

- Support for system users

- Authorization of application development and installation

- Upgrading of hardware and software.

- 

A set of records describing the system components and procedures for their maintenance is established during installation and before initiation of operations. The records identify components, describe characteristics, and list all problems and maintenance activities over the life of each device.

Procedures address both the GIS operations and their accompanying functional activities. Major procedures are designed through careful analysis (again by a group with adequate expertise) of the function's requirements, the operating environment, and the system capabilities.

GIS application programs are developed as described in Step 14 to support the operating procedures. These two design activities are closely coordinated to ensure integration of the applications into the procedures.

### 9.3.5 Step 10--Site Preparation

Although electronic equipment requires fewer environmental controls than ever before, it is still necessary to prepare for the installation of GIS hardware devices and the communications network. This step includes selection of optimal locations for the individual devices, allocation of adequate space for all components, preparation of detailed plans for the space, construction of necessary facilities. Moreover, the installation of an adequate power supply, environmental controls, and communications lines and devices must be addressed.

The activities of this step are changing as GIS hardware systems change. In the past, virtually all GIS configurations required the construction of an environmentally controlled facility for certain hardware devices. This is still the case with some configurations. Large mainframe and some minicomputer systems require (or operate more efficiently with) an air-conditioned, humidity-controlled, raised-floor environment. Plotters, printers, and disk units often are placed in such a special facility to minimize their impact on the office environment and to control operating conditions.

The typical workstation requires space comparable to what an office desk or drafting table occupies, but other necessary devices require larger accommodations. During the transition from manual to automated operations, space is required for the new GIS equipment in addition to the manual operations that have not yet been phased out.

Another consideration is optimal placement of the system's hardware devices. Some organizations require multiple workstations spread throughout the organization, while others concentrate stations at a single location or share them among multiple users.

While most hardware devices today operate on standard office power, the availability of adequate electricity must be determined prior to installation. Organizations that overlook that seemingly simple detail encounter serious problems. A power upgrade for a building can be time-consuming and costly, but it may be required if the current usage approaches capacity. Site preparation can be complex, involving separate contractors, permits, permissions from building managers, and other logistical arrangements.

A plan is prepared to determine the optimal placement of all devices and necessary support facilities, including wiring and communication devices. The plan is based on the detailed system design configuration, the requirements of each system user, and the physical characteristics of the various devices. Office layouts with GIS devices need also to include furniture and equipment, wiring diagrams for both power and communications, construction drawings, and technical descriptions of any materials and equipment.

Site preparation may include contracts with separate firms for tasks such as moving walls, constructing environmentally controlled areas, and installing heating, ventilation, air conditioning, wiring, or fixtures. This may require planning and scheduling a separate procurement. If construction, wiring, or other significant changes are necessary, permits and permissions from the local building code organization and the building's owner or manager may be required.

## 9.4   Operation

The five steps of operational stage are shown in Figure 9.5.
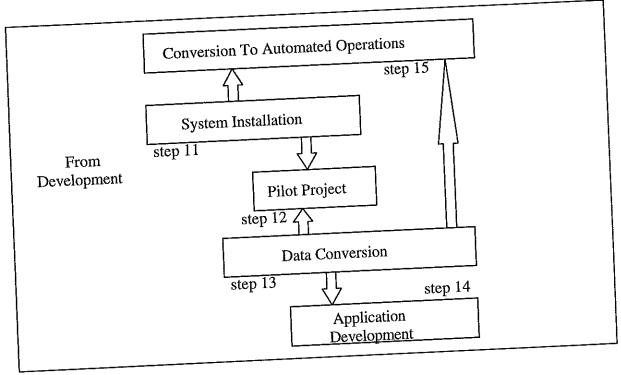
Figure 9.5. Five Steps in Operational Stage

### 9.4.1 Step 11--System Installation

This step includes the delivery, installation, and initial operation of the GIS hardware and software configuration. An installation plan based on information from the design, acquisition specifications, and contract documents guides all activities.

Installation is conducted under the direction of the organization's system manager. Other participants in installation often include the vendor's project manager and staff, the GIS staff and user organization staff, a communications firm, and technical consultants.

An installation team is designated and tasks assigned as appropriate. The plan for installation is prepared in coordination with the vendor during or immediately following negotiations for the acquisition contract. Preparations for installation are made in the period between contract execution and delivery.

The vendor typically tests all system components when delivered to the customer site. Installation includes cabling of components and the communication network if one is involved. In addition, the software components are loaded into the appropriate processors.

When all components have been installed, a series of tests is conducted. Initially, a site test is performed to verify successful installation and operation of all hardware and software components. These tests are performed by the system vendor and are observed and verified by the purchaser. The purchaser also may have the functionality of specific system components and their ability to meet contract requirements tested by either the vendor or in-house staff. If these tests are completed successfully, the system is accepted and payment is authorized. In many GIS installations, not all hardware components may be available or operating properly, or software may not be fully operable at the time of the tests. In these cases, it is necessary to reach an agreement on a revised operation date, and, if appropriate, penalties that apply. Training for staff in system operation often is offered by the system vendor during the installation period.

Technical problems are often encountered during installation and testing of a system, but most are resolved with minimal difficulty by the installation team. Problems also may develop between vendor and purchaser if tests are not completed successfully. To minimize disagreements over test results, it is important to clearly define all aspects of system capability and capacity in contract specifications and to agree to the tests and criteria for verification of acceptance prior to system delivery.

## 9.4.2 Step 12--Pilot Project

Because of the magnitude of a GIS project, many organizations begin operations with a pilot project. Several approaches may be taken, depending on the requirements and resources of the organization. Objectives of a pilot vary and are undertaken to do the following:

- Verify the operability and usefulness of GIS technology
- Verify the costs and benefits estimated in the feasibility study
- Create a data base for system selection benchmark testing

- Build prototypical databases that assist the organization in identifying the format and structure requirements of the selected GIS software.

- Verify procedures for data base development

- Provide hands-on training for organization staff.

Numerous other objectives may be identified. In addition, a pilot study can be useful at several stages of system implementation. In some cases, a contractor is retained to conduct the pilot or to provide a pilot system and data base before the organization purchases a system. In most cases, a pilot is conducted by the organization itself following acquisition, sometimes with the assistance of vendors or consultants.

Undertaking pilots was once an obligatory step to establish the credibility and performance of software and hardware products. Pilots are now employed most frequently as a vehicle to assess the technical, procedural, and cost implications of data base development, and, secondarily, to establish that critical applications can be accommodated. A plan for the pilot project defines its objectives, identifies tasks, assigns responsibilities, defines the pilot area and data base contents, and specifies the tests and evaluation criteria.

A small geographic area representative of typical or critical conditions is defined. If an objective is verification and refinement of data base procedures, all or most of the data is entered for the pilot area. If this is not an objective, a subset of the data may provide an adequate sample for the evaluation.

A series of tests or exercises is planned for the pilot; these may include digitizing and entry of data, map production, simple applications, and data retrieval and analysis functions. The tests are selected to verify crucial capabilities and to give prospective users an opportunity to test and observe the system in operation. Some applications may be fully implemented for the pilot; others may be implemented only partially or simulated, depending on the time and resources available.

If a pilot is conducted before system acquisition and a contractor provides the hardware and software, the organization should decide whether the contractor must provide a specific vendor's system.

This decision may influence the selection of the contractor. If a specific system is required for the pilot, the qualifications of the pilot contractor and the proposed system must be carefully evaluated. Alternatively, an organization could decide to keep the pilot separate from final software or hardware selection. In either case, the GIS used in the pilot must be able to provide a valid test. Development of the data base for the pilot includes:

- Digitizing Quality control and spatial registration of multiple sets of map features

- Development of the selected application programs

- Preparation and execution of the planned tests

- Evaluation of the experiences procedures, costs, and other aspects of the pilot.

Following the evaluation, system and data base designs, data base development procedures, and decisions on implementation may be revised to respond to the pilot findings.

The pilot requires staff sufficiently knowledgeable to develop applications, operate the system, and conduct the tests. Since the pilot frequently takes place in the early stage of the GIS implementation before the in-house staff has obtained adequate experience, organizations may retain a consultant to conduct some aspects of the pilot. If the pilot is conducted by a contractor or with consultant assistance, the purchaser should participate actively to ensure the necessary organizational involvement and to provide practical, realistic tests of the system capabilities. Also, the pilot serves as an important educational experience for the organization's staff. Its outcome typically leads to design refinements rather than drastic changes in course, particularly if the pilot is a component of a thoughtful approach to system implementation.

The duration of a pilot depends on the magnitude of the GIS project and the extent of the testing. The pilot should, however, be completed within a reasonable time to allow adjustments in the implementation project and to avoid loss of momentum. Three to six months is reasonable for many GIS pilot projects.

Technical problems can be anticipated as the pilot is conducted; their identification is one of the major purposes of the pilot. Problems with staffing and organizational coordination also may arise. If contractors are involved, their contracts should be sufficiently flexible to allow adaptation to changing conditions and preliminary findings.

### 9.4.3 Step 13--Data Conversion

The creation of the data base is the most time-consuming and costly aspect of the GIS implementation. A detailed plan for the data base development was prepared as part of Step 5. The plan, in addition to the specifications for the data, describes the order of data entry in terms of both geographic areas and map features or layers, the allocation of assignments between contractor(s) and internal staff, and the mechanisms for combining various sets into the integrated data base.

The GIS data base usually is developed through the combined efforts of in-house staff and a contractor. The data base specifications are defined in terms of the system's data management software. As digital data become available, they are loaded into the GIS.

The loading begins with a rigorous quality-control effort. The quality-control procedure evaluates the contents, completeness, positional accuracy, logical consistency, proper definition (e.g., separation into correct layers or types), and other quality characteristics of the data.

As data quality is verified, data are entered into the permanent data base. Subsequently the data base directory and control mechanisms are updated with the characteristics of the loaded data. Any required logical relationships between data base components are established in the loading procedures. A verification ensures that all data have been properly loaded. Upon successful loading, the data base manager certifies the data base for operational use, and data base maintenance procedures are initiated to provide updated map features and data as changes occur.

The initial loading often involves only a portion of the full GIS data base. The initial data base may include a part of the geographic extent that will eventually be covered or a subset of the features that will eventually be included. The remainder of the data is loaded in phases as it becomes available from compilation and digitizing activities.

Data base loading is supervised by the data base administrator, who is responsible for the quality of the data and for loading the data in its proper structure. The data base administrator also maintains records on the data base's contents and quality characteristics. In the operational phase, the data base administrator manages the loading of various phases and components until the data base is complete, and then coordinates its maintenance.

### 9.4.4   Step 14--Applications Development

The GIS extends its efficiencies and benefits to the organization through its application. The designs of specific application programs are a logical outgrowth of their earlier definitions during the requirements analysis.

Generally, the applications support standard, often-used functions of the GIS. They may link together a series of tasks, retrieve or organize data, perform calculations or logical tests, among numerous other operations. These programs are produced using software and macro language tools provided with the GIS, or with a programming language such as FORTRAN or C.

Application programs are developed to support and enhance the efficiencies of numerous activities. Some are very simple programs that automate a few steps in one procedure. Others are complex, incorporating dialogue with the operator and performing data retrieval, computation, quality verification, or other processes. The application programs define parameters for data entry, data to be operated upon, processes to be performed, products (e.g., displays, plots, reports), interactions with the operator, and other functions.

The design of applications may be formal or informal, depending on the complexity of the application. In the most sophisticated cases, a specific application design task is performed, including detailed requirements analysis, design, programming, testing, debugging, and documentation. In the simplest cases, an operator trained in a macro language prepares a program with little planning and no formal process.

Very sophisticated application programs may be acquired from the GIS vendor or third-party firms specializing in such services. Application programs also may be acquired from other organizations with the same type of GIS and similar functions. These may be obtained free, at low cost, or in exchange for locally prepared programs. User groups formed among those who have acquired a specific vendor's GIS also exchange application programs.

The system manager establishes procedures for the development, maintenance, and control of application programs. The manager controls application development to ensure that applications do not adversely affect operation of the system or data base, that they receive the widest practical use, and that they are maintained properly. Complex applications require detailed documentation for maintenance and may require separate documentation for the operators and users. Training of operators also may be necessary for certain applications.

A set of application programs often is produced in the period between selection of the GIS and its installation so that they are available for initial operations. GIS vendors may also provide applications with the delivery of the system. Following installation, additional applications are developed formally and informally by the support team and system users.

## 9.4.5 Step 15--Conversion to Automated Operations

In most cases, the GIS is implemented in phases over an extended period of time. Conversion of the current manual operations and activities and initiation of newly available automated operations will require

months, if not years. While data base development is underway, manual maintenance of existing maps and day-to-day operations continues. Resources must be allocated between the data base development tasks, preparation of source materials, data conversion, quality control, and the continuation of current manual operations.

As components of the data base are completed, loaded, and verified, a transition is made to automated maintenance and operations. Because time will have passed since the source materials were committed to conversion, it will be necessary to bring all records up to date. At that point the maintenance will shift to the automated GIS, although a parallel manual operation may continue for some time until automated operations are proven satisfactory. Access controls to system resources and data base components are then initiated and allocated to authorized persons and organizations.

The transition to automated operations must ensure that no gaps or lapses occur in updating records, that no data enter the data base without proper verification, and that resources are not wasted during the transition effort. The transition may involve multiple organizations and persons, including the GIS manager and data base administrator, the new GIS maintenance and operations staff, the manual map maintenance and production staff, the data conversion contractor, and the GIS users and operators.

## 9.5 Audit

In the audit stage, an organization evaluates all aspects of its GIS and plans improvements and expansion.

### 9.5.1 Step 16--System Review

Things change. Even the best designs and implementations of GIS must remain flexible to shifting organizational mandates and structures, advancements in technology, introduction of new techniques, and personnel changes and additions. Moreover, in the frantic pace of system implementation, small changes in

direction, the necessity of addressing immediate and short-term issues, and the press of external demands frequently result in cumulatively large departures from plan.

Periodic reviews, or audits, play an invaluable role in keeping a project on track (or bringing it back onto track). The reviews can be targeted to particular aspects of the GIS implementation, such as personnel, hardware, software, or application development. Or, a more comprehensive view can be taken, comparing each of the diverse range of components to the original plan and the current institutional and technical setting. The audit can take either a high-level, strategic perspective, or one that is more focused on operational issues. Periodic reviews of both types are essential to an audit program.

The methodological foundation of the audits is not unlike the steps taken to develop the initial detailed plans for system implementation. Typically, interviews with technical and managerial staff of the involved organizations are accompanied by a review of prior planning and implementation documents, goals and objectives, and budget and expenditure histories. These efforts are followed by an objective analysis of the project's current status relative to prior plans and the nature of the current institutional and technical setting. Problems, opportunities, and corresponding actions are identified.

The audit culminates with a revised statement of goals, policies, procedures, and actions to be taken within specific time frames and budgets. In those instances where the focus is heavily influenced by operational issues, a revised operational plan often results.

Care must be exercised to insure that the analysis will be objectively accomplished and viewed by others as such. In situations where organizational issues, both internal and external, are influential or where technical considerations require an "arm's-length" evaluation, the use of a third party to conduct the audit is frequently warranted.

### 9.5.2 Step 17--System Expansion

Audits to support system expansion definitions are a special case of the previously described technical and management audits. Software components of a GIS are ever-changing through new releases of a particular product and the introduction of new products by the industry. As the cost of equipment continues to decrease relative to increased capabilities, review of hardware requirements should take place with some regularity and formality. By doing so, a coherent path can be maintained irrespective of the momentum and hyperbole of new releases, trade shows, advertisements, and sales calls. Similarly, the release of new software from a primary or third-party vendor and the development of application software can best be guided by a routine review.

In these instances, the methodology is limited to an assessment of contemporary and pending application requirements, identifying software and hardware functions, and proceeding to assess them in a manner comparable to those detailed earlier. The most significant variance is that the software and hardware platforms are likely to be more constrained by the installed system.

## 9.6 Elements Of Success
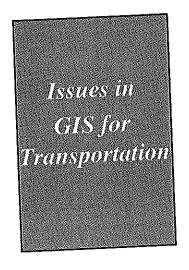
Efforts to implement GIS over the past two decades, both successful and otherwise, have extended contemporary understanding of what contributes to success or failure.

Expectations are important. If an organization's expectations of the level of effort, the need for planning, and systems costs are realistic, appropriate levels of resources are more likely to be available in a timely and predictable manner. Success is most likely when an organization's expectations of the system's utility are practical, the system is directed to priority applications, the time allotted for implementation is adequate, and sufficient numbers of experienced staff are hired early in the process.

Instilling realistic expectations within both senior managers and users requires understanding the balance between practical benefits and the resources needed to achieve them. Should unrealistic attitudes

develop, even reasonable accomplishments will be measured against unrealizable expectations and the

system will be perceived as unsuccessful.

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# CHAPTER 10

# ISSUES IN THE GIS-T IMPLENTATION PROCESS

Transportation agencies planning to develop and implement geographic information systems are faced with important issues requiring difficult and perhaps agonizing decisions. It is important to recognize these issues early on since the successful implementation of a GIS depends, to a great extent, on how adequately the issues are addressed and resolved. In this chapter, attention is given to GIS development and implementation issues in order to provide the transportation department with an overview of the kinds of decisions that will have to be made in order to implement a Department-wide GIS. It is important to give detailed consideration to the issues presented, rather than focusing attention primarily on hardware and software. Even the best GIS hardware and software are only a tools, not a solution in itself. These tools and the goals they are intended to implement require careful thought.

To emphasize the above point, the following section is quoted from a report (Bacon and Moyer, 1989) summarizing the recent MSHTO specialty conference on GIS in Orlando, Florida:

"The question most often asked is what is the best way to implement a GIS in my organization. In this regard, a number of specific questions related to application issues, management issues, data issues, and technology issues were identified:

## Application Issues

- How do I start?

- What scale maps should be used?

- How do I coordinate with others?

- What area do I implement first (pavement management, bridge management, safety, road inventory)?

- How do I interface with my existing data bases?

## Management Issues

- How do I get top level support for the resources needed?

- Who should have the lead for GIS within my organization?

- What will it cost?

- What is the best way to get started with GIS?

- How do I prepare a GIS plan?

- How do I educate my organization about GIS?

## Data Needs and Acquisition Issues

- What digitized data is already available?

- What scale map should I use?

- How do I put together digital data with attribute data?

- How do I obtain latitude/longitude for existing data?

- How do I keep the data up-to-date?

## Technology Issues

- What GIS system should I use?

- Should it be mainframe, mini or micro?

- How do I interface with our existing data bases and CADD systems?

The conclusion was that it is not IF to implement a GIS, but rather HOW to implement a GIS. The technology already exists to do the job. The key is obtaining answers to the issues raised above, which in turn depends on getting educated on all facets of GIS in order to effectively implement a GIS in the organization."

The above important issues arise from three basic questions that are relevant to all development efforts, namely:

1. Where are we now?

2. Where do we want to go?

3. How are we going to get there?

The above questions seek to establish the current environment in order to develop a point of reference. It is necessary to identify where changes are needed, what capabilities can be carried over from the current environment to the new, and what impacts would occur if the current environment was changed. The impacts brought about by change are sometimes difficult to handle. To illustrate, a transportation agency seeking to develop and implement a GIS will more than likely have information systems and data bases already in place. Thorough decisions must be made concerning what portions of the existing data system are scrapped, what portions are converted into a new format, and what portions are left unchanged. A good GIS will allow a transportation agency to build upon what it already has. However, this is not to say that existing systems can simply be interfaced with a GIS, without any changes being made.

To explain further, it is known that some form of geographic referencing is required in a GIS. However, a transportation agency will usually find that existing data on the highway network are not referenced geographically. Moreover, it is perhaps not uncommon to find a variety of referencing schemes

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being used for the various data bases that exist within the Department! This situation brings with it a host

of questions for which answers may not be easy to find. These questions include:

- Do we convert to a single referencing system?

- If we decide to develop a unified referencing scheme, how are we going to develop one?

- How long would it take to develop a unified referencing scheme and is the time involved

  acceptable?

- How do we implement the unified referencing scheme?

The development of a unified referencing scheme is advantageous from the viewpoint of

establishing uniformity in the way data are referenced and in completely tying together all the data within a

particular agency. However, its development may be a long, arduous process. Often, it is difficult to build a

consensus among a variety of groups with a diversity of needs. Still, a transportation agency may decide to

develop a unified referencing scheme because it believes that, in the long term, it is the policy.

Another aspect of this issue is to allow the existence of multiple referencing schemes in various

layers of the GIS provided that a common geographic coordinate system is used to tie together all these

layers. This alternative may be easier to implement but the multiple referencing schemes will always exist.

Although the common geographic coordinate system will allow various groups to exchange information on

the highway network, within a particular group, data will be referred using the same scheme that has

always been used in the years past. Thus, this alternative may be good only as a short term solution, and a

better alternative may be to combine it with a development plan for a unified referencing scheme. The

multiple referencing schemes will be used only until a unified scheme is developed. In this way, the

transition to GIS is made as smooth as possible.

Other issues that transportation agencies will have to resolve in developing a GIS arise from the

diversity of user requirements characteristic of almost all agencies. Within any transportation agency, one

will find planners, pavement managers, and district engineers who make decisions at the network level.

However, there are also pavement design and geometric design engineers, at the other end of the spectrum, who concern themselves with very specific projects. Within this wide range of users, one can expect the data requirements to also vary widely.

In this situation, one issue that requires attention is the level of accuracy to build into the digital spatial data base of the GIS. People who make decisions on a network level are not going to require as much accuracy as those concerned with the engineering design of very specific projects. For example, people who are responsible for developing schedules of maintenance, rehabilitation, safety improvement, and widening projects are probably going to be satisfied with 50 to 100 foot accuracy. On the other hand, those who will be engaged in the actual engineering design of scheduled projects may require 1 to 5 foot accuracy, and very large-scale digitized maps.

To some, the answer to the question of what accuracy to strive for may be deceptively simple - just strive for the highest accuracy that will be required based on the survey of user needs. However, the issue is really much more complicated. For one thing, an agency should ask itself how much accuracy it can afford. A highly accurate, large-scale digitized land base can be very costly and time consuming to develop.

Assuming that a transportation agency has the money to build this kind of digitized land base, the development time will be so long that interest in the GIS project will be very hard to sustain. For another thing, not all users will require the high accuracy. More than likely, there will be groups who can use already existing digital spatial data bases, such as those developed by the USGS and the Bureau of Census, to begin implementing a GIS and realizing its benefits. Very careful consideration must be given to developing an implementation schedule for a GIS. This schedule must cover both short-term and long-term goals. A possible short-term goal is to bring the benefits of the technology as quickly as possible to those groups of users who do not require too much accuracy. A long-term goal might be the development of a highly accurate, large-scale land base with the idea that initially developed land bases of lesser accuracy will gradually be phased out as portions of the highly accurate land base start coming on-line.

Another item that must be considered in the development of an implementation schedule is the maintenance of the digital land base. Highway segments change and provisions must be made for updating the land base. Depending on the accuracy of the land base, a transportation agency may find that it has to develop new capabilities to maintain the land base. For example, supporting a highly accurate, large-scale land base may require the application of Global Positioning Systems (GPS) technology (discussed later).

Still another item to consider in developing and implementing a GIS is the identification of the specific types of data with witch various users work. More than likely, this will cover a wide range. Those who are responsible for the programming of projects, for example, will require data on the condition of pavement sections in the highway network, the traffic volume on specific lengths or corridors of the network, and accident data, to name a few. Those who are responsible for designing specific projects will require data on thickness' of various pavement layers, material properties of each pavement layer, the existing traffic on a specific project, and topographic data. The types of data are important to consider in developing the structure of the data base for the GIS. In addition, when evaluating the types of data to include in the GIS data base, a transportation agency would be wise to ask itself the following questions:

- What types of data do we really need and what benefits are obtained from having the data?

- What does it take to get information on each data type?

- How much data collection can we afford?

- What new capabilities must we develop to facilitate data collection?

Obviously, the kinds of data to include in the GIS data base will also depend to a great extent on whether the agency can afford to be collecting the data on a regular basis. For example, pavement layer thickness' are examples of data items for which pavement decision engineers have a need. However, maintaining data on layer thickness' is difficult and can be very costly. Consequently, there may be a need to identify research and development efforts in the area of data collection techniques that could lead to better methods for collecting data and thus facilitate the maintenance of the GIS data base.

This discussion illustrates that there are a variety of issues in GIS development and implementation that would require careful and thoughtful deliberation on the part of transportation agencies. An attempt has been made herein to identify some of the issues which may be potential stumbling blocks in the development and implementation of GIS technology. Alternatives for resolving these issues have been identified, but it should be emphasized that the solutions raised may not necessarily be appropriate for the Texas Highway Department nor will the solutions be the same from one agency to another. This of course just underscores the importance of giving careful consideration to the issues raised vis-à-vis the objectives of a particular transportation agency.

## 10.1 Overall Planning Process

The stages and steps that are discussed in the previous chapters can be used to design and implement the GIS-T in state DOT's. Additional tips and recommendations from the NCHRP (1993) report are provided in this chapter. The overall process for GIS-T implementation begins with an assessment of agency needs and resources. This is a feasibility study in which the agency decides whether or not to implement GIS-T. If the answer is affirmative, then the agency proceeds to develop goals and objectives, identify alternative GIS-T software, evaluate the software alternatives, select the best software and implement it. The focus here is on software, rather than hardware. Hardware costs have declined dramatically in recent years and will continue to decline. Thus, hardware should be selected to support the software and applications-not the reverse.

## 10.2 ORGANIZATIONAL RESPONSIBILITY

The key to successful implementation of GIS-T is the support of top management. The management team has overall responsibility for deciding the direction GIS-T will take in the agency. Because GIS-T will have agency wide impacts, the management team must include top managers from all

agency divisions. If GIS-T is viewed as only an MIS activity, then the full power of GIS-T to integrate information across agency lines will be less likely to be achieved and the speed of implementation will be slowed. The management team must include a Sponsor-an individual who at least initially is committed to exploring the feasibility of GIS-T and ultimately will be committed to securing the resources required for successful GIS-T implementation.

The second, and equally important, organizational requirement is the technical team. The technical team is composed of technical managers who will be responsible for planning and implementing GIS-T.

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

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

Use of consultants will speed the planning and implementation process, and when used effectively, enable agency staff to climb the learning curve more quickly. The level of involvement of consultants could

range from a single personal services contract to a complete turnkey package including an agency wide application. Each agency will have different needs for a mix of management and technical level consulting services and for the level of involvement of the consultant. Ultimately, some level of in-house expertise must be developed to support database maintenance, development of additional databases, and development of additional applications over time.

## 10.3 Assess Needs and Resources

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

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

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

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

The overall GIS-T data architecture and strategy must be defined to the extent possible. This has important implications for the staff resources required as well as for the applications that are feasible. Other agencies' experiences with implementation of different architectures and their relationships to feasible applications are invaluable here. The primary trade-off in the choice of an initial database is between the lower cost of a smaller-scale database with fewer potential applications and the higher cost of a larger-scale, more detailed database with different and perhaps a larger set of potential applications. (See NCHRP, 1993 for a more complete discussion.)

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

## 10.4 Develop Goals and Objectives

Development of GIS and objectives for GIS-T planning and implementation follows directly from the assessment of agency needs and resources. The goals provide the broad policy framework within which GIS-T will be planned and implemented. The objectives are more specific statements of how each goal is to

be achieved including guidance as to scope, timing, and duration. As the goals and objectives are developed and refined, more information on agency needs and resources may be required resulting in an iterative process. For each objective one or more measures of effectiveness (MOEs) should be developed. Ideally, the MOEs will provide a quantitative measure of how well a particular alternative meets the relevant objective. In some cases the MOEs will only permit a qualitative assessment of performance.

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

## 10.5 Identify and Evaluate Software Alternatives

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

Full evaluation of the GIS-T software alternatives requires in-house "hands-on" testing of the most promising alternatives. There simply is no other way to demonstrate that the software performs as claimed,

is compatible with the agency operating environment, and meets the primary DOT functionality requirements.

Initial screening of the entire set of alternatives probably will be needed to reduce the alternatives selected for in-house testing to a manageable number. The "trade-off and balance sheets evaluation methodology is appropriate for the initial screening where many qualitative assessments must be made based on limited information" (Lockwood, 1977). The methodology involves matrix form display of all relevant information about the extent to which each alternative satisfies each objective. Simple descriptive information as well as quantitative and qualitative ratings may be included in the matrix. Decision makers use the information in the matrix to identify trade-offs in the performance of alternatives and then to select alternatives that "on balance" are the best.

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

The "trade-off and balance sheet" evaluation methodology used for initial screening of GIS-T software alternatives is also appropriate for the final evaluation of the most promising software alternatives. The in-house evaluation is likely to show that each alternative has strengths and weaknesses. It is important to identify as clearly as possible the trade-offs that are apparent and to reach a consensus

among the technical team and the management team as to which alternative "on- balance" best meets both short- and long-range goals and objectives.

## 10.6 Select the Best Alternative and Implement

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

### 10.6.1 GIS-T System Procurement

This section focuses on alternative approaches to procurement, the content of RFPs, and evaluation of bids. In many cases full implementation of new GIS-T software will require additional computer hardware. Acquisition of hardware may be incorporated with the software in a single RFP or, more likely, may be made separately.

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

staff required for procurement. The systems manager approach also has been used successfully for the procurement of systems involving advanced technology (Rowe, 1993).

Both approaches require first that the procurement specifications be developed by an organization that does not have a vested interest in the primary product being acquired and second that competitive bidding be used for the primary product (Wilshire, 1985). Both approaches may also use a two-step procurement process in which the low-bid process is modified to include contractor (vendor) pre-qualification.

## 10.6.2 Selection of Procurement Approach

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

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

The two approaches may produce some what different plans and specifications. Because the systems manager has responsibility for implementation, the manager may choose to develop more detailed specifications that focus on how specifically the GIS-T will be integrated with existing agency hardware

and software. In contrast, the engineer/contractor may produce more generic specifications focusing on the overall functionality requirements rather than specifically on how the functionality is to be achieved.

### 10.6.3 Request for Proposal (RFP) Content

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

1. Invitation to bid--a summary of the project and bid procedures;

2. Instructions to bidders-a detailed description of how bids are to be prepared and the format for submission. Permitted exclusions and substitutions are identified;

3. Bid proposal--the actual response by the bidder in the format specified in the "instructions to bidders," includes a budget for completing the work and commitment to complete the work if selected;

4. Bonds--may include bid bond, performance bond, or labor and materials payment bond;

5. Agreement--legal document that identifies the parties, the work to be performed, the time allowed, the amount of the award, and signatures binding the parties;

6. Conditions--definition of general contractual relationships and procedures;

7. Contractor qualifications--identification of the minimum experience and qualifications necessary to submit a bid and instructions for submitting specific data on qualifications.

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## 10.6.4 Evaluation of Bids

Experiences with acquisition of advanced traffic control systems have shown that conventional "low-bid" procurement procedures used for major highway projects "result in mismatch of equipment, poor workmanship, and excessive contractual disputes." (Rowe, 1993) While some components of a high-tech system may be obtained on a "low-bid" basis, others should be obtained through negotiation with the best qualified supplier. Where Federal funds are involved, flexibility in procurement exists in Federal-aid requirements. More restrictive provisions, however, may be imposed by state and local agencies (Wilshire, 1985).

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

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

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

## 10.6.5 Software Testing and Acceptance

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

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

## 10.6.6 GIS-T Pilot Project

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

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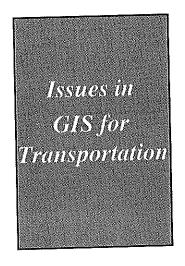
### 10.6.7 Application Enabling

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

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

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

staff are likely to request their turns for training and database development. Thus, GIS-T is implemented in phases, with the speed of implementation governed by the level of resources available and the interest and commitment from the "bottom-up."

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# CHAPTER 11

## COMPARISON OF GIS SOFTWARE

The following chapter on comparison of GIS software is based on reviews of vendor's literature and on GIS software surveys. As of July 1988, the GIS WORLD journal identified, in preparation for a software survey, a list of 45 GIS vendors. Since it was inappropriate for the purpose of this pilot study to review all of the products available, it was decided to base the comparison on products that were better known or on systems that were seen in real working conditions, either during a vendor demonstration or at an installation were a particular system was actually being used.

## Criteria for Comparison

The criteria used for the comparison considered the following system characteristics:

Hardware Requirements     Minimum computer requirements such as computer types, minimum RAM required, and mass storage required and recommended, numeric CO-processor if applicable.

Operating System     DOS, UNIX, XENIX, others.

Database Management     DBMS systems supported, features, and pertinent limitations, if any.

Other System Capabilities     Geographic referencing systems (map projections) supported; vector or raster type system; arc networking capabilities; automatic distance and area calculation capabilities; and other special features.

System Price Range     For software only. CPU dependent.

## 11.1   Systems Reviewed

### 11.1.1 ARC/INFO

Developed by Environmental Systems Research Institute (ESRI), of Redlands, California, ARC/INFO was first introduced in 1982, and is today one of the most flexible GIS's available. It runs on the broadest range of computers: IBM PC/AT or other AT compatibles under DOS 3.1 or higher, DEC under VMS, Prime under PRIMOS, Sun, Apollo, RT, and Tektronics, all under UNIX, IBM mainframe and minicomputers under VM/CMS, and Data General under AOS. ARC/INFO handles most map projections and spatial data input formats and it can be interfaced with INFO, Oracle, SQL, RDB, and other DBMS's. The PC version of the program was introduced in March of 1987 and is available in modules starting at $2,500. The complete set of six modules, licensed to run on a single PC station costs $9,500. The minicomputer and workstation versions cost $18,000 to $88,000 depending on CPU. Packages for coordinate geometry (COGO), triangulated irregular network (TIN), and other engineering applications are available.

### 11.1.2 DELTAMAP

A product of Deltasystems, Inc. of Fort Collins, Colorado, DELTAMAP is a GIS containing a specialized spatial DBMS for coordinate storage, manipulation, projection transformation, retrieval, and display. The system is implemented on the following computers: HP Vectra RS/20 and RS/25 under

XENIX, HP 9000 series 300 and 800, CDC 910, and Sun under UNIX. DeltaMap can handle any of twenty map projections and, with the addition of the DeltaRef module, it will accept IGES, SIF, DLG, DXF, and other spatial data input formats. The GIS includes an internal attribute DBMS which is capable of SQL linkages to Oracle and INGRES RDBMS's, scripting capability and applications manager software. Prices for DeltaMap start at $8,000 for the HP Vectra machines and $27,000 for the workstations. Additional modules include: DeltaCell for raster and DEM processing ($8,000), DeltaRef for data import/export ($3,000), and DeltaCom for intercomputer DBMS communications ($5,000).

## 11.1.3 EARTH OHE

Developed by C. H. Guernsey & Company, this package incorporates a comprehensive data management system with capabilities for the capture and maintenance of graphics and facilities data. The system will run on an IBM PC/AT or other AT compatibles under DOS 3.2 or higher. Also, a UNIX version that will run on the Sun family of workstations is currently under development. EARTH ONE can handle all map projections, and it accepts DLG, and DXF data input formats. However, it outputs all map products only in DXF format. All data base management functions are handled via a fully integrated proprietary RDBMS with QBE and SQL querying capabilities. Price: $12,000 to $28,000.

## 11.1.4 SYSTEM 9

A GIS developed by WILD Heerbrug Systems of Englewood, Colorado, that integrates connectivity among features, associativity of attributes with features, and comprehensive and flexible analysis and reporting functions. This system, which is designed to run on the Sun family of workstations under UNIX and SunOS, can handle all map projections and several input formats such as ASCII, ISIF, DLG, SNA, GBF, DIME, and TIGER. Its data base management functions are handled through a specially designed data base structure which interfaces with the Empress Data Sciences RDBMS. The data base

structure supports specialized applications such as COGO, polygon processing, digital terrain modeling, network analysis, and others. Approximately 900 stand-alone application programs from third party vendors are available. A single workstation license for SYSTEM 9 costs $40,000.

## 11.1.5 TransCAD
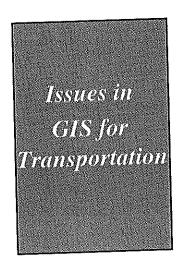
This comprehensive GIS, specially designed for planning, management, operation, and analysis of transportation systems and facilities, was developed by Caliper Corporation of Newton, Massachusetts. It incorporates functions for digital mapping, storage and retrieval of geographically-based data, creation of transportation and operations research models, statistical procedures, and presentation graphics, all within a user-friendly environment. This GIS, which runs on IBM PC/AT's or AT compatibles under Dos 3.1 or higher, and that automatically converts from any map projection to latitude-longitude is limited only to DLG and TIGER input formats. Data base management is provided via a fully integrated proprietary RDBMS with SQL interface. The current retail price for the system is $20,000.

## 11.1.6 TIGRIS

TIGRIS, which stands for for Topologically Integrated Geographic and Resource Information System, was developed by Intergraph Corporation of Huntsville, Alabama TIGRIS is an object-oriented GIS environment which provides core capabilities such as data collection, data management, data manipulation, query and presentation. The TIGRIS GIS Environment (TGE) is designed to run under UNIX on the Intergraph Clipper family of workstations. It handles most map projections, produces IGDS, DXF, DIME, TIGER, SIF, DME, HPGL, and DLG input/output formats. TIGRIS uses a proprietary object oriented RDBMS. Add on modules include: Analyst, for query and spatial analysis ($10,000); Imager, for image processing ($20,000); Modeler, for terrain modeling ($10,000); Scanned Data Capture,

for hardcopy data conversion ($10,000). The price for the basic TGE package (MAPPER + MICROSTATION 32) is $8,300.

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# CHAPTER 12

# TECHNICAL AND ORGANIZATIONAL CONSIDERATIONS

The technical and organizational factors that are considered in this chapter are geographic databases, methoda of data capture and system architecture.

## 12.1 Geographic Database

A number of alternatives are possible for the general nature of GIS-T databases and their administration. These alternatives are centralized, application-development and confederation.

1. All databases (spatial and non spatial) could be centralized. With this model the computing environment is certain to be in place and there is central control over database structure and content. However, there might be significant delays in response time during heavy use and users have very little flexibility, with no control over data and very little control over their applications.

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

3. Another option is, a confederation of GIS-T databases. This leaves users responsible for their own applications, and to some extent, their own attribute databases which they connect to centrally

maintained, corporate, spatial databases. The spatial databases connect the applications and the attribute databases to one another. It is under this model that GIS-T serves as a database integrator (NCHRP, 1993).

## 12.2 Methods of Data Capture

The transformation of map features from analog to digital form is perhaps the most time consuming and expensive task in the development of a GIS. The objective of this task is to produce computer-compatible digital files that satisfy accuracy requirements specified by the user and contain spatial and topological information on the map features of interest. A significant amount of pre-processing and post-processing is usually involved in digitizing cartographic documents to ensure that clean and usable digital files are produced. In this section, methods to generate digitized maps for GIS applications are reviewed.

### 12.2.1 Manual Digitization

Manual digitization is usually done with a graphics digitizer. In this method, maps are digitized by an operator who moves a cursor along individual map features and defines points associated with those features. Depending on software, it may be possible for an operator to attach attributes to map features, and specify topological relationships between features at the time digitization is being conducted.

The most common digitizer is the transmitter/receiver type, with the cursor transmitting a low level electrical charge and the tablet sensing its location. The digitizing tablet has an imbedded wire mesh that is electrically charged. The intersections of wires running in the vertical and horizontal directions form a series of addressable coordinates with the lower left corner having the coordinates 0,0). Tablet resolutions vary, but typically, tablets with 1,000,000 addressable coordinates per square inch are available.

Manual digitization is most appropriate when the volume of data to be digitized is small or where labor costs are inexpensive. The data volume will of course be dependent on the user defined requirements for a GIS. These include the required accuracy of the digitized maps, the types of features that must be encoded, and the resolution specified for each map feature. Obviously, as the data volume increases, the cost of manual digitization may become very prohibitive. In this situation, alternative procedures that allow for the automatic or mass digitization of maps become more feasible. These procedures are presented below.

## 12.2.2 Automatic or Mass Data Capture

Automatic or mass data capture typically involves generating a raster image of a map and subsequently converting the raster image to a vector format. The raster image is produced by scanning a map row by row with a raster digitizer or scanner. The most common scanner used in digital cartography is the drum scanner.

An important consideration in the use of raster digitizers is that every point on the source document that is detected is recorded. Thus, highway names, airport symbols, railroad lines, contour elevations, and political boundaries (to name a few) are all recorded. It takes subsequent computer processing to distinguish between the various features and to add structure to the data by separating various feature types and symbols into different layers. Within a GIS, cartographic data is usually separated into various layers or coverage's that are all tied together through a single referencing system.

The amount of editing that is required after maps are scanned may be so costly so as to that mass data capture is rendered a less attractive alternative than manual digitization. However, the amount of editing that would be required after scanning can be minimized by using map separates, instead of the composite map. Map sheets are commonly made from a series of color separations that correspond to various thematic features. For example, hydrographic features are normally contained on a "blue line"

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plate. The plates are in black and white and the colors are just added in the map production process. Use of map separates that are normally available from the U. S. Geological Survey can greatly facilitate the structuring of scanned data.

In addition, re-scribing of the original map document into a form more suitable for scanning may be done, especially when editing costs are such that re-scribing can be justified. For example, modified contour maps may be prepared prior to scanning where the contour lines are of uniform line weights and are without the usual breaks associated with the placement of contour elevations. The use of uniform line weights and the absence of breaks and the associated numeric values can greatly facilitate the automated interpretation of scanned data later.

The application of pattern recognition techniques fecilitates the interpretation of an array of dots in a raster image which identify map features. Significant strides have been made in recent years in using template matching and statistical methodology to analyze and identify pixel clusters (Skiles, 1988). This makes it possible to recognize and extract textural and symbolic information directly from the raster image data.

Template matching compares a sample pixel pattern or template, from a user defined knowledge base, with pixel clusters in the raster image. The greater the correlation between the template and a pixel cluster, the greater the probability that a match has been found. With the statistical recognition technique, detached pixel clusters are identified from the raster image. A statistical model for each pixel cluster is then prepared based upon physical characteristics. This model is subsequently compared with models in a user defined knowledge base and the probable identity of the pixel cluster determined. Based upon the degree of certainty in the identification, the feature is then recorded into the data base or presented to the user for manual verification.

In contrast to template matching, statistical recognition is relatively more tolerant of the variability in cartographic features. With the former technique, pixel clusters are compared to a template which, by

nature, is fixed. Thus, highly variable features such as handwritten text or symbols may not be reliably recognized. For these cases, statistical recognition may be a more viable alternative for the interpretation of scanned data. However, one should remember that with this method, target clusters must be identified and detached from the raster image. Consequently, a significant amount of editing may be required before interpretation can be achieved.

The interpretation and structuring of raster data are major tasks that are conducted after scanning operations have been completed. Certain GIS applications can be implemented once the interpretation and structuring of raster data has been achieved. An example would be the identification of land areas that satisfy certain criteria related to land use, soil type, slope, and flood-plain location. In this instance, the analysis may involve overlaying of raster data residing in the pertinent land use, soils, slopes and flood-plain coverage's. However, there are GIS applications, such as network analysis, that are inherently vector oriented. For these applications, the conversion of raster data to vector form will be necessary. Consequently, depending on user requirements, raster-to-vector conversion may have to be conducted after scanning operations have been completed.

Peuquet and Boyle (1984) present several methods for raster-to-vector conversion. A very recent development in this area is the VTRAK system introduced by Laser Scan Laboratories (Woodsford, 1988). VTRAK is an interactive system for raster-to-vector conversion that operates on a line-follower scheme. It is based on the Digital Equipment Micro VAX II/GPX or VAX station 3000 series platforms.

VTRAK uses raster images from scanning operations as input. A raster image is displayed on a high resolution monitor and vectorization is conducted in either a semi-automatic or fully automatic mode. In the semiautomatic mode, the user selects a feature for raster-to-vector conversion by positioning the screen cursor close to the feature using a Mapstation console equipped with a trackerball and function keys. The function keys are used to give feature codes and control instructions.

The screen cursor follows the feature path, vectorizing the feature as it goes at high speed. The progress of the vectorization is indicated on the screen by a "digitizing trail". At points of ambiguity, user intervention is solicited to provide a resolution. This may occur, for example, when closely spaced contour lines are being vectorized. The user can intervene at any time to demark a feature or to prevent misinterpretation in areas of complexity or poor clarity.

The system can recognize dashed lines and gaps in lines such as those where contour elevations are placed on topographic maps. Point features and junctions are automatically recognized and their locations determined. Feature coding is provided by the operator and is used by the system in conjunction with a Rules Table to generate optimal vector data and to minimize errors.

For source data with uncomplicated features, the fully-automatic data capture mode may be used. Referred to as the Autopass option in VTRAK, features are automatically located, followed, vectorized, and painted out upon completion of the conversion process. To minimize potential errors, the operator can define areas for which the Autopass option is to be implemented. Additionally, the Rules Table can be set up to reject all potential errors. All rejections that occur in the Autopass mode are routed to a guidance file for subsequent manual verification by the user.

In summary, VTRAK implements a raster-to-vector conversion methodology that is a hybrid of manual digitization and fully automatic, mass digitization. The burden of manually digitizing nodes, arcs, and polygons is lifted from the operator through the implementation of an automatic line follower scheme. User is left with the responsibility of classifying and interpreting the data, in effect becoming the instrument for pattern recognition. Additionally, the user is responsible for structuring and validating the data.

## 12.2.3 Global Positioning System (GPS)

GPS involves the use of orbiting satellites to determine position on the earth's surface. There are two satellite systems available for this application at the present time. One is the TRANSIT system

consisting of six satellites in more or less polar orbits at an altitude of approximately 500 miles (Merrell, 1983). The TRANSIT system was installed in the 1960's and is used by the U. S. Navy for navigational purposes. It is scheduled to be phased out in the 1990's and replaced by the new satellite constellation referred to as the Global Positioning System. This system has 24 satellites in orbit. All satellites in the GPS constellation will be in orbit at an altitude of approximately 12,500 miles.

Currently, seven satellites are in place, providing a measurement window of 5 to 6 hours within which survey data can be collected. This is accomplished using portable receivers to measure certain changes in the characteristics of the transmitted signal from a satellite. The characteristics that are measured are either the observed shift in the satellite transmitted frequency at the receiver site (i.e., the Doppler shift) or the phase angle of the satellite signal received. These measurements are used to compute the range vectors between the satellite and the receiver. These are subsequently used with data on satellite position to determine location on the earth's surface. Information on satellite position at any given time (ephemeris data) is coded within the transmitted signal from the satellite.

The determination of geodetic positions of high accuracy is possible through GPS. Consequently, this technique is well suited for GIS applications requiring a high degree of accuracy from the digitized map data. Utility companies, for example, may have need for locating buried cables, gas lines, or electric utility poles to an accuracy of +/- 5 feet. This need can certainly be met through GPS. The technology also offers a possible 6:1 increase in speed over hand digitization (Simkowitz, 1989).

## 12.3 Sources of Digital Spatial Data

The preceding discussions have revealed the complex nature of converting map documents to digital form suitable for computer processing within a GIS. This is a time consuming and expensive task and it would certainly be advantageous if the digitization could be minimized, or even eliminated outright, through the use of available digital spatial data. Fortunately, an increasing number of digital cartographic

data is becoming available, and GIS activities within the Federal government are expected to contribute to

this growth.

## 12.3.1  U. S. Geological Survey (USGS)

The USGS provides digital cartographic data to the public. This is broadly referred to as U. S. Geo-Data. U. S. Geo-Data include four main groups of cartographic data:

1.  Digital Elevation Models (DEM's);

2.  Digital Line Graphs (DLG's);

3.  Land Use and Land Cover Data;

4.  Geographic Names Information.

Of relevance to the highway community are the USGS DLG's, which include planimetric data on two major features - hydrography and transportation. Transportation data consists of three sub-categories: 1) roads and trails; 2) railroads; and 3) pipelines, transmission lines and airports. The user need only purchase the digitized files that he or she needs. It is possible, for example, to get only the files containing roads and trails, leaving out the other sub-categories in transportation. Hydrographic data consists of flowing water, standing water, and wet lands.

USGS DLG's are available in small, intermediate, and large scales. All DLG's have a topologically structured format making them directly useful for spatial analysis in a GIS. The 1:2,000,000-scale DLG's are available for the entire United States. These are organized into 15 geographic sections for the conterminous 48 states, 5 sections for Alaska, and 1 for Hawaii for a total of 21 geographic sections. DLG's for 1:2,000,000-scale maps are sold by geographic sections. These DLG's were used in the development of the land base for the GRIDs package developed for the Federal Highway Administration by Pennsylvania State University and Caliper Corporation.

A 1:2,000,000-scale DLG is likely to be too small to be of considerable use to the highway community. However, the 1:100,000- and 1:24,000-scale DLG's can offer enough resolution for many practical applications. In a 1:100,009-scale map, an inch on the map is equivalent to 1.58 miles in the field which is comparable with the lengths of most Pavement Evaluation System (PES) sections in Texas, for example. The 1:100,000 DLG's are available for the continental United States and are sold in 30 x 30 minute blocks.

For even finer resolution, the 1:24,000-scale DLG's may be used. At this scale, an inch on the map is equivalent to 0.38 miles in the field. However, 1:24,000 DLG's are only available for certain areas. For Texas, the availability is very limited. Most DLG's for the state at this scale cover mainly Brown and Bexar counties.

Even though the DLG's may save the user time, effort, and money that would otherwise have been spent digitizing maps, there are still a number of operations the user must perform to use the DLG's within a GIS. First, the individual 30 x 30 minute blocks have to be edge matched, which may involve a significant amount of editing. In addition, features must be identified and tagged with appropriate symbols and names to generate a visual display that is meaningful to the user. In certain cases, the feature codes that are part of the DLG's provide specific information as to the name of a particular feature. Roads, for example, will have their route numbers imbedded in the feature code. However, city names, street names, or names of hydrographic features are not included in the feature code and in many instances, specific feature names have to be determined by the user. The feature codes in the DLG's primarily provide information as to what a feature is (e.g., river, stream, navigable canal, interstate road, U. S. road), but do not provide specific names or labels except for route numbers.

In addition, certain highway applications may require that roadbeds of divided highways (or even individual lanes) be digitized so that specific information on pavement sections can be accessed and

displayed. These applications would require mapping at scales much larger than those used in generating the DLG files. In all of these files, roads are represented only by their center lines.

Finally, the user needs to link the attribute data in his/her data base with the DLG's. However, the attribute data may not necessarily be referenced in the same way as the DLG's, where locations are specified in latitude/longitude coordinates. Consequently, the user may have to do conversions on the attribute data to conform to the latitude/longitude referencing scheme.

## 12.3.2 Bureau of Census

In order to automate the support process for censuses and surveys, the U. S. Bureau of Census has undertaken to develop and implement a system that will produce computer generated maps, assign addresses to geographic units, and delineate geography for the collection, tabulation, and publication of census data (Sobel, 1986). This effort has resulted in the Topologically Integrated Geographic Encoding and Referencing (TIGER) System.

At the core of TIGER is a digital map data base developed from USGS 1:100,000-scale DLG's and the 1980 Census GBF/DIME Files. GBF/DIME stands for Geographic Base Files/Dual Independent Map Encoding. USGS 1:100,000 scale DLG's were used when no GBF/DIME files were available for a particular area. The DLG files were updated by the Census Bureau to include features that were non-existent at the time the DLG's were prepared. These features include recently constructed highways or railroads.

For major urban areas, GBF/DIME Files from the 1980 Census were available and were used to generate TIGER Files. As with the USGS DLG's, the GBF/DIME files were updated to reflect changes that have taken place since the 1980 Census. The files were also edited to remove topological errors, and extended to the nearest 7.5-minute quadrangle boundaries.

The GBF/DIME files and the USGS 1:100,000-scale DLG's were subsequently merged to form a seamless, nationwide data base from which county files are to be extracted. The generation of a seamless data base reduces the likelihood of getting adjacent files that do not match correctly. However, errors in edge matching have been found to materialize when county files are extracted from the integrated data base. In most cases though, mis-matching along adjacent boundaries is not expected to occur.

Of particular interest to the transportation community is an extract from the TIGER data base known as the TIGER/Line File. This file includes digital data on political boundaries, statistical area boundaries such as tracts and blocks, and transportation features such as roads and railways. Prototypes of TIGER/Line Files for all counties of the United States are available. Updates to these files will be made from time to time by the Bureau of Census.

## 12.3.3 U. S. Soil Conservation Service

The U. S. Soil Conservation Service (SCS) is developing three soil geographic data bases to improve the storage, manipulation, and retrieval of soil map information (Reybold, 1988). These data bases are the Soil Survey Geographic Data Base (SSURGO), the State Soil Geographic Data Base (STATSGO), and the National Soil Geographic Data Base (NATSGO). Each data base represents a different scale of soil mapping. Components of map units of each data base are generally phases of soil series.

The SSURGO data base is primarily intended for use in county, parish, township, and watershed resource planning and management, and in farm and ranch conservation planning. Soil maps in the SSURGO data base are made from field observations and transects, and are prepared at scales ranging from 1:15,840 to 1:31,680. Detailed attribute information on soils will be compiled for the SSURGO data base. Examples of information that will be included are particle size distribution, bulk density, available water capacity, soil reaction, salinity, organic matter content and depth to bedrock.

STATSGO is intended primarily for basin, multi-state, state, and multi-county resource planning, management, and monitoring. Soil maps for STATSGO are made by generalizing more detailed soil survey maps. The soil maps comply with national SCS guidelines and standards, and are made at a scale of 1:250,000.

NATSGO is intended primarily for use in national, regional, and state resource appraisal, planning, and monitoring. The boundaries of the Major Land Resource Areas MLRA) and Land Resource Regions (LRR) were used to form the NATSGO data base. The MLRA boundaries were developed primarily from state general soil maps. Map unit composition for NATSGO was determined from the 1982 SCS National Resource Inventory. NATSGO maps are made on a scale of 1:7,500,000.

The availability of digitized soil maps from the three geographic data bases is very limited at the present time. For Texas, the digitization of STATSGO maps is expected to be completed by the end of 1989. In addition, digitization of SSURGO maps has just been recently initiated so that no digitized SSURGO maps for the state are yet available to the public.

## 12.3.4 State DOT's

Transportation agencies planning to develop geographic information systems should also look in-house for sources of digital spatial data. Many transportation agencies have equipment and personnel devoted to surveying and mapping operations. For these agencies, it is likely that digital spatial data already exist in-house. If so, the suitability of using the available data in developing the GIS should be evaluated.

In Texas, the State Department of Highways and Public Transportation (SDHPT) has an on-going program for digitizing the highway network in the state. Detailed county maps are currently being digitized from 1:24,000 USGS quad sheets. These digitized maps contain data not only on highway routes, but on other features as well. Examples are transmission lines, power plants, pump stations, rivers, and USGS

triangulation stations. To date, 50 counties have been digitized but not all have been annotated. Only about 18 of the 254 counties in the state are considered complete. However, there are also digitized maps for all districts within the state that do not contain as much detail as the digitized county maps but are already available to the public. These digitized files are updated every year.

Digitized district maps have been generated to automate the production of official highway maps for the state. District maps were digitized using different scales depending on the geographic extent of a particular district. Five different scales were used, namely: 1) 1 inch =2.5 miles; 2) 1 inch = 3 miles; 3) 1 inch = 4 miles; 4) 1 inch 5 miles; and 5) 1 inch = 6 miles. The individual district files can all be merged to form a digitized state map on a scale of 1:250,000.

The production of digitized maps within the Texas SDHPT is done using INTERGRAPH work stations and software. The digitized files are in Interactive Graphics Design System (IGDS) format. Maps are digitized manually by personnel from the Planning Division of the Texas SDHPT. Digitized maps are compared with paper maps to check for errors in the digitizing process and corrections are made accordingly. The digitized maps are in state plane coordinates.

## 12.3.5 Oak Ridge Highway Network

Oak Ridge Laboratory has developed a digital spatial data base consisting of 355,000 miles of inter-states and primary roadways in the continental United States (Simkowitz, 1989). It is based on the 1:2,000,000-scale digitized maps developed by the USGS. The data base is divided into sub-networks for each state to facilitate manipulation. Each sub-network contains several files of nodes and links with their associated attributes. For a node, the geodetic location, and sometimes a city name are used as attributes. A link on the other hand is defined by its starting and ending nodes and by its shape. A separate file stores the information on the shape of each link.

Due to its small scale, the Oak Ridge data base is primarily useful for planning purposes at the state or federal level.

## 12.4  System Architecture

Just as there are alternatives for the structuring of databases, there are alternatives for the structuring of the functional capabilities of the system architecture. A number of alternatives are possible for the GIS-T system architectures. These alternatives are Standalone and server-net model.

### 12.4.1 Stand-alone and Mainframe/workstation

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

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

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

The alternatives to immediately implementing a server net are (1) not networking computers together at all (unreasonable); (2) assigning so many functions to single nodes (mainframes) in such an undifferentiated way that those nodes are indispensable to continued functioning of the network; and (3) incremental development of systems from the bottom up (which will lead to a server-net, if that is a long-term goal).

## 12.4.2 Server-Net Model

The framework proposed in this section is intended as one of the goals for planning. This goal addresses includes adopting and exploiting more technological developments than just GIS. Several new technologies of importance to DOTs complement each other and should not be planned for and introduced in isolation from each other. The following are characteristics of a server net:

1. Network nodes are specialized, with computing labor divided among them

2. Each node operates both as a server of other nodes and as a client of other nodes

3. Nodes may vary substantially not only with respect to specialty, but also with respect to capacity. That is, some nodes may be super computers or mainframes and others much smaller (e.g., those providing single-user terminal services). However, the larger machines do not in general serve as network centers or controllers. No one node is indispensable to continued functioning of the network, only to whether its specialized service remains available

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

For more description of conceptual server-net model, see NCHRP (1993). Good technical overviews of the server-net concept are presented in references (Coulouris, 1988, pp. 1-52; Svoboda, 1984; Tanenbaum, 1988, pp. 454-465; and Tanenbaum, 1985), and popular overviews are presented in Francis, (1990) and Sinha, (1992). Application of the concept specifically to GIS environments is discussed in Ferreria, (1988). The seminal ideas are introduced and defined, and the original, prototyping Xerox PARC

research establishing the feasibility and practicality of the concept is discussed in references Lampson (1979 ; 1981), Mitchell (1982 and 1985), Sturgis (1980) and Swinhart (1979).

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

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

There are other advantages of the server-net model. Important among them is the increased system reliability that results from different hardware platforms in a net being able to perform the same server functions and thus providing backup for each other. The division of labor among nodes can be made to

reflect the existing organizational division of responsibility and labor, thus avoiding the dictation of unwanted organizational change as a result of technology adoption. Other organizational advantages include increased independence of particular vendors because, as open-system standards are realized, different servers can be based on products from different vendors.

### 12.4.3 GIS-T Server-Net Architecture

The "Server-Net" technology has been suggested by the NCHRP 20-27 Report (Vonderhoe, et al., 1993) as the basic hardware infrastructure for geographic information systems for transportation (GIS-T). The support for this recommendation is primarily given as the "multiple technology problem." That is, "There are several new and imminent information technologies, including GIS, for which plans must be developed. For instance, a GIS technology adoption plan can not and should not be developed independently of a networking technology plan." The Server-Net is the most significant technological recommendation of the NCHRP report.

Design of a server net begins with determining feasible and appropriate division of labor among servers. The ideal presented in this section for the GIS-T functions performed within a DOT computing network, is intended as planning goal.

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

In the meantime, much of the coupling of servers will be quite loose, with transfer of significant amounts of data often being by physical transfer of disks or tapes. Beginning with a conceptual client-server architecture, as a strategic principle underlying information-technology planning, facilitates timely adoption of the technology when it has matured. As indicated in earlier sections, a major justification for long-term planning is to prepare the way for predictable technological developments so that when they do become available their adoption and exploitation is not disruptive

NCHRP (1993) discusses a division of labor for GIS-T is among 15 kinds of servers:

1. Spatial data servers

2. Attribute data servers

3. Spatial image data servers

4. Nonspatial image data servers

5. Complex object data servers

6. Overlay servers

7. Analytical computation servers

8. User interaction and display servers

9. GIS application development servers

10. Spatial data capture and transformation servers

11. Cartographic data servers

12. New technology servers

13. General purpose servers

14. History servers

15. Specialized application servers.

The particular division of labor suggested here in this report among GIS-T servers is 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 difficult but essential part of computer system design.

## 12.4.4 Drivers for Server-Net Technology Model

There are four major drivers, or reasons, why the Server-Net model is the only viable strategy for implementing new information technologies in to the GIS-T organization. 1) pace of technological change is constant and pace is accelerating in the information technology field; 2) almost all work is distributed or geographically dispersed; 3) data, information and knowledge are becoming more critical resources in carrying out work; 4) time compression, i.e., the demand for reduced delivery time for products and services.

First, the pace of *technological change* has become so accelerated, that investments in information technology must be adaptable. Any organization involved in procurement of workstation technology in the last few years will attest to this. The technology that was cutting edge at the time of RFP writing is no longer so by the time of procurement. The buyers in the x86 desktop computer market are sure to recount similar stories.

For state DOTs, the change is also very pronounced. These agencies have invested significant dollars in mainframe technology, usually in the tens of millions over the last three decades. However, the trend toward downsizing and similar activities makes these previous investments questionable now. Obviously, hindsight is always 20/20. Nevertheless, information technology investments, at least, from now on must take for granted that such a pace of change is normal. Therefore, the question should be not how another obsolete system can be avoided in the near future. Rather, the question should be how can these investments be made more adaptable.

Second, there is growing recognition that almost all *work is distributed* in the organization, and the real task is fitting the technology to the distributed work at the users location and not fitting the work to a

centralized technology. The conventional wisdom holds that the level of communication and collaboration required for a work group to function as an integrated entity can best be achieved by collocating people in the group. Intuitively, bringing people together physically so they can share common facilities will enable them to work better together. Again, the Server-Net technology provides the infrastructure that will help avoid force-fitting the group work to the technology.

Third, *the data, information, and knowledge about work* is becoming increasingly more important than many traditional physical aspects of the work itself. Many commentators have likened many traditional businesses as information businesses. For instance, Tom Peters has attributed the success of Wal-Mart stores to the fact that this chain treats information about the retail goods as more important than the good itself, i.e., how much? how many? when? where to ship?, etc.

In the transportation business, the state DOTs are realizing also that in the age of scarce resources they are more likely in the business of managing existing transportation infrastructure than the traditional one of "laying down pavement". This new perspective requires volumes of information as well as its efficient and effective management and distribution. The ISTEA management systems are one aspect of this phenomenon as mandated by the federal government. However, they are not the only ones. As the age of the existing road networks increase beyond its initial life cycle, the allocation of funds for repair and maintenance requires more and better information to enable cost-effective investment and maintenance decision-making.

Fourth, the *time to delivery* of products and services is becoming increasingly compressed. As all these other factors are at work, this factor that has gradually gained importance: quick delivery or responsiveness to customer demands. In the private sector this is manifested in the shorter and shorter time to market cycles for new products and services. In the public sector, this is manifest in the quest for more efficient government and customer service, advocated by an increasing number of governmental units, and demanded by the public.

In the transportation business this change is manifest very clearly as well. For example, it used to be adequate for a road construction to take 3 to 5 years with two to three parties involved. Now the design process must take less time but involve at least three to four independent parties: state DOT, FHWA, state EPA, federal EPA, environmental interest groups, MPOs, and neighborhood interest groups. Another example, is the timeline for the planning and implementation of ISTEA management systems. Most of these systems are required to be in the planning stage by October 1994 and in place by October 1995. These implementation schedules are quite compressed and leave little room for error.

## 12.4.5 Implications of these Drivers for New Information Technology Investments

Currently the nature of state DOT work and its emphases are changing. This work is more data/information knowledge intensive and it must be accomplished in shorter time frames. Previously, the information technology support for state DOT work was quite useful. These information systems investments made in the 60's, 70's, and 80's provided centralized mainframe access to both computing power and databases. However, the current changes in state DOT work and its compressed time schedule call for radical restructuring of the new information technology investments.

The new investments must clearly and explicitly accommodate the two of the four major factors presented above. First, rapid pace of technology has to be planned for. Second, information technology must adapt to the distributed nature of work and augment it appropriately. These attributes can be accommodated by the Server-Net technology much more readily than previous generations of technologies.

The Server-Net technology, because of its inherent design features, is able to accommodate a growing heterogeneous computing environment. The Server-Net technology is based on the philosophy of the "Open Systems". The "Open Systems" approach to information technology is deliberately layered to separate various elements of information technology investment from others. In this manner, if one

technology layer must change then all other layers are protected. The implication for the state DOT

managers is that, probability of with being locked into obsolete hardware/software are much less.

This flexibility is afforded at a cost: higher level of complexity in terms of management and skill

and much higher level of sophistication on the part of the organization in dealing with information

technology. That is, no more centralization of information technology know-how in one place, but pockets

of capability are developed as needed by different groups and individuals in state DOTs.

If the experience of the centralized information systems/data processing (IS/DP) departments in

state DOTs is any indication, this distribution of know-how will be a welcome change in the long run. In

the short run there are bound to be problems that must be adequately managed for the transition to be

effective. Therefore, our suggestion in this report is that, the Server-Net technology is a useful

technological paradigm for implementing information technologies in state DOTs.

While server-net tackles some of the problems that have plagued the traditional centralized

approach to providing computing power and data to state DOT users. It would be remiss to present Server-

Net technology as a new "fix" to solve problems created by an older "fix" without adequate attention to the

management and organizational issues. This report lays out some important management issues that must

be addressed if the Server-Net technology implementation is to achieve its intended effect.

## 12.4.6 The Management Challenges of the Server-Net Model

There are two independent sets of demands on the state DOTs in the 1990s: greater internal and

external integration and interdependence. The internal demands are generated by at least three sources:

changes in information services function roles, (e.g., CASE tools, relational DBMSs, etc.) data sharing

across functions induced by new technologies, (e.g., GIS-T's common spatial referencing systems) and

information technology changes, (e.g., Server-Net network infrastructure requirements). These changes

necessitate organizational approaches that cut across traditional hierarchical structures and call for more partnership across functions in the state DOTs.

The external demands fall in at least three categories: federal mandates, (e.g., CAA, and ISTEA) state government collaborative requirements, (e.g., North Carolina transportation/environment legislation) and downsizing pressures, (e.g., citizen tax revolts and raised public concern over cost effectiveness of government). These demands also translate into greater external interdependence and integration among the various functions currently performed by state DOTs. In the previous era, the state DOTs business was usually 90 percent "laying down" pavement. Now, it is moving toward creation and management of an efficient and effective transportation system that is environmentally friendly and less expensive to maintain.
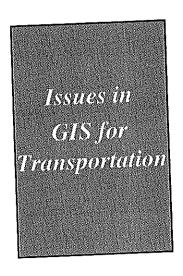
Information technology can play an enabling role in satisfaction of these new demands on state DOTs. There are two particular technologies of interest here, namely, the GIS-T data models and software, and the Server-Net environment. The GIS-T data models and software are the tools needed to create and manage the transportation system more efficiently and effectively. The Server-Net environment has all the ingredients of a technological solution that will not be obsolete before it is off the drawing board. The combination, if properly managed, can go a long way to address the demands facing the state DOTs currently. However, the key word here is managed. That is, the fixation on the technology must give way to a balanced approach that views technology as a tool to address specific demands, and therefore management of the process of greater integration and interdependence as important.

Two distinct sets of management challenges are identified for state DOTs to tackle in order to realize the full potential benefits of the GIS-T and Server-Net technologies. First, there are challenges faced by the information services function. The IS function can be either an effective agent of change in this process or a change resistor/subject of change. The former is proposed as the only viable option for the IS function. Second, there are those challenges that are faced by the top management of the state DOTs. These are challenges that require direction, policy and involvement from top management if state DOTs are to

transform themselves from pavement layers to transportation system managers. Each of these is discussed below in modest detail. The discussion of the IS function challenges is more technologically detailed due to its nature. The top management challenges are more general and relate to the general manager's tasks in a state DOT.

# PART IV

## EMERGING USES IN GIS-T

Issues in GIS for Transportation

# CHAPTER 13

# IVHS AND GIS-T

This section provides an overview of the Intelligent Vehicle Highway System (IVHS) program as it is presently evolving, and will describe a variety of IVHS geographic information requirements that can be fulfilled with GIS-T technology.

## 13.1 Introduction

### 13.1.1 IVHS Background

Although the United States has one of the best surface transportation systems in the world, continued growth in travel is severely straining the system. The level of mobility on which we have come to depend can no longer be taken for granted.

Congestion on the Nation's highways continues to increase, particularly in urban areas and along heavily-traveled inter-city corridors. The annual cost of congestion to the National highways lost productivity alone is about $100 billion, exclusive of the costs of wasted fuel and environmental damage. In addition, more than 40,000 persons are killed and another five million injured each year in traffic accidents, at an additional annual cost of over $137 billion to the Nation's economy.

Even though highway fatalities have been declining in recent years, the loss of so many lives unconscionable in an era when technology would permit us to save many of them. Additionally, in many areas of the country the building of enough additional roads cannot be supported financially or environmentally to solve cognition problems. What is needed is a "smarter" surface transportation system, one that annually functions as an integrated intermodal system that offers increased performance in many respects.

## 13.1.2 IVHS Technology

The Intelligent Vehicle Highway System (IVHS) is a national program designed to applying advanced concepts and technologies in areas of communications, navigation, and information systems in order to reduce traffic congestion, to increase transportation efficiency, to enhance mobility, to improve highway safety, and to reduce harm to the environment caused by automobiles.

Since the enactment of the Intermodal Surface Transportation Efficiency Act (ISTEA) in December 1991, the IVHS program has gained tremendous national interest and momentum. The IVHS program uses advanced technologies in communications, navigation, and information systems in order to reduce traffic congestion, to improve highway safety, and to mitigate the impact of roadway transportation on the environment. IVHS is an "umbrella" term encompassing five information systems and technologies: Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Advanced Public Transportation Systems (APTS), Commercial Vehicle Operations (CVO), and Advanced Vehicle Control Systems (AVCS). There are also many ancillary technologies which contribute to all of the aforementioned systems including: Automatic Vehicle Location (AVL) systems; Automatic Vehicle Identification (AVI) systems; Electronic Toll collection and Traffic Management (ETTM); "Smart Cruise Control"; collision avoidance systems.

All of these IVHS components require geographic information in various forms, and there is considerable overlap in the information needs of IVHS and GIS-T. Furthermore, there is a great deal of geographic information required by IVHS that can best be provided and maintained by GIS-T professionals and systems.
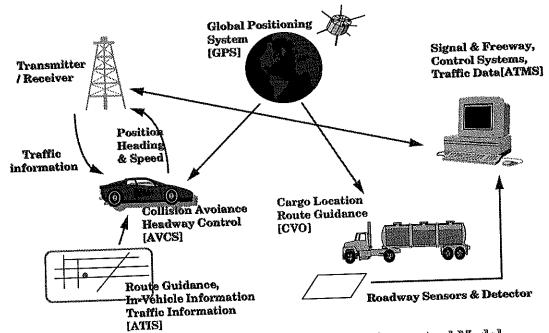
## 13.2 IVHS Components

The figure on the next page illustrates the basic components of IVHS technologies, and their interaction.

### Advanced Traffic Management Systems (ATMS)

These systems integrate information on traffic movement obtained from sensors (such as magnetic loops in roadways and closed-circuit TV, IR detectors, etc.) in order to measure congestion, to detect incidents, and to manage traffic flow through control of traffic lights, ramp metering signals, and variable message signs. They can also provide priority for public safety, transit, and high-occupancy vehicles through lane control signs and signals. A number of such systems are already in operation, (e.g., Los Angeles and San Jose) and many expanded and additional systems are being planned and installed.

Since virtually all information used for ATMS systems is geographically referenced to roads, digital road maps are invaluable and already featured prominently on GIS platforms at traffic management centers in order to display the locations and severity of roadway congestion and the positions and status of incidents. They can also be used to display and control cycles of signal lights on arterioles and at freeway on-ramps. These displays provide operators with a geographical perspective from which they can graphically access more detailed information from complex and extensive databases.

Global Positioning System [GPS]

Transmitter / Receiver

Signal & Freeway, Control Systems, Traffic Data[ATMS]

Traffic information

Position Heading & Speed

Collision Avoiance Headway Control [AVCS]

Cargo Location Route Guidance [CVO]

Route Guidance, In-Vehicle Information Traffic Information [ATIS]

Roadway Sensors & Detector

U.S. DOT-Federal Highway Administration: Conceptual Model

Joseph R. Francica, 93 GIS-T

## Advanced Traveler Information Systems (ATIS)

These systems provide assistance to travelers in planning and making trips both using private vehicles and/or public transportation. They support pre-trip planning with the aid of microcomputers in kiosks, homes, offices, or portable (notebook and handhold) applications, and they can include address finding, geographic business listings (yellow pages), tourist information, intermodal public transit information (routes, schedules, fares, transfers), and driver pathfinding. [Note: "Pathfinding" is used here to mean the procedure for selecting the "best" (e.g., fastest, shortest, or simplest) route from an origin to a destination. Route guidance refers to turn-by-turn instructions for how to follow that route.] Pathfinding may be augmented with average congestion models or with real-time and projected congestion information (e.g., planned lane closures or special events) obtained through modems or through radio and TV subcarrier data broadcasts.

In-vehicle systems include real-time tracking and map display of vehicle location by navigating with the aid of dead reckoning, map-matching, roadway electronic benchmarks, Global Positioning

Satellites (GPS), and/or other technologies. These systems can also permit destination finding via entries of street addresses, or with the aid of business listings (showing hotels, restaurants, banks, stores, etc.), and with tourist guides (showing museums, theme parks, monuments, etc.). Turn-by-turn route guidance from the present location to selected destinations is generally also provided. Real-time digital-data radio broadcasts of traffic conditions can permit dynamic route guidance that adapts in real-time to changing traffic conditions in order to provide the fastest route to a destination. Such capabilities have already been demonstrated by projects such as the TravTek project in Orlando, Florida.

Various combinations of traffic data broadcast receivers, GPS (or other radio-location devices), and notebook or handhold computers could produce a completely portable device with all of the in-vehicle functionality described above. Such a device could be used in any vehicle, or in handhold form it could be used by a pedestrian, a bicyclist, or a tourist utilizing public transportation. Figure 1 illustrates the information flow for a real-time traveler information system.

Digital map databases are fundamental assets for most ATIS devices. They are essential for pathfinding, and they are invaluable for efficiently displaying present location, destination, and route information. They also contain geographically-based business listings that can find the closest Italian restaurant to the present location or the nearest hotel to a future destination.

The advances in speed, storage capacity, computational power, and miniaturization of microcomputers and navigation sensors, combined with the speed, functionality, and storage efficiency of digital road map databases are leading to a revolution in ATIS applications and devices that will impact vast numbers of travelers

## Advanced Public Transportation Systems (APTS)

APTS technologies are aimed at improving the safety, efficiency, and ridership of a wide variety of public transportation systems including buses, trains, subways, ferries, car pools, taxis, and demand-responsive services (e.g., dial-a-ride). APTS approaches generally utilize ATIS technologies to assist

travelers in pre-trip planning, and they utilize ATMS technologies to track transit vehicles and to maintain headway's (i.e., prevent buses from bunching together as a result of non-uniform route delays). Sensors are used to track the transit vehicles in real-time so that schedules can be dynamically adjusted to maintain headway's, and so that passengers can be advised of schedule deviations.

As mentioned before in the ATIS description, digital road map databases are extremely useful in providing multimodal trip-planning assistance for public transportation users (1) through microcomputers in homes, offices, and kiosks, and (2) through central computer systems used by human operators to assist telephone callers, or accessed by remote terminals through telephone modems. The various APTS components and their interactions are illustrated in Figure 2.

Automatic Vehicle Location (AVL) systems combined with digital map displays can also be extremely effective in real-time passenger information systems that show current transit vehicle locations and their expected arrival times at various stops. Such displays could be provided in terminals, in lobbies, at bus stops, and even in transit vehicles themselves so that passengers could tell exactly where a vehicle is, when it will arrive at a particular stop, and how long they must wait for a transfer. AVL sensors are required to keep track of vehicle locations and schedule adherence so that passenger information systems can be updated in real time.

Paratransit (dial-a-ride) and ride-sharing (car pooling) services are rapidly gaining popularity. AVL sensors combined with digital maps and microcomputers can play an important role in organizing routes and schedules and in tracking and dispatching vehicles. In-vehicle navigation devices are one way of tracking vehicle positions, and they can be of great assistance to paratransit drivers in locating unfamiliar addresses, in finding efficient routes, and in avoiding congestion.

### Advanced Vehicle Control Systems (AVCS)

AVCS technologies include such areas as smart cruise controls (that can automatically maintain vehicle spacing), collision avoidance systems, vehicle platooning, and other systems that could enhance

safety and permit closer spacing of vehicles for increased roadway capacity. Ultimately, in a more futuristic goal, AVCS might enable auto-piloted vehicles to take passengers to their destinations without human driver intervention. Digital road maps will be essential to AVCS routing of individual vehicles and to global optimization of traffic under AVCS control.

### Advanced Rural Transportation Systems (ARTS)

The Rural IVHS application area is a recent addition to IVHS. A disproportionate share of fatal accidents occur on rural roads, and much of the ARTS emphasis is on improving safety in rural environments. Problems needing solutions include collisions with animals (livestock and deer), collisions with slow moving vehicles on country roads, running off roads (due to excessive speeds on curves, terrain limited visibility, or driver drowsiness), and weather induced accidents (fog, dust storms, ice, etc.). Search and rescue of distressed motorists can be especially difficult in rural settings. If a vehicle runs off the road in a remote area and is hidden by foliage or terrain, sometimes the driver can be trapped and not discovered for hours or days.

A variety of solutions are being considered for these problems. Electronic beacons have been proposed that could be operated on slow-moving vehicles (such as farm equipment) or deployed by public safety personnel at an accident site to warn approaching motorists of danger ahead via sensors in their vehicles. "Radio signposts" have also been proposed. These could be integrated with regular road warning signs (such as speed limit signs or slow curve signs) and could be read by an in-vehicle sensor and then presented on an in-vehicle text display or by a synthesized voice. Such radio signs could warn of routine hazards such as a tight curve ahead, or they could be changed via cellular modem to warn of adverse weather conditions, roadwork or accidents ahead.

Cars could be provided with emergency beacons that could be activated manually by the driver or automatically by air bag deployment. These beacon signals would summon help and could be used to locate a vehicle that may have crashed well off the road. Existing satellites might be used to detect emergency

beacons in very remote areas where motorists in distress might not otherwise be discovered. Such satellite beacon systems are already in use for marine and aircraft applications.

Digital maps are needed in rural applications for all of the same purposes as in urban applications. It is important to realize that a significant portion of the people traveling in rural areas do not live there. They are urban dwellers on vacation or traveling between urban areas. They will want the same types of ATIS services that they have available in urban environments.

### Commercial Vehicle Operations (CVO)

These applications include technologies to improve the safety and efficiency of commercial and public safety vehicles and fleets. Examples include fleet management (real-time vehicle tracking, dispatching, routing, etc.), distribution planning and scheduling, automatic toll-taking, weigh in motion, stolen vehicle recovery, etc.

Many CVO technologies are already operational, and their utilization is rapidly spreading. Fleets of ambulances and fire trucks use in-vehicle map-matching navigation systems for AVL, and provide rapid response to emergencies by using the control center's ability to dispatch the nearest vehicle and by using the vehicle's ability to pick the most efficient route. AVL systems and microcomputer based digital road maps are indispensable, both to track vehicle locations at the dispatch center and to provide vehicle position and pathfinding within the vehicle.

Other systems are using vehicle radio transponders to recover stolen vehicles and to track and dispatch commercial fleets. This technology is being used by fleets with 10 or fewer vehicles as well as by fleets with hundreds of vehicles. They all use AVL and digital map displays at their control centers to assist in tracking and dispatching vehicles.

Digital road map databases have been found to be highly effective for designing and planning product distribution routes and schedules. Fleet reductions of 10% to 15% have been regularly realized as a

result of the regional perspective and route planning efficiency made possible by digital road map databases and their associated routing algorithms.

## 13.3 IVHS Architecture

The Department of Transportation is responsible for providing the leadership and guidance necessary to ensure national compatibility among IVHS technologies over the long term. That compatibility relies upon establishing a unifying system architecture.

An IVHS architecture describes how multiple IVHS subsystems communicate with each other and what information is shared among the subsystems. Some typical subsystems are roadside control and communication devices on-board vehicle systems, and transportation information centers. The architecture also describes how the provision of services are integrated. Defining an open, national IVHS architecture will lay the framework for guiding deployment and evolution of IVHS into the future.

The delineation of a common method for vehicles to communicate with roadside devices or transportation management centers, or establishment of national compatibility is important. Not only is it necessary to permit IVHS equipped vehicles to travel throughout the country and have their IVHS remain useful, but it is critical in fostering private sector investment in the development of such products and services.

In addition to different communication methods, IVHS architectures can vary in the way costs are distributed among subsystems. The architecture determines whether most of the capital costs are borne by the end-user, as with a vehicle-based architecture, or by an operating agency, as with an infrastructure-based architecture. Both of these example architectures can provide similar user services. There is a need to establish measures of effectiveness and analyze alternate architectures to determine which one is the best architecture, both technically and administratively, for IVHS. The national IVHS architecture must be both technically sound and feasible for widespread deployment by operating agencies, manufacturers, and other

groups interested in and affected by IVHS. This establishment of common interfaces stimulates the deployment of IVHS and the development of standards and products.

The national IVHS architecture must be an open system architecture that can accommodate a wide variety of technologies including existing transportation management systems and equipment. However, the most technically robust architecture will be worthless if it is not implemented or accepted by those responsible for deploying, operating, and maintaining IVHS. Therefore, developing consensus is a critical element in defining the nationwide IVHS architecture. Because of the wide range of people and organizations that will be influenced, and since no single entity is responsible for deploying and operating IVHS, it is important that the stockholder organizations are able to meaningfully participate in the establishment of the national IVHS architecture. The organizations include industry groups, professional societies, public sector agencies, and user groups. As the development of the national IVHS architecture proceeds, this consensus will be formed by sharing intermediate products of the development process with the stockholders and receiving feedback from them.

## 13.4   Vision and Benefits of IVHS

This is a vision of future with safer and better informed travelers. Accurate and timely information on traffic conditions and transit services will be available to travelers before they begin trips. Navigation and route guidance and improved traffic control systems, as well as systems aimed at increasing the efficiency of commercial vehicle and transit operations, will provide assistance once a trip is underway. The safety of highway travel will be significantly increased through products which ensure the driver's own state of fitness, enhance driver perception on a continuous basis, give warning of impending danger, and eventually intervene with emergency control to prevent accidents from occurring. This vision also includes automated highways that improve the safety, efficiency, and convenience of the highway system, while simultaneously extracting greater productivity out of the infrastructure.

IVHS technologies and services will significantly enhance the efficiency of transit and commercial vehicle systems by providing accurate information on the location and status of the vehicles and traffic conditions, and two-way communication with the drivers. This information will also help make transit systems more user friendly to passengers. Still other technologies will aim to reduce the motor freight paperwork burden associated with the issuance of State permits and the monitoring of size and weight compliance.

IVHS can be an important part of the solution to the surface transportation problems facing us in the future, just as the Interstate Highway System was in the past. Applications of cost-effective IVHS technologies have the potential to help save lives, save time, and save money. It will also multiply the effectiveness of future spending on highway and transit facility construction and maintenance, increase the usefulness and attractiveness of public transportation, and provide new tools for managing travel demand. Of course, these benefits will not be achieved without considerable costs. The trade-offs between benefits and costs will be assessed when making public investments in the technology.

The benefits of IVHS will likely be experienced by all segments of the population. For example, measurable reductions in traffic congestion are attainable through better network surveillance and management, and a better-informed traveling public. While this results in obvious advantages for the traveler, the indirect consequences are also significant. These include reduction of "secondary" or congestion-related accidents, improved transit service, less fuel wasted from sitting in traffic jams, and fewer emissions from idling engines. Productivity gains result not only from workers who waste less time commuting, but also from lower commercial trucking costs and greater returns on capital investment in public transportation.

While cognition is the primary traffic problem in urban areas, rural areas suffer from a higher traffic fatality rate due to road conditions and higher rates of speed. The increased margins of safety provided by IVHS crash warning and avoidance technologies have the potential to reduce the number and

severity of both rural and urban accidents Additionally, IVHS communications capabilities will improve rural emergency response times and improve levels of rural public transportation service.

Improved vehicle management systems will assist transit in operating more efficient and attractive services. Ride-sharing arrangements will be made more convenient. Electronic fare collection will reduce the exact-change barrier to the convenient use of transit.

Increased collection and creative use of information will assist travelers in making informed decisions to use transit and other ride-sharing arrangements. Less vehicle-miles of travel will result, with associated environmental and energy conservation benefits. Personal mobility will be enhanced by making service better understood and more accessible, especially to the transportation disadvantaged, including the elderly and disabled, and residents of geographically remote communities.

Electronic toll collection, a convenience in itself, also provides the necessary technology base for congestion pricing, a demand management tool for which ISTEA has authorized research and development, and which may be an important part of the long-term solution to many transportation problems. Commercial vehicles also stand to gain from systems which replace hand-to-hand document transfer with electronic information transfer, minimizing stops for tolls, weighing, safety inspections, and other delays. These same technologies can lead to similar benefits for passengers using public transit by electronically integrating fare and billing systems.

Although there are substantial risks, an entirely new plane of benefits may be realized with the complete automation of certain highway facilities. An automated highway could provide a nearly accident-free driving environment and result in an increase of two or three times the capacity of present-day facilities, while possibly encouraging use of more environmentally benign propulsion methods.

IVHS technologies and systems also promise to remove much of the uncertainty, aggravation, frustration, fatigue, and general stress associated with travel that many of us experience today.

# 13.5 GIS-T and IVHS

## 13.5.1 IVHS Geographic Information Needs

As is evident from the above descriptions, different IVHS applications generally require different types of geographical information. However, all IVHS applications fundamentally require digital road maps.

### *Digital Road Maps*

IVHS maps obviously need to contain very current and complete road networks. Positional accuracy's should be 15 meters or better absolute accuracy, and 5 meters or better relative accuracy in order to support in-vehicle navigation and automatic vehicle location. Road classifications ranging from Interstate Freeways to alleys and gravel roads are needed to provide logically readable displays at various zoom levels, and to support efficient route finding. Precise road interconnectivity is critical to route finding and to route guidance. Interconnectivity is often difficult to determine, however, because turn restrictions and small street barriers are often not evident from either paper maps or aerial photographs. Street names and address ranges are necessary for destination finding, and -- since many streets are known by multiple names (e.g., first and last) -- aliases must also be included. IVHS digital maps also need various landmarks and area fill features (such as bodies of water, parks, and golf courses) to make the maps recognizable and easy to use.

### *ATMS*

The different IVHS application areas have specific geographic information requirements in addition to the digital road map requirements that the various applications generally have in common. ATMS centers require the locations of traffic sensors as well as the locations of traffic signals and changeable message signs used to control traffic flow. They also need information about numbers of lanes,

high-occupancy-vehicle (HOV) lanes, one-way streets, turn-restrictions, barriers, speed limits, and roadway flow capacities. In addition, they use AVL and a variety of other sources to obtain real-time geographic information about congestion and incidents, and to provide priority to public safety, public transportation, and HOV vehicles.

## APTS

Detailed maps are required for APTS in order to support planning and operations of both fixed-route and paratransit services as well as to support trip-planning services for customers. These maps must include transit routes and schedules, locations of transit stops and terminals, intermodal transfer points, taxi stand locations, and perhaps even car rental locations. In addition, APTS operations require real-time geographic information on congestion, transit vehicle schedule adherence, and vehicle locations in order to maintain headways, to compensate for delays or incidents, and to control and dispatch paratransit services.

## ATIS

As mentioned previously, the destination-finding features of ATIS require current and complete street names and addresses. Furthermore, ATIS utility is greatly enhanced by inclusion of geographic tourist guides and yellow pages that enable travelers to select destinations based on proximities to other places (such as the closest Holiday Inn to the convention center, or the closest metro stop to the museum). In addition, pathfinding requires precise information about transit routes and schedules, one-way streets, turn restrictions, and road classifications. Pathfinding can be enhanced by information about posted speed limits, and about locations of stop lights and stop signs. Route guidance can be improved by precise sign and lane information (e.g., "Get into middle lane and angle left onto Blossom Street following sign for State Highway 16 to Littleton."). Finally, pathfinding and route guidance can both benefit by real-time transit and traffic information derived from APTS, ATMS, and ATIS information sources.

*ARTS*

In addition to the road map and other ATIS items described above, ARTS can benefit from information regarding safe speeds (as well as posted speed limits), grades, passing/no-passing zones, hazards, dangerous curves, services, and rest areas. Information about truck stops, height restrictions, and restricted radius turns might be of use to tourists driving campers or pulling trailers (as well as to truckers) in rural environments. Geographic tourist guides and yellow pages may be just as important to travelers in rural areas as they are in urban areas.

*CVO*

Geographic information needs for CVO include truck routes, height and weight restrictions, turning radius restrictions, grades, posted truck speed limits, dangerous curves, safe speeds, rest areas, break inspection areas, truck scales, truck stops, and runaway-truck ramps.

## 13.5.2 IVHS and GIS-T Synergy

It is clear that IVHS fundamentally depends on GIS-T related information, and that, when unavailable from existing GIS databases, the needed information is being captured using GIS tools. It is also evident that most geographic information being captured for IVHS applications has value as well in other GIS-T applications aswell. Examples of such data include one-way streets, turn restrictions, connectivity, plus highway sign locations and content. Such information often does not exist in databases of any form, let alone in digital form, and yet this data could be of considerable value to state and local DOTs, public works departments, and public safety agencies as well as to IVHS. In most cases, the only way presently to obtain such data for IVHS is to send out field-data-capture teams to drive the streets and to record the data. Obviously, capture and maintenance of IVHS data in that fashion is a very expensive proposition.

It seems more reasonable to capture data on one-way streets, turn restrictions, connectivity, lanes, signs, etc., at the time of installation, construction, modification, or maintenance of the roads themselves. Such information can probably best be captured and maintained by local DOTs, public works departments, and their contractors. Perhaps "as-built" data could be entered into local standardized digital databases as a routine requirement for contractors performing road construction work or for public works departments performing road maintenance and modifications. Data from GIS-T and IVHS sources could be pooled into common databases which could then serve the needs of both IVHS and GIS-T applications. The rapidly falling costs of GIS systems, and their increasingly widespread adoption by local DOTs make this prospect far more likely than might have seemed possible even a year or two ago.

All these IVHS components require geographic information in various forms, and there is considerable overlap in the information needs of IVHS and GIS-T. Furthermore, there is a great deal of geographic information required by IVHS that can best be provided and maintained by GIS-T professionals and systems. Different IVHS applications generally require different types of geographical information, however, all IVHS applications fundamentally require digital road maps.

It is clear that the GIS could serve as the supporting data base from which the maintenance systems are driven. While the GIS data base is ideally distributed across platforms as appropriate for the applications, the integrating solution for the Maintenance Management Information System (MMIS) as well as other DOT systems is the geographic solutions. All of the integrated systems, including even contracting systems are relateble through their geographic indices or keys of their data bases.

GIS technology and the conceptual models of IVHS have been on a collision course. The immense problems associated with traffic congestion in this country, and the burdens already placed on Departments of Transportation for simply maintenance activities, have made it necessary for politicians and transportation administrators to seek a technological solution. GIS is being investigated to serve at the core of Advanced Traffic Management Systems, and other systems. GIS however only fits into, to solve the

problem of efficient implementation of public transportation systems. Traffic management must use GIS in order to collect, manage, and analyze real-time data that is received from road-side sensors, travelers, public safety agencies, and departments of transportation.

GIS is an enabling technology that is finding its way into many applications for transportation planning and maintenance. The fit for GIS with IVHS/ATMS is in the use of the technology for real-time spatial data input and analysis for traffic management. This will allow traffic managers a geographical perspective of highway conditions and events. Many applications, from routing to dynamic segmentation, can be employed in the development of a command and control environment for traffic mitigation.

## 13.6 STARBASE, A Nationwide Tracking System

STARBASE is a real-time nationwide transportation tracking system which has been fully operational for several years. The purpose of the system is to provide two-way communications between a control center and a moving vehicle carrying high value cargo. The process starts several weeks before the shipment occurs, with a shipping request. The cargo information, along with time windows about pickup and delivery at the destination, site are entered into the computer. The convoy is configured with vehicles and personnel the week before the trip and convoy is activated into the system the morning of departure.

Automatic route adherence is accomplished by comparing the position of the vehicle to a pre-planned route. The control center operators can also access a number of displays using touch screens. Digital maps overlaid with the current position of the vehicles and various other pertinent information such as vehicle description are available to allow an operator to coordinate a response team to the location of the vehicle in the event of trouble. An operator can send a pre-defined message, send a long text message, or establish a two-way voice link with the vehicle at any time.

Considerable redundancy is built into the system to insure that no single piece of hardware or software can fail and prevent communications with a convoy. The position of the vehicle is obtained from

GPS, Transit and dead reckoning. The position data is merged with data from various sensors on the vehicle and with data that can be entered through the keyboard in the cab of the vehicle. All data is then encrypted and sent to the control center by two methods: 1) HF radio band using a set of antenna sites around the country; 2) satellite link using equipment that is commercially available.

The antenna sites have multiple antenna and receive on multiple frequencies. Additional data is appended by redundant computers at the antenna sites such as signal strength and antenna number. The data is forwarded to the control center by satellite link and leased line.

One of the control center main operator consoles consists of eight 19" high resolution (1280 x 1024 pixel) monitors, one 27" very high resolution (2048 x 2048 pixel), two 13" ASCII terminals for system interaction and two 21" NTSC monitors for CNN and weather channel. The control center computers decrypt and acknowledge the vehicle message, then overlay the vehicles position onto color maps on high resolution displays. The map database of the United States is the USGS DLG 1 :1000K which contains all the Interstates, US highways, state and local roads, city streets, dirt roads, and jeep trails. It also contains all rivers, streams, lakes, dry arroyos, airports and power lines. Like most national databases of this size it has errors and omissions. For example, if a vehicle carrying high value cargo the situation would require an accurate detailed description of the vehicles location anywhere in the US inorder for state police or the FBI to assist quickly. Asking police in a neighboring state to respond to an incident at 35 degrees 15 minutes north by 106 degrees 47 minutes west probably would get a poor response. Most of us do not think and work in latitude and longitude coordinates. Law enforcement agencies and most people can identify with local landmarks and prefer directions like "The incident is located 1/4 mile west of mile marker 126 on Interstate 40 in the west bound lane". Unfortunately, no single database tells us everything we want to know. Data fusion of multiple map coverage's is required along with dynamic analyses.

A program is underway to augment this database with others such as TIGER, SPOT, LANDSAT, DEM, DTED, DFAD, scanned NAPP, JOG and local printed maps. Several additional datasets are

integrated such as national law enforcement offices, FBI offices, safehaven location, and others. Putting all this data "on-line" is possible by putting all of the map data on optical disk cartridges and using a robotic jukebox. Each optical cartridge can hold up to six gigabytes of data. Today's jukeboxes can hold several terrabytes of data with access times in the range of 10 to 30 seconds.

Since the major objective of the system is to allow control center personnel to obtain assistance for the vehicle quickly, considerable effort was devoted to insuring that emergencies are handled efficiently. Evidence has shown that adrenalin will flow as hard in the human at the control center as it does in the person hundreds of miles away where the vehicle is located. When the adrenalin is flowing, operators misunderstand tone alarms, make lots of mistakes on a computer keyboards, mis-dial the telephone, and forget critical steps in procedures. This situation has encouraged extremely user friendly displays using touch screens, autodialers, automated procedures and voice synthesizers for annunciated alarms.

Several functions are also supported such as maintenance tracking over 100 mechanical components on each vehicle. Since the vehicles are maintained at three different sites across the US, the computer network allows the maintenance record for each vehicle to be accessed from any of the sites. All personal gear and personal physical prerequisites are also maintained on the system. The communications system hardware maintenance and repair person contacts phone list are accessed through the Technician Automated Diagnostic System (TADS). There are over 20 computers in the nation-wide network excluding micro-processors.

## 13.7   The Highway Risk Information System

### Problem Statement

The Highway Risk Information System (HWRIS) is intended to address the dual problems of *information defect* and *information overload* commonly found on rural highways. To understand what is meant by these terms, consider the following statistics. According to the Fatal Accident Records System

(FARS), as reported by the Pennsylvania Department of Transportation, 56.3% of US highway fatalities in 1990 occurred in single vehicle crashes, and 27.6% in cases where the vehicle hit fixed objects, typically off the road. Single vehicle fixed object crashes are predominantly rural, occur primarily on lower classification routes (only 20.7% occur on Interstates, primary arterial and urban expressways), occur at night (67%), and on curves (45%). Major causes of these accidents are *inappropriate driver behavior* (speeding, reckless driving, inattentiveness, fatigue), *adverse driving conditions,* and *poor response to hazards.* Alcohol, which leads to both inappropriate behavior and poor emergency response, is involved in 60% of the accidents. Similar causative factors lead to single vehicles hitting pedestrians or overturning.

A lack of adequate, convincing information is a theme underlying all three causative factors. Clearly, drivers in unfamiliar places and situations are at greater risk from all causes than commuters who have a thorough knowledge of where they are, what comes next, and what might occur. Providing the driver with information about her or his environment is particularly crucial in rural areas, where roads are curvier, visibility is poorer, and lanes are narrower. In a very real sense, the information problem for rural drivers is extreme. Even if one has driven a country road for years and knows every curve, he or she still does not always know what might be around the next curve.

The provision of relevant information to the driver is one component of safer vehicle systems. But there is also a problem of information overload. A driver is surrounded constantly by a flood of data felt through the vehicle, seen through the windshield, or heard from the road surface; one can even detect certain dead animals by smell far in advance of sight. The geometry of winding rural roads itself contains high information content when compared with Interstates. The problem is how to *fuse* all these data, *extract risks* from them, and *present* relevant and *only* relevant warnings to the driver. We cannot expect a driver, especially in unfamiliar territory, to sit down before a trip, memorize the route, rehearse contingencies, etc., like a military pilot before a bombing mission. We also cannot expect a driver to react to hazards as a

trained race-car driver or to react to an increased flow of information *as information* with anything but resistance, even hostility, especially if the system feeds back criticisms of behavior.

However, an information *management* system can be built that will provide warnings to drivers following the *fusion* of raw information, and it would be used if its warnings are relevant, significant, and, most importantly, reliable. Inappropriate driver behavior can be tempered by an information management system that senses such behavior and issues clear warnings and/or takes corrective action itself. Recognizing adverse driving conditions is a matter of common sense, but even the most sensible of people may be mentally preoccupied and may not fully appreciate that an upcoming bridge may be covered with ice when the pavement leading to it is wet. A clear warning that occurs when and only when icing conditions are present for an upcoming bridge will save lives. Also, providing warnings far enough in advance, in an intuitive manner that does not worsen the information overload problem, will improve the driver's chances of responding effectively to unpredictable hazards. Types of warnings which could significantly reduce the number of fatalities on rural highways are:

- Warnings of environmental conditions, including fixed attributes of roads and local conditions

- Warnings of excessive speed, with consideration of local road geometry

- Alerts for obstacles in the driving lane

- Alerts for other vehicles dangerously close

- Alerts for inattentiveness.

### Solution Approach

The HWRIS concept is to provide significant and reliable warnings of environmental hazards and dangerous driver behavior by combining Geographic Information System (GIS) technology, Global Positioning System (GPS) technology, precise road geometric and state data, state-of-the-art proximity sensor technology, and multi-sensor data fusion techniques. HWRIS does this in a way that is transparent

to the driver and that is fully autonomous, posing no infrastructure requirements. The HWRIS is intended to aid the driver in averting single vehicle run off-the-road and rear-end crashes, and collisions with objects on or off the road, by fusing information from sensors and providing warnings about risky situations and behaviors.

## 13.7.1 HWRIS Description

HWRIS is composed of an *in-vehicle computer*, a *static risk data base, GPS-based vehicle navigation hardware and software, dynamic risk sensors, decision software*, and *warning devices*. Each of these components will now be discussed in turn.

### *In-Vehicle Computer*

The in-vehicle computer contains software for interfacing with the navigation hardware, sensors and warning devices, and decision support software to integrate risk data from the static risk data base with dynamic risk data from the sensors. It is a small form-factor system configured using industrial components for reliability, and using a real-time, preemptive scheduling operating system kernel. Hardware interfaces include communication ports for the GPS receiver, analog and digital sensor control, warning device control, and display and user controls. Static risk data can be stored on memory cards, hard disks, and/or CD-ROM devices.

### *Risk Data Base*

Internally, HWRIS contains a "risk data base" of highway configuration and static risk information, such as:

- Locations of risk zones, e.g. deer crossing zones, one lane bridges, "slippery when wet" pavement, school bus stops and turn-arounds, railroad crossings, and dangerous intersections;

- Recommended maximum speed for curves as a function of weather conditions;

- Recommended g-forces on curves;

- Recommended/posted speed limits.

Clearly, the risk data base contains attributes not commonly provided in digital data bases and which therefore must be collected for a system like HWRIS to function most effectively. The subset of required data base access functions which are required include proximity and map matching operations, along with retrieval of related attribute information. The risk data base can hold data at a resolution matching that of the map matched location, and can be tuned to reduce spurious driver warnings.

## Navigation Hardware and Software

HWRIS maintains the current location of the vehicle within the digital map road network and consequently within the risk data base, by a combination of Global Positioning System (GPS) instrumentation, dead-reckoning hardware, and map-matching software. Map-matching software converts the latitude/longitude position provided by the GPS receiver to a specific road segment within the digital map, and hence to specific risk data associated with that road segment. Map-matching is required to correct errors in both the GPS location as well as in the map data base itself. Map-matching tracks the vehicle within the digital road network using sensor information such as information from the steering wheel turn sensor- to resolve ambiguities.

Furthermore, differential GPS is required to accurately locate the vehicle. It is anticipated that a nation-wide public differential GPS network will be operational in 1994, providing adequately low positional errors. Dead reckoning hardware is integrated with the GPS receiver to provide continuous tracking, even in urban environments where the GPS signal is often blocked by high-rise buildings.

## Dynamic Sensors

The static risk data are supplemented with data from a suite of environmental sensors, defined here to include the following:

Vehicle dynamics sensors: One important external sensor is an accelerometer, which detects instantaneous changes in vehicle position and orientation. Other sensors, such as digital compasses, digital odometers, and gyroscopes, are required as part of the location/dead-reckoning sensor suite.

Physical environment sensors: An ambient temperature sensor and a relative humidity sensor are required to determine the potential for freezing rain and frozen bridge surfaces. Thermal infra-red radiometers would ultimately be more useful for detection of road surfaces at the ice point, although such sensors remain expensive. Even microphones are potentially useful for determining road surface conditions when coupled with signature detection algorithms.

Object detection/warning sensors: Devices to detect objects in a vehicle's path have been the subject of much recent interest and research. Such devices include infra-red laser range finders, either scanning or fixed points, millimeter-wave radar's, and sonar. Most sensors such as these direct a narrow-to-wide beam of energy in a fixed direction; a few scan with a narrow beam and use pattern recognition algorithms to detect objects and lanes. This is an area where defense contractors and university labs have technological experience particularly relevant to IVHS.

Driver performance/monitoring sensors: A wheel sensor providing direction and amount of steering wheel turn can be used to characterize typical and abnormal behavior for a given driver. The possibility of automatic report of the in-vehicle atmosphere for breath constituents related to alcohol consumption also exists.

## Decision Support Software

Static risk data and parameters from the risk data base are passed asynchronously to the decision support software, where they are combined with dynamic data from sensors attached to the vehicle. Sensors may monitor environmental conditions continuously or respond to the presence of hazards. Sensors of the former kind are polled by the decision support software; those of the latter kind report asynchronously.

The decision support software interprets and integrates static and dynamic data from the risk data base and the dynamic sensors by the use of decision rules. When the conditions of decision rules are met, actions are taken by the decision support software to activate warning devices to alert the driver to the hazards encountered. Decision support software includes a function to maintain the vehicle's recent history and its immediate path, as well as current location and situation.

The synergistic combination of static information and sensed events is key to the HWRIS concept. For example, maximum safe speeds for a location depend on weather conditions alarm/alert thresholds are adjusted accordingly. Some of the warnings which integrate static and dynamic data are:

- Too close following of vehicle ahead based on current velocity;

- Tailgating vehicle behind;

- Upcoming curves when velocity exceeds recommended speed;

- Temperature at freezing when approaching a bridge at high speed;

- Obstructions on roadway when not stopped at an intersection.

### Warning Devices

The driver is alerted to roadway risk through a suite of human-computer interface (HCI) methods that include audible signals, synthetic speech, lights, and visible displays. The sensitivity of the sensors may be adjusted by the driver within limits of effectiveness. The driver may also enable or disable individual warning types using the control panel, or by voice recognition software. In all such cases, HWRIS should display clear indications that a warning has been disabled.

## 13.8 Research Directions

What has been discussed so far is only a concept. Our intention is to generate interest in and attention to defining what is possible when data fusion techniques are applied to safety problems, using the

entire range of technologies available today. Thus, the overall intent of this section has been to inspire research toward future systems. Three directions for research are considered that are particularly important to rural highway safety.

### False alarm detection

A major concern with a warning system such as HWRIS is that the system will detect too many risks, flooding the driver with alerts and thereby reducing the effectiveness of any valid warnings (the "cry wolf" problem). This problem can be addressed by allowing the driver to adjust the parameters and sensitivity of the warning system, within limits. An additional refinement is for the system to keep track of its own reports and adjust its reporting strategy when necessary. For example, after a period of time the system should know when a route is new to a given driver, or how often it has been traveled in the past, and how many times a "slow down" warning has been issued in the last number of minutes. System *Adaptivity is* possible and probably necessary for user acceptance. A related problem is that of *false alarms,* which occur when the system reports warnings during non-risk situations. If the frequency of false alarms reaches a critical point, the driver either will turn the system off, or ignore any warnings that are generated on the assumption that they are false alarms also (the "cry wolf" problem).

HWRIS solves these problems in two general ways: by the fusion of various environmental and situational clues; and by incorporating a level of intelligence sufficient to judge risks and be silent when silence is appropriate within an overall system context. "Intelligence" used here means that the system is aware of its own history, and also that it knows something about the driver and his or her behavioral tendencies. Thus HWRIS data fusion is *temporally adaptive* as well as *situationally adaptive.*

An example of situationally adaptive behavior is the screening of false alarms that occur with sensors which detect obstacles in the roadway, in particular those that look straight ahead rather than scan. For detection to occur in sufficient time for driver action, the look-ahead distance is typically large, perhaps 80-100 meters. On small rural roadways with curves of small radii, this distance results in many false

rectums from objects such as trees or signs alongside the road, or vehicles in approaching lanes. False alarm rates of over 10% have been recorded for radar systems on rural roads. However, by knowing the local geometry of the roadway, HWRIS can (based on the decision rules) either adjust the parameters of the sensor to detect obstacles at close distances only, steer sensors into the curve, or ignore the sensor altogether.

An example of temporal adaptation is drowsiness detection based on steering wheel monitoring. A wheel sensor providing direction and amount of steering wheel turn will provide a continuous stream of data that can be used to characterize typical and abnormal behavior for a given driver. One research hypothesis is that drivers falling asleep will interact with the wheel differently than those who are awake, and that wheel turn "signatures" will differ significantly between different drivers as a function of factors such as blood alcohol level, training, or age. Following the requisite research, HWRIS should be able to analyze wheel turn data and develop recognizable *risk signatures for lane keeping* for a given driver, in essence *leading* to better define risks as it ages.
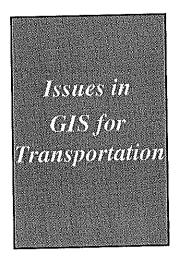
### Vehicle-to-vehicle communications

A logical place for communications between HWRIS-equipped vehicles is within the bandwidth of active object detection sensors. For example, an infra-red laser device will distinguish its own reflected signal from signals emitted by other vehicles, typically by a coding protocol. Such a sensor is already engaged in communicating with other vehicles who are similarly equipped, in the sense of agreeing not to communicate. Further use of signal bandwidth for coding intentional information (e.g. my steering wheel is pointed in your direction and my driver appears to be asleep; there was an object such as a deer in the road a quarter mile back) should be a simple technical matter, and inexpensive to implement. Considerably more effort and cooperation between interested parties will be required to determine what kinds of data are important and to develop standards for format and content for systems such as HWRIS.

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*Map data base accuracy requirements for map matching*

In order for HWRIS to function effectively, correlation must occur between the location hardware and the locationally-based static risk data. All components of the location system have statistical error, and the map matching process correlates clues from system components so that overall error is minimized, i.e. vehicle location *relative* to risk is precisely known. Note that this requirement does not imply that HWRIS needs a geometrically correct three-dimensional map in order to function. In fact, it doesn't need a conventional digital map at all, since map display is not essential to the concept. It does need a *topologically correct road network* for navigation, and an accurate *mapping* of risks and risk zones to distance between network nodes. This is not to say that road geometry is unimportant to HWRIS, but that the manner in which geometry is represented is flexible. For example, a curving road can be represented by a series of numbers corresponding to vertices within a latitude-longitude space. It can also be represented by a series of numbers specifying instantaneous compass bearing as a vehicle travels the road. In fact, the later form would lend itself to rapid cross-correlation with typical dead-reckoning hardware output.

Generally, accuracy requirements for navigation data bases are not well-specified and are the subject of attention by IVHS America and SAE standards committees, among others. The importance of this effort should not be underestimated, nor the difficulty of establishing procedures and social infrastructure for making and maintaining up-to-date national digital maps for vehicle navigation. Requirements for this purpose are simply not the same as they are for such tasks as environmental resource management or agricultural land monitoring. The particulars of HWRIS data structures, and the requirement imposed by the HWRIS concept that additional information (risks) be added to digital maps, are complexities *on top of* the need for geometrically and topologically correct digital road maps, consistent across the nation, for navigation purposes in general. The data problem is the *achilles heel of IVHS*, and a most significant research direction.

# CHAPTER 14

# TRANSPORTATION MODELING WITH GIS

Transportation data processing activities have progressed for the past twenty years in many parallel paths, among them are Geographic Information Systems (GIS), and spatial analytical modeling.

## 14.1 Introduction

A spatial analytic model is taken to mean a set of numerical expressions implemented in stand-alone software, principally for describing, explaining, and possibly predicting some particular, special aspect of present, past, or future geo-reality (Nyerges 1991a). A spatial analytic model implements either qualitative and/or quantitative measurements, discrete or continuous space at small or large geographic scales. Such a model must be computational in character, and readily implemented by computer software. The transportation models are a primary example of spatial analytic models.

There are several similarities in spatial analytic models and GIS, e.g., the need for geographical data and the ability to process that data. Without the similarities between GIS and models they could not be interfaced in a synergistic manner to enhance spatial information processing. Just as there are similarities, there are enough differences at present that are not discussed here. The differences tend to deal with a

matter of emphasis. A spatial analytic model tends to emphasize content and process of a spatial reality. Whereas, a GIS tends to emphasize content and structure of a spatial reality.

Interfacing GIS and models is not a new topic (See Nyerges 1991b for a brief review of early work). However, there has been more interest recently because of the many applications and emphases within several software packages that have evolved to maturity over the past several years. The strengths and weaknesses in both motivate the work on interfacing.

Several discussions exist in the spatial data handling literature that one can draw from to develop a reasonable understanding of GIS and model interfacing. However, the subject matter has not been presented in detail, and lacks synthesis. The discussion in this chapter focuses on the development of a conceptual framework for interfacing GIS and models. The framework synthesizes the issues and can help to better understand what can be gained and lost by pursuing development of certain interfacing environments. To some extent, the ideas presented here on interfacing GIS and spatial analytic models transfer to other contexts such as interfacing land information systems and geographic information systems or geographic information systems and computer-aided drafting systems. However, the focus here remains on GIS and spatial analytic modeling (Transportation Modeling).

## 14.2   Issues in Interfacing GIS and Models

Before discussing interfacing models and GIS, it is important to point out that the terminology is not stable. For example, the terms "linking" and "coupling" commonly are taken as synonymous because they have yet to be differentiated systematically in the literature. "Linkage" between a GIS and a model could be defined as a connection between two sets of generic functions such that data flows from one to the other, regardless of the software and/or hardware used. "Coupling" between a GIS and a model could be define as a software and hardware connection that implements the linkage. Although these definitions seem useful, they are stretching the distinction commonly made between the two terms at this time. In this report,

linkage, coupling and interfacing are used as synonyms. A better way to make the distinction between the

two ideas just presented is to refer to the coupling (linkage) of generic functions at a logical or conceptual

level, and the coupling (linkage) implemented by software/hardware at a physical level.

The spatial analytic modeling in GIS was represented as missing link hypothesis. As shown in

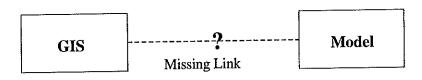Figure 14.1, the link between these two are missing.



Figure 14.1. Missing Link Hypothesis

Several approaches have been used to characterize strategies for interfacing GIS and spatial

analytic models. Each of them tackling a major aspect of the interfacing problem. Through such

discussions a series of issues arise, some authors giving more or less emphasis to various issues. Some

fundamental issues are:

- Substantive issues dealing with coupling effectiveness (Burrough et al. 1988) for application topics

  such as: transportation (Granzow and Lockfeld 1990 Lewis 1990 Nyerges 1990, 1991a) environmental

  contaminant (Fedra 1991, Nyerges i991c), location-allocation of public services (Armstrong and

  Densham 1990), urban policy evaluation (Birkin et al. 1990), and soil loss/erosion (Burrough et al.

  1988);

- Characteristics that differentiate a spatial decision support system (SDSS) from a GIS, mainly in terms

  of the significance of modeling (Armstrong and Densham 1990, Fedra 1991, Kessell 1991, Birkin et al.

  1990);

- Design of custom SDSS (Armstrong and Densham 1990, Fedra 1991, Kessell 1991) versus linking

  existing GIS and models (Lewis 1990, Nyerges 1990, Kessell 1991, Kilbom et al. 1991);

- The importance of software architectures and their influence on coupling (Granzow and Lockfeld 1990, Lewis 1990, Nyerges 1990, 1991c, Fedra 1991, Kilborn et al. 1991);

- Interface services used in a coupling environment (Smyth 1991, Strand 1991).

The list is not prioritized because all issues are equally significant. In addition, it is expected that the list is not exhaustive, as other designers might identify some other concerns. However, the list is reasonably complete.

## 14.3 Types of Modeling Interfaces

Interfacing can occur through any combination of the GIS and model subsystems, implementing graphic, analysis and data management functions. However, the most common interfacing occurs through the data management subsystem. Consequently, the data management subsystems form the basis of the interfacing architecture. The compatibility of data models for the GIS and the analytic model determine how easy or difficult it is to couple the two (Nyerges 1991c).

Granzow and Lockfeld (1990) describe four approaches that can be used to interface transportation models and a GIS: 1) independent applications with data transfers, 2) federated applications with common data definitions and separate data management systems, 3) linked applications with cross-referenced data between data management systems, and 4) centralized/integrated applications with a common data management. Independently, and at the same time, Nyerges (1990) developed a framework with the same basic four categories for coupling transportation models and a GIS suggesting that the integrated data model approach is the most effective for interactive modeling. This is the same perspective as in the decision support system literature. However, Granzow and Lockfeld (1990) developed the cross-referenced approach in considerable detail, stating that this approach makes the most sense for interfacing independent models and GIS. Given the mature state of many commercial software packages, they argue in

favor of building a cross-reference solution because it requires less development than the more tightly coupled solutions.

### 14.3.1 Classification of the Interfaces

In terms of the modeling technique, models can be integrated into GIS in the following three ways:

**1. External modeling -** This is a low level of interface in which models are implemented externally and then can be loosely linked to GIS by a batch mode.

**2. Internal modeling within GIS -** This is a intermediate level of integration in which modeling is done by using GIS provided language or related functions.

**3. Integrated Modeling -** This is a high level of integration in which entire modeling is done within GIS.

In this report, the following sections discuss interfacing spatial analytic modeling and geographical information systems in the perspective of modeling techniques. Discussion in this chapter will concentrate on the incorporation of spatial analytic modeling tools into GIS software. For further classification of the modeling interfaces , see Vellanki (1994).

## 14.4 Modeling Interfaces

### 14.4.1 External Modeling

This approach uses a GIS package for the things for which it is best suited and, when other facilities are required, the output from the GIS system is taken as input into other software. This type of modeling interface is also called as loose coupling.

This type of interface is shown in Figure 14.2. The data output from the GIS system is taken as input into other external modeling software.
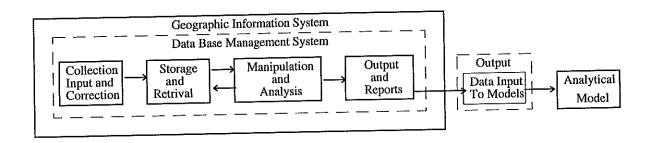


Figure 14.2. Interfacing the Model and GIS Externally with Flat Files (Loose coupling)

There are two possible approaches in this kind of interface:

1. Loose coupling by the interchange of ASCII files between packages.

2. Loose coupling by packages using a common binary file format.

*Loose coupling by the interchange of ASCII files between packages.*

Here data are passed from the GIS into another package by editing the ASCII output file produced by the GIS. This is the approach described by Gatrell (1987) in which output from ODYSSEY(GIS software) is passed to GLIM(spatial analysis package).

The strength of this approach is the logic of tackling each task with a package which is best suited to that task. There is also no need to write extra software (apart from the writing of Geolink itself). One drawback is its dependence on the format of the output from the package remaining constant over different versions of the software. It may also require the use of several large pieces or software at the same time (e.g., ARC/INFO and ORACLE in the Edinburgh work) which has implications for memory requirements. For mode details about modeling Interfaces with ARC/INFO, see Vellanki (1994).

*Loose coupling via binary files*

The alternative approach is to ensure that different packages can all read and write data files in an

agreed format. This approach has become very popular in the world of commercial software for the IBM

PC with the growth of packages which can work with the data formats used by industry standard software

(e.g., Lotus *1-2-3* .WKS files and dBase .DBF files) and with generally-supported file transfer formats

(e.g., .DIF files).

A standard file format is important here, either to be agreed upon between vendors, or to emerge by

vendors following the success of a market leader.

## 14.4.2  Internal Modeling

Internal modeling uses a GIS supported internal macro language to interface with the models. The

modeling is either done only by a GIS supported macro language or by embedding other modeling routines

into a GIS Supported macro language. This type of modeling interface is also called as close coupling.

This type of interface is shown in Figure 14.3. The data from the GIS system is retrieved by

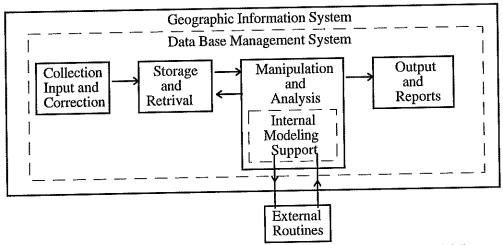Internal Modeling support and routines are used for analysis.

Figure 14.3. Interfacing the Models and GIS Internally with the Internal Model Support (Close Coupling)

Close coupling covers a variety of methods which all involve modifying the operations of the GIS software itself in some way. A variety of mechanisms are already offered by many packages including: macro languages which, at the simplest level, allow complex sequences of commands to be packaged into a single macro while more complex ones offer true programming language capabilities. Further, 'hooks' to user routines written in standard languages such as FORTRAN or C are offered. Libraries of user-callable routines to access the low-level data structures within the GIS are also available. These are potentially very powerful because they offer the developer access to both the standard user-interface facilities of the package (for example, macros can be written so that they appear to the user simply as extra commands), and to the underlying data structures used for handling the locational and attribute data.

There is some doubt as to whether the facilities currently offered are sufficiently powerful to provide the facilities needed for spatial analysis. A case in point is the 'W' connectivity matrix based on the length of the common boundary between adjacent areas. Many vector systems store information about area boundaries explicitly. The key question is whether or not the information is available to a user-written routine which can then construct the 'W' matrix. (See Yeumin Ding and Fotheringham (1991) for constructing 'W' matrices in ARC/INFO).

### 14.4.3 Integrated Modeling

Integrated modeling is done by integrating techniques of spatial analytic models fully within GIS software. This approach means using only GIS supported integrated models. These types of modeling interfaces are high level interfaces.

This type of interface is shown in Figure 14.4. The GIS system is used only for data retrieval and analysis.
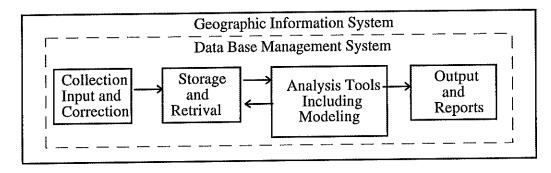
Figure 14.4. Interfacing the Models with in the GIS as Analysis Tools (Integrated Modeling)

There are two possible approaches in this kind of interface:

1. Full Integration.

2. Stand-alone Modeling Software.

## Full integration

Full integration means integrating the different analytical models into GIS. These are the analytic modeling tools that are available along with the existing spatial data analysis models. This type of integration was shown in Figure 14.5.
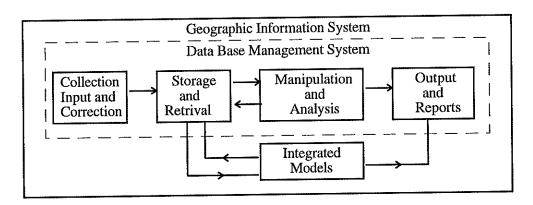


Figure 14.5. Integration of Models with in GIS along with the Complete Manipulation and Analysis Tools (Full Integration).

This approach has a number of advantages: software is documented and supported by the vendors; the techniques are available to all users of the package, and not only to those who happened to

have written their own routines to interface with it. However, despite these advantages, there are problems in following this method. It might result in some techniques becoming ossified within GIS systems and might require vendors to make major changes which would not be necessary for other users. As commented earlier, it would be difficult to persuade vendors to adopt such an approach without pressure from the market for such facilities.

### Stand-alone modeling software

The final approach which might be taken is to produce a stand-alone spatial analysis/modeling software. Stand-alone modeling means integrating the analytical model into the manipulation tool of GIS. This type of integration is shown in Figure 14.6.
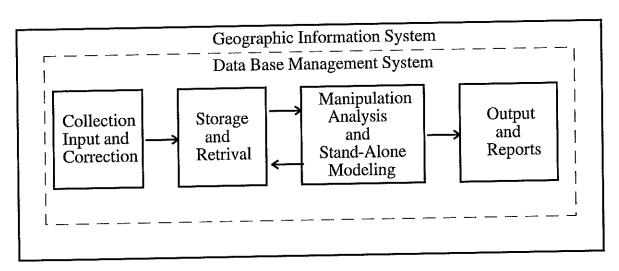


Figure 14.6. Integration of Models within GIS tools that are developed mostly in Modeling Perspective (Stand-alone modeling software).

In general, only a commercial company would have the resources to produce a comprehensive spatial analysis/modeling software package. However, there are some situations where writing software from scratch may be a sensible option, for example, to perform one specialized piece of analysis, which is not easily related to anything offered by a current GIS. A good example of this approach is the Geographical Analysis machine (GAM) developed by Openshaw et al. (1987).

GEOTRANS

The Geographical Optimizer for Transportation(GEOTRANS) is an implementation of a Geographical Decision Support System (GDSS) for rural transportation. Functionally, GEOTRANS includes capabilities one would expect from a GIS: independently selectable map layers of roads, railroads, cities, and regional borders; a data base with a flexible query language; a full set of map and data editing tools; and arbitrary zoom-in. These features are augmented by several transportation models: shortest path, facility location, route construction, and network flow.

Algorithms and specialized data structures were developed to accomplish accurate and efficient solution of a suite of network flow optimization models for use in GEOTRANS. These include shortest path, assignment, transshipment, capacitated transshipment and facility location models. The design of GEOTRANS is expandable, to easily accommodate a larger repertoire of modeling tools as they become available. The models can be used to directly support transportation decision making in a map-based environment in rural states.

GEOTRANS can be used in wide variety of rural transportation applications. Several examples are given below.
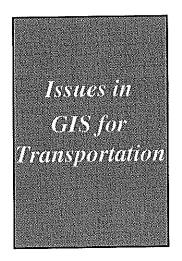
- Customized maps and reports (on screen and printed)

- Facility location analysis

- Shortest route analysis (based on distance or time)

- Point-to-point transportation analysis

- Regional demographic data displays

- Truck and bus routing and scheduling

- Census data analysis

- Location and siting analysis

For more description of the GEOTRANS, see Nygard (1994a).


SCHOOLMAPS

The SCHOOLMAPS is an implementation of a GDSS for School Districts Mapping and Transportation. Functionally, SCHOOLMAPS includes GIS. The map layers of roads, railroads, cities, and regional borders are independently selectable. The school district boarders can be selected individually. A data base with a flexible query language is supported. A full set of map and data editing tools and zoom-in provided. This software uses the real world coordinates.

The SCHOOLMAPS software is still under development. There is an ongoing effort to investigate the methods that would provide a measure of transportation performance for arbitrary school districts. Two areas of primary focus are spatial tessellations and data development analysis. Several transportation models (For example: Multi depot vehicle routing problem, Optimal routing etc.) are going to be supported in future (Nygard 1994b).

*Issues in GIS for Transportation*

# CHAPTER 15

## CONCLUSIONS

The first part of this report attempted to provide the fundamentals of geographic information system. The definitions, elements and tools are discussed in both the GIS and GIS-T perspective. The second, third and fourth parts of this report focus only on the issues related to the GIS and transportation. CAM and AM/FM can be used to store, manipulate, and retrieve geographic data, but a GIS is specifically designed for spatial analysis and is needed to fully analyze geographic data.

Spatial data in the GIS are usually managed by the customized software. The attribute data might be managed either by same software or by a third party DBMS. GIS software usually provides one or more interactive interfaces so that the users can initiate system operations. 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.

## 15.1 GIS-T Requirements

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

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

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

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

1. A topological data structure that enables appropriate representation of highway networks.

2. Input and editing capabilities for geographically structured data.

3. The ability to link locational and attribute data (including dynamic segmentation).

4. The ability to perform spatial analysis, including map overlay extended to include network overlay.

5. The ability to display geographic information.

### 15.1.1 Software

Selection of software and hardware is an important step in the GIS implementation process. Before selecting the GIS software, the organization should talk with a number of organizations which use the software under consideration, and whose situations are similar to the organization's own. Organizations should also make every effort to become knowledgeable about GIS software so that they can make the best possible choices among competing products. One important problem is that first-time buyers are unable to distinguish real differences between the capabilities of the various competing software's. Some of the available GIS software's are summarized in this report. It is very difficult to compare GIS software's with one another because of the large number of features and options that each one offers. Therefore, if an organization is trying to select a GIS to buy, it is very important to begin with an assessment of what functions organization need in a GIS and compare various GIS programs to the organization needs, rather than to one another. The minimum required functions for GIS-T development are listed above. These functions are to be further divided when evaluating the organizational needs.

### 15.1.2 Hardware

Another major consideration in GIS-T implementation is specifying the hardware. The vast majority of computer hardware used in GIS is general purpose Electronic Data Processing (EDP) hardware, so it is possible to prepare an RFP which will permit many vendors to bid on the hardware for most GIS. Problems can arise in attempting to connect hardware from different vendors. Designers need to know whether the devices are compatible or whether various conversion processes or devices will be required. Another problem in specifying the system is how to choose the best size hardware system. Experience here is clear: successful GIS implementations tend to generate greatly increased user demands for capability, so buying extra hardware capacity at the outset is probably a wise investment in most cases. Otherwise, one can expect to have to upgrade a successful GIS within a year or two of it coming on line.

### 15.1.3 Architecture

This report along with the National Cooperative Highway Research Program (NCHERP) 20-27 report suggests, that the GIS-T enabled networked organizational approach is the important organizational design phenomenon for transportation agencies. Organizations will potentially turn to network approaches with the goal of improving performance through the existing organization. In this report, several key characteristics of the more networked organizational approach are identified and specific areas where organizations are attempting to increase performance in the transportation business are discussed. Next, it argued that in their efforts to increase performance, organizations are recognizing the need for more effective management of greater interdependence and integration across sub-units and people within the agency. GIS-T enabled networks are the most effective way for state DOTs to manage this interdependence.

Specific aspects and implications of networks for the transportation managers are discussed. Further research must consider two key questions:

- How do specific characteristics of the networked state DOT contribute to improved aggregate transportation agency performance and transportation system performance?

- What are the implications of these network characteristics for managing greater integration and interdependence effectively in the state DOT environment?

### 15.1.4 Implementation

The seventeen steps and five stages outlined in this report represent a successful GIS implementation in a transportation organization. Depending on the size of organization and the extent of the GIS applications, the level of detail and manpower committed to this process may vary. However, the sequence of steps and the logical process involved would essentially remain the same. Some GIS programs

left management feeling disappointed because the results did not meet their expectations. In most of the cases, the GIS program did not follow the systematic stages of concept (defining), design (implementation plans), development (operating procedures), operation (implementation) and audit (evaluation) as described in this report.

## 15.2 System Justification

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

A number of studies have shown that the return on investment for GIS is substantial given that a critical level of investment is reached (Dale, 1988, pg. 184). For example, Gillespie (1992) reported that, as a result of 40 case studies at the federal level, efficiency benefits alone justified the cost of GIS and that effectiveness benefits were many times larger. Efficiency benefits are those that result from completion of the same tasks at reduced costs. Effectiveness benefits are those that result from completion of tasks that could not or would not be done otherwise.

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

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

### 15.2.1 Benefits

The concept of information as a resource leads to recognition of the most significant benefits from improved information management-improved efficiency in operations and effectiveness in program delivery (Huxhold, 1991). These are among the perceived host of benefits resulting from the shared integratable databases that have long been sought by transportation agencies. Antenucci et al. (Antenucci, 1991, pp. 65-82) identify five types of benefits resulting from GIS:

#### *Type 1*

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

Production of thematic maps such as traffic count maps is enhanced because there is now intelligence associated with the maps. Any attribute that is stored in a highway network database can easily be displayed. With time series data on traffic in the database year-to-year changes in traffic, as well as average growth rates, can be computed and displayed. In the planning area, the benefits of GIS-T can be estimated from the reduction in time needed to create new traffic analysis zones (TAZs) or to revise existing TAZs.

#### *Type 2*

Second, there are benefits arising from expanded capabilities. A multipurpose GIS-T facilitates completion of tasks formerly left undone. These benefits are the equivalent of additional staff and can be measured in labor equivalences and non-labor costs that would be incurred without GIS-T. They result

from readily integratable databases, new analytical capabilities, and more flexible output (Guptil, 1988, pg. 21). An example is avoiding the labor costs associated with the otherwise nearly insurmountable task of linking highway data and other attributes to maps and then performing spatial analysis.

Type 2 benefits escalate with the complexity of the data and analysis. For example, GIS-T is well-suited for the linking of land use, transportation, and air quality data and models required by recent amendments to the Clean Air Act (CAA) (Fletcher, 1993). The required analysis will be greatly inhibited without GIS-T.

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

### Type 3

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

### Type 4

Fourth, there are intangible benefits, or benefits that produce intangible advantages. These vary widely in type and significance. They can play a crucial role in system justification.

Elimination of redundant data and improvements in the quality of data reduce mistrust and lower the risk in decision making. Using GIS-T, data collected in the field can readily be displayed with thematic maps. These maps permit easy identification of many omissions or obvious errors in field data. Field data become readily accessible to operations staff in the field who can then make better decisions. As a result,

field staff are more likely to do a better job collecting field data and to suggest new ways of collecting data that will make it even more useful. Enhanced confidence in data and decision making can lead to increased use of GIS-T.

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

The enhanced planning associated with GIS-T can lead to avoiding future pitfalls such as planning failures and design failures (Fletcher, 1993). Visualization provides benefits in effectively communicating results of GIS-T analysis. A thematic map presents a comprehensive geographic view that is much more easily interpreted than a textual report, especially for large volumes of data with many comparisons.

*Type 5*

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

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

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

## 15.2.2 Costs

The costs of GIS-T vary considerably with the size, configuration, and level of sophistication of the System and with the scales of the spatial databases. According to Gillespie (Gillespie,1991, pg. A-86), there are three primary types of costs associated with GIS implementation:

### Type 1

Computing environment costs these include costs for hardware, software, and networking infrastructure. Hardware and software costs rarely exceed 20 percent of overall system costs. Life cycle costs of hardware and software (maintenance and replacement, including software upgrades) should be considered. Software maintenance (e.g., technical support and documentation) and upgrade fees can soon exceed initial costs (Antenucci, 1991). Some software is licensed according to the number of simultaneous users. In these cases, the cost of the license might increase with time as the number of users grows. Some states have statewide agency licenses covering acquisition and maintenance of software.

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

### Type 2

The second type of costs are data costs. The largest cost component of GIS (up to 80 percent) is typically associated with data. These include costs for database design, data acquisition, database

development, and database maintenance--all of which might have internal or external cost components or both. Data and services can be purchased or the cost of data can be reflected in internal personnel costs.

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

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

*Type 3*

Additional personnel costs include costs associated with overall system planning, design, and implementation, direct costs of training plus lost production time while staff is in training, time devoted to application development and user support, and so forth. Both salary and fringe benefits should be considered. As a result of substantial demand for GIS personnel, salary premiums might be required to retain highly trained staff (Fletcher, 1993).

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

*Type 4*

The NCHRP (1993) report identifies a fourth type of cost that need to be considered:

Intangible costs (Antenucci, 1991). These can include costs arising from modification of existing practices, diversion of attention to the new program, resistance to change, and concerns about liability associated with data sharing (particularly if data is to be shared externally).

### 15.2.3 Justification Strategy

Successful justifications proposed by NCHRP (1993) for GIS-T have included thorough identification of the breadth and depth of applications on an agency wide basis, a sound implementation plan, and quantification of costs for preliminary budgetary purposes during a 4-5 year period.

It might be possible to quantify some Type 1 benefits by determining the cost associated with a current task and projecting the cost of that task when using GIS-T. However, if quantification becomes a matter of conjecture, other arguments for GIS can be undermined (Dale,1988). Quantification of benefits is most meaningful after-the-fact. It can be used for future system evaluation and continuing justification.

#### *Benefit-Cost Relationships*

A general depiction of the relationship between benefits and costs of GIS-T over time is presented in Antenucci et al. (1991). They compare cumulative costs of doing business, with and without GIS-T, beyond the point where the curves intersect and benefits begin to outweigh costs. Benefits can be thought of as future costs that have been avoided.

#### *Additional Arguments for GIS-T*

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

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

GIS-T is the latest step in the evolution of technology. It represents a technological breakthrough, as did CAD and database management systems (DBMS). It's value is in information delivery. GIS-T provides at least as favorable an advantage over current practices as DBMS provided over management of flat files.

## 15.3  System Evaluation

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

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

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

2. Determination of user satisfaction. The following questions should be addressed: a) How many active users are there of GIS-T in the organization? How does this compare to the number that have been trained? b) What is the extent of the organizations application portfolio? c) Has the users' confidence in data and decision making increased? d) Is there a higher morale?

3. Quantitative benefit-cost analysis. System evaluation can have a larger comparative economic component than did initial justification. Empirical determination of required resources is now possible. For example, the effort required for completion of a specific task with GIS-T can now be measured. Type 1 and 2 benefits can be quantified.

Recent research has shown that many of the benefits of GIS are quantifiable (Gillespie, 1992, and 1991). For example, Gillespie described the procedure used to determine the value of risk avoided from the Oak Ridge National Lab's use of GIS to examine population density when routing nuclear waste shipments (Gillespie 1991, pp. A-90-91). In fact, Gillespie developed and tested methods and analytical models for quantifying the benefits of improved decision making with GIS in general. Under certain circumstances, some apparently intangible benefits might be quantifiable.

## 15.4 Statewide Cooperative Efforts

An integral part of a DOT's information technology and GIS plans must be coordination with other state agencies. There is significant potential for sharing of at least some spatial database construction and maintenance costs. Recognizing this, every state has some GIS coordination activity among state agencies (some extend the activity to include local governments and the Federal Government, and even the private sector) (Warnecke, 1992).

### 15.4.1 Approaches

In some cases coordination is ad hoc and informal with periodic or irregular meetings among interested individuals. In other cases coordination takes place under executive order, with agency designees having memberships on committees or commissions.

In yet other cases coordination has been legislated and there may be an office or board responsible for statewide GIS coordination. For example, Vermont has a State Office of Geographic Information

Systems, North Carolina has a State Center for Geographic Information and Analysis, and Wisconsin has a

State Land Information Board.

Compatible or confederated systems development to facilitate data sharing is the primary objective

of many of these efforts. Some have taken a decentralized approach and concentrated on standards and

mechanisms for data sharing. Typically, each state agency agrees to be the responsible "custodian" of the

spatial data that is primary to its mission, to maintain that data according to agreed on standards, and to

make it available to other participants. In this way, DOTs become the custodians of transportation data,

Departments of Natural Resources become the custodians of hydrography and wetlands data, and so forth.

The Growth Management Data Network Coordinating Council in Florida facilitates data sharing

among eight state agencies and offices. North Carolina is operating under a statewide GIS library network

concept. Some states have developed GIS data clearinghouses (the Arizona Land Resources Information

System, the Teale Data Center in California, and the Resource Geographic Information System at the

University of New Mexico are examples). A data clearinghouse can be either a source of data (the actual

data is on hand) or a source of information on how to obtain data (users are directed to appropriate agency

contacts).

Some states have used a top-down approach, at least to the extent that a single base map scale has

been established for state agencies (e.g., Vermont and New Hampshire). Some statewide efforts slowed

GIS development within individual agencies until conclusive statewide directions had been established (e.g.,

Kentucky and Kansas). Some states have or are developing blanket-order mechanisms with preferred GIS

software vendors. And some states have used consultants to develop statewide GIS strategic plans (e.g.,

Minnesota).

Typically, state agencies do not have common GIS hardware and software. A number of data

exchange format standards have been used-all with their limitations. Problems arise from the

incompatibilities of proprietary data models. Typically, either information is lost or spurious information

appears when translating among various vendors' exchange formats. Implementation of neutral, robust standards, such as the Spatial Data Transfer Standard (SDTS) is vital to efficient data sharing efforts.

## 15.4.2 DOT Role

DOTs often have primary roles in statewide GIS efforts. There are three reasons for this:

1. DOTs have a tradition of map making and geographic data management;

2. Many other agencies need transportation data. Among other things, highway and road networks are often used as reference systems by others;

3. DOTs have always worked closely with local governments (e.g., with MPOs in transportation planning and with engineering offices in geodetic control, aerial photography, and large-scale mapping).

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

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

## 15.5 IVHS

The rapid growth of IVHS interest is extraordinary. This trend seems likely to continue and to accelerate in the future. All elements of IVHS require geographic information, and GIS-T technologies are being used to acquire and maintain IVHS data. IVHS is requiring information that has not previously been captured for GIS-T applications but that clearly has GIS-T utility in the future for state and local DOTs. Combined GIS-T and IVHS efforts and databases are clearly desirable in order to reduce duplication of effort and to maximize the cost effectiveness of data collection efforts. Standard database formats and interchange formats will clearly be beneficial to this combined effort. The information needed by IVHS is simply additional GIS-T data that could be best captured and maintained at local levels by GIS-T professionals using GIS-T technologies. Furthermore, this IVHS information is clearly useful for a variety of GIS-T applications in addition to IVHS applications. IVHS is, therefore, a new GIS-T application.

Finally, the practical design and application of digital geographic information systems is a young field, and an interdisiplinary one. Smith et al. (1987a) discuss what should be required of a GIS. They state that a GIS should:

- Be able to work with large, heterogeneous spatial database;

- Be able to query the databases about the existence, location, and characteristics of a wide variety of objects;

- Operate efficiently, so that the user can work interactively with the underlying data and the required data analysis models;

- Be easy to tailor to a variety of applications, as well as to many kinds of users;

- Be able to "learn" in significant ways about the data and the user's objectives; and

- Be able to supply a readily interpretable output product for the ultimate users of the system.

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