Potential for Geographic Information Systems in Transportation Planning and Highway Infrastructure Management

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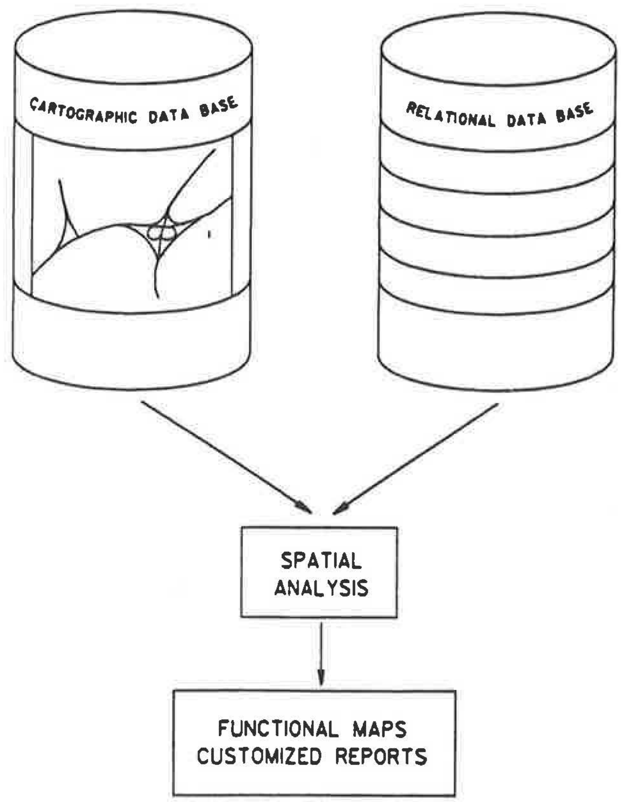
As increasing demands are placed on the nation's highway infrastructure, governments at all levels are required to meet these needs with fewer staff and lower budgets. The efficient use of information throughout an organization becomes not only a political, but an economic imperative. Geographic information systems (GISs) may play a central role in serving users in executive, administrative, technical, and support staff positions. GISs provide an intrinsically logical, visually oriented display of information. Because many users are far more interested in, and more attuned to, their quantitative information under consideration than in the methods used to retrieve it, this visual interface is a critical element in the system. Additional information management tools, contained in some GISs and compatible with others, provide gateways to the applications required by the users; these include relational data bases, numerical analysis models, photolog records, decision support systems, and economic assessment and budgeting procedures. At the state and national level, many of these applications are operational, or are in the advanced development stage. A framework for development of a GIS is required for various applications; a number of these applications are assessed within that context. GIS applications that will be addressed are (a) the FHWA Geographic Roadway Information Display System, (b) FHWA's GIS for policy analysis, (c) Wisconsin DOT GIS for pavement management, (d) North Carolina GIS for the Division of Highways, and the (e) FHWA/Columbia Metropolitan Planning Organization, application of the Bureau of the Census, the Topologically Integrated Geographic Encoding and Referencing system for a metropolitan planning organization.

The geographic information system (GIS) could be used as a tool for highway infrastructure management in a way similar to its current application in land-based information. GIS procedures provide a coordinated methodology for drawing together a wide variety of information sources under a single, visually oriented umbrella to make them available to a diverse user audience (Figure 1). GIS tools can be applied to aid technical and administrative specialists both in managing costly and intensively used resources and in supplying information to decision makers.

Highway infrastructure management systems generally consist of a number of individual modules, often operated independently of one another. These modules include construction quality control, pavement management, maintenance management, bridge management, traffic systems management (traffic operations management for traffic corridor analysis, highway construction-oriented rerouting, hazardous materials routing, incident management, and safety elements management) roadside safety appurtenances, and accident data.



SOURCE: NC DOT, Division of Highway, Geographic Information System Task Force, Feasibility Report, May 1988.

FIGURE 1 Geographic information system.

Thus, potential applications for GIS in highway infrastructure management include the following:

- Executive information system,
- Pavement management system,
- Bridge management,
- Maintenance management,
- Safety management,
- Transportation system management (TSM),

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- Travel demand forecasting,
- Corridor preservation and right-of-way,
- Construction management,
- Hazardous cargo routing,
- Overweight/oversize vehicle permit routing,
- Accident analysis,
- Environmental impact,
- Land side economic impact and value-capture analysis, and
- Others.

Although not often included in the management system, highway agencies also place a significant emphasis on surveying and designing new and reconstructed facilities. In addition, the costs of financing, constructing, and operating these facilities are tracked, although this information may be highly aggregated for some items and disaggregated for others. Historically, these modules have been the responsibility of diverse organizational elements in a highway agency. Each organizational element has developed methods for information gathering, organization, access, and analysis suited to its own particular operations. The diversity in information management practices throughout a highway agency can easily mask their common highway system concerns.

A highway agency elects to use GIS tools to aid in the decision-making process for many reasons. Many of these have been discussed by Simkowitz (*1*). The rationale may be grouped into two major objectives.

1. *Map/display* provides a familiar, visually oriented basis for accessing, interrogating, and presenting data from a wide variety of sources. These functions are important to all users at all levels, from the technician to the executive.
2. *Data integration* develops a logical, coherent, consistent platform from which to integrate diverse data bases. Events and information under one office's responsibility may affect how another office conducts business. For example, the pavement surface data collected by the materials section is directly related to the location of some wet-weather accidents in which loss of skid resistance was a contributing factor. FHWA's new policy on pavement design and management recognizes the key role of integrated information sources. The policy further states, "A means of linking data to physical locations should be integral to the design of a data base system, as this can provide for significant additional capabilities to other data sources maintained by a [State Highway Agency] . . ." (Figure 2) (*2*).

Information flow becomes more critical as agency staff levels continue to drop and highways become more expensive to build and maintain. In this information age, groups that lose access lose the ability to make informed decisions. When billions of dollars worth of infrastructure investment, millions of hours of lost user time, and thousands of lives are at stake, the severity of the problem is highlighted.

WHAT IS NEEDED TO GET STARTED?

Application

The agency must identify potential issues that can be addressed through a GIS application more efficiently, more effectively, and more economically than with prevailing methods. The time spent at this stage can be the most creative, and the most frustrating for the agency's working group. The real institutional need to avoid large risks by developing small pilot applications and system prototypes must be balanced by the technological necessity of providing sufficient flexibility for future growth. Additional and expanded information sources will need to be incorporated, along with links to analysis tools that cannot rely on formal data bases and data base constructs—engineering analysis software and knowledge-based systems.

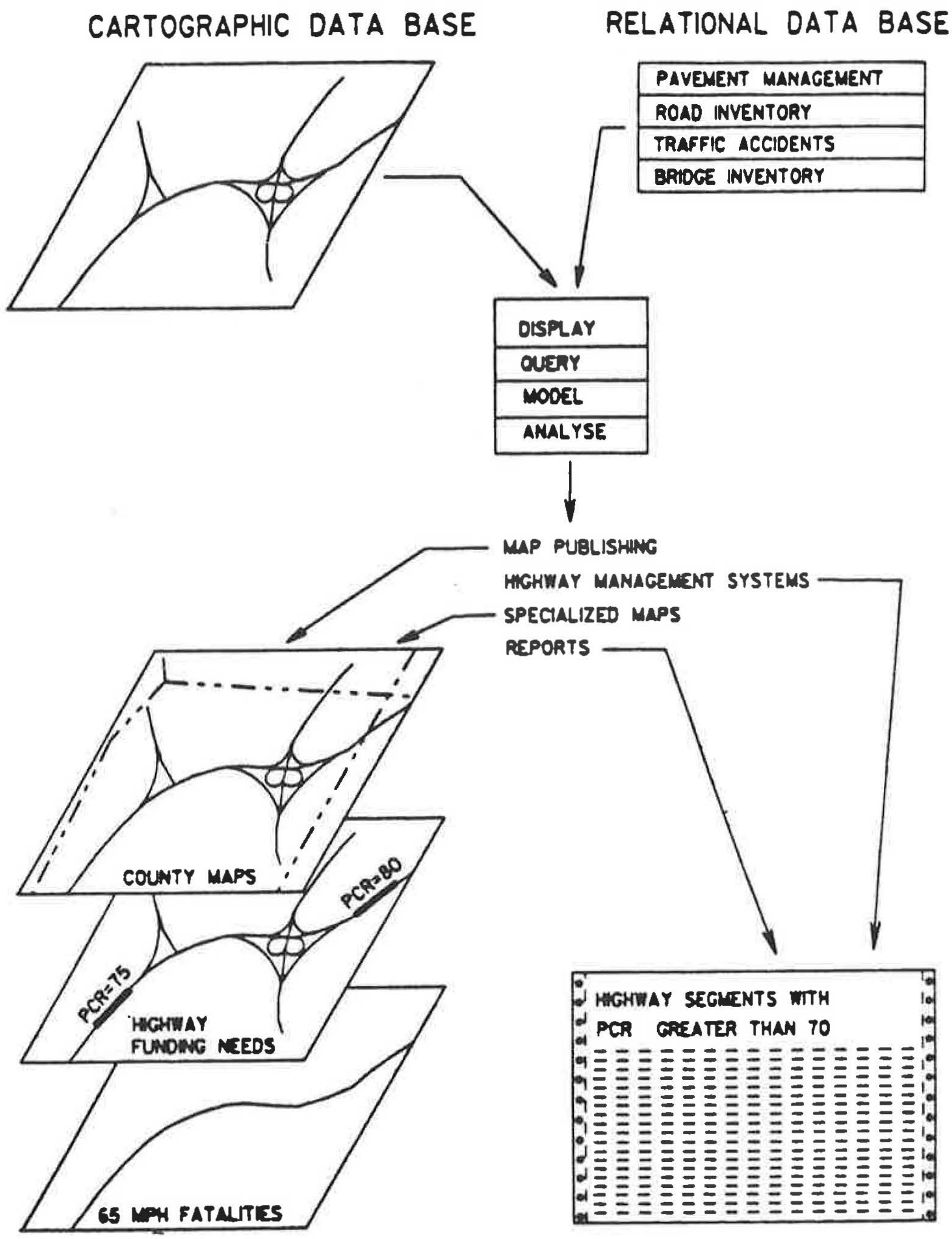
Once an organization has committed itself to a specific tool, it may then be restricted to selecting applications that fit the tool's requirements. It is preferable to select the application first and then find a tool with a range of functions best suited to addressing its needs. Granted, a balance should be struck between the feasibility of using tools in which the organization has a sizable investment (such as mapping and CADD/CAM products) that might be amenable to functional modification, and the risk of trying a new product with its attendant start-up cost and learning curve. Limiting the size or geographic extent of pilot projects and arranging for short-term software licensing and hardware leasing can minimize the dollar investment. More important, the end users must have hands-on experience with the application. To hire a consultant to recommend products or to depend on the vendors themselves for their recommendations may be more expedient, but agency staff must be sufficiently familiar with the applications, and the agency's institutional organization, to be able to assess potential of the application for successful implementation.

Location Referencing System

A GIS-based application has as its foundation the latitude, longitude, and, if needed, elevation of point locations. In a survey conducted by Tom Henderson of the New Mexico Department of Transportation, it was found that the Department used 10 location reference systems; the system used least frequently was the latitude-longitude coordinate (*3*).

By its nature, a GIS-based application forces a certain degree of formalization and consistency into the process of differentiating one highway network or roadside location from another. Unlike most natural features, highways do occasionally move through rerouting and relocation. These changes may generate some creative location referencing schemes in milepost-oriented systems, but may have little or no effect if link-node systems are in use. Even if a road is rerouted and reconstructed, there may still be a need to retain data on the original road from the information system.

An agency can make a choice. It may mandate the use of a single location referencing system or it may develop a method to convert the prevailing location reference systems to geographic coordinates. Given the large investment in existing data bases and the potential in the near future to obtain latitude and longitude quickly and easily using global positioning systems, the second option is generally preferred. Once the conversion to latitude-longitude references is completed, the agency is capable of accessing both archival and contemporary data, using a single location reference key, without changing the way the data collection activities themselves are conducted.



SOURCE: NC DOT, Division of Highway, Geographic Information System Task Force, Feasibility Report, May 1988.

FIGURE 2 GIS for transportation.

If the intended applications extend beyond the realm of the highway infrastructure itself, the referencing system should be organized to dovetail with the location-referencing schemes developed for other information sources. A prime example of this is the U.S. Bureau of the Census information coded in the Topologically Integrated Geographic Encoding and Referencing (TIGER) geographic support system. TIGER, a major departure from previous methods of encoding census data, is necessary for developing transportation forecasts. All data for the 1990 census will be referenced to the TIGER files by latitude and longitude. Thus, by using a location referencing system that incorporates latitude and longitude coordinates, an agency will be able to take advantage of available population data such as total population, population by time of day, and journey to work for transportation planning studies. These geographic coordinate systems are already used by state and federal agencies for land-based applications, most notably natural resources. As an example, data from the U.S. Geological Survey and the U.S. Environmental Protection Agency can be used to analyze information and prepare documents for environmental impact assessments.

Information location accuracy is a function of the intended use. In general, an accuracy of 0.01 mi (about 50 ft) will often be sufficient. A higher degree of accuracy is needed if the information will be used as a direct design input. This is discussed by Nyerges and Dueker (*4*). Recent projects and conferences addressing the issue of referencing systems and the integration of highway information include the following:

- NCHRP Synthesis 133: Integrated Information Systems.
- NCHRP Project 20–23: Integration of GPS Satellite Surveying with Digital Mapping.
- AASHTO, FHWA, and others: GIS in Transportation Symposium, Orlando, Florida, Feb., 1989.
- Urban and Regional Information Systems Association conferences.
- FHWA Databank pilot.
- Strategic Highway Research Program: geographically referenced data.
- FHWA pooled-fund study: state-of-the-art roadway photologging.
- Proposed national data base of soil types for road and airfield design.
- NCHRP Adaption of Geographic Information Systems for Transportation Project 20–27.
- FHWA, Demonstration 85, Geographic Information System and Video Imagery.
- FHWA TIGER pilot studies for Columbia, Missouri; Johnson City, Tennessee; Washington State; and St. Louis, Missouri.
- FHWA/NASA/Ohio DOT, Multi-State Study, Global Positioning System (GPS) for Transportation Planning.

Tools

There is an extraordinary range of software packages that are presented as tools for developing GIS applications. The July/August 1989 issue of *GIS World* (*5*) listed 63 GIS software systems currently available. Most of these are sold as application software only or as turnkey systems that include hardware, software, and user training. A few are offered as consulting services. Some of the products such as base networks or data files for which the user must develop data input and retrieval routines, are limited in form but broad in scope. A summary of these offerings follows:

AGIS
ARC/INFO
Aries
ATLAS Graphics
Axis Mapping Info
Cries-GIS
Deltamap
Earth One
EPPL7
ERDAS
File Vision IV
FMS/AC
Gas, Electric, Water and Municipal FM
Geo Sight
Geo-Graphics
Geo Spread Sheet
Geo Vision
Geo Vision "GeoPro"
Geo Vision WOW
GFIS
Gimms
GISIN
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GRASS
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System 9
Territem/Mgtsys
Tiger tools
TIGRIS
UltiMap
USEMAP
VANGO
Zone Ranger/GDT
MunMap
Topologic

Hardware platforms for GIS tools range from stand-alone microcomputers to networked minicomputers, workstations, and mainframes. This array suits the potential range of applications and attendant need to share information sources, intermediate combinations of source data, and output products.

In summary, the three driving elements of applications, referencing systems, and tools must fit together in a cyclical decision process. Location referencing requirements that are developed must find their counterpart tools to achieve them. Applications themselves may well drive the selection of the referencing system. With many tools available and more being developed, the agency should select tools to fit the applications, and not settle for having the tools define them. The agency must also look at the wider picture to try to avoid premature selection decisions.

GISs in Transportation

Although most states have had several years' experience in computer-aided drafting and design and in computer-aided mapping (CADD/CAM), their introduction to GIS applications has been limited. Most of the GIS products currently on the market cater to local government needs for parcel-oriented information management such as zoning, land use, and natural resources. Few are designed to deal specifically with complex point, network, and area impact information that would be used by a transportation agency—most of the network-based products on the market are designed for use by cable and pipeline utilities and are designed around transmission system characteristics. Some vendors of CADD/CAM systems are developing methods and products for adding geographic location codes to existing files because current conversion methods are relatively slow and costly and do not necessarily guarantee consistent coding across map sheets.

Although the use of GIS tools to manage large amounts of highway data maintained by diverse departments in a state highway agency is emphasized, the data sources themselves must be considered. Every state has its own set of sources with different contents, formats, collection and review cycles, and degrees of accuracy. The data sources may be maintained on a single mainframe computer, on a network of computers, on paper forms or maps, or (most likely) a combination of them. The various departments, bureaus, or offices each has its own needs for information, and expectations of the picture its analyses should provide. Coordinating among a diverse group of users requires that the individual needs be met while providing an overall view of the information to legitimate users throughout the department. Conversion of individual information sources is time consuming, exacting, and often tedious manual labor. The planning for information coordination may take as long as the conversion process itself.

APPLICATIONS

Applications are the true test of any tool's usefulness. This section provides a discussion of current GIS applications at the federal, state, and local levels. At the federal level, two efforts will be described: first, the development of a GIS system to display and analyze the Geographic Roadway Information Display System (GRIDS) Highway Performance Monitoring System (HPMS); second, the development of a 1:2,000,000 scale GIS for highway policy analysis used in evaluating the *Status of the Nation's Highways* (*6*). At the state level, two statewide GISs are in the implementation stage: Wisconsin DOT's implementation of a GIS for highway infrastructure management that targets pavement management for its initial application; and the North Carolina DOT's implementation effort to create a business management tool for highway management. At the local level, a pilot effort by Columbia, Missouri, to test the usefulness of the TIGER line files as a base map for a GIS will be reviewed. These five applications of GISs for highway infrastructure management—from national policy, nation system condition, and state system management to local safety management and analysis—demonstrate their broad range. These five examples show why GISs are an important technology at all levels of government for managing our highway infrastructure.

GRIDS

The FHWA developed a sample-based approach to access the condition of the Nation's highways using key data items from the HPMS. The FHWA Office of Planning developed the GRIDS system as a tool to display and analyze data on the Interstate highway system. GRIDS is a microcomputer-based software package that can display any data item on a state map of the Interstate system. GRIDS begins by showing a map of a specific state that includes state and county boundaries, city location, population, and the Interstate highway network (Figure 3). GRIDS can zoom in on any section, produce pie or bar charts, display specific data items, and look up specific highway section data. The digital base map in GRIDS is the Oak Ridge National Laboratories (ORNL) 1:2,000,000 scale National Highway Network.

In the future, the FHWA hopes to continue to develop its GIS capabilities by placing all of the HPMS data on three different GIS systems (Arc/Info, TransCAD, and MunMap). This policy will improve data distribution and enhance FHWA's analysis capabilities.

GIS for Policy Analysis

The FHWA Office of Policy developed a GIS system to evaluate the National Highway Network and to evaluate the impact of future highway policy changes. The system is based on the 1:2,000,000 national highway planning network developed by Oak Ridge National Laboratory (ORNL) (*7*) with support from the U.S. Army Forces Command, the FHWA, and the Military Traffic Management Command. The system operates on a Compaq 386 microcomputer and uses PC Arc/Info software. In the last year, a large volume of data has been added to the basic Oak Ridge 1:2,000,000 highway network data base. To enhance the ability to analyze the current conditions of the Nation's highways and access the impact of new policies, the following data sets have been added to the basic network:

- 1987 HPMS Interstate,
- Interstate truck volumes,
- State boundaries,
- County boundaries,
- Congressional districts,
- Urban areas,
- Ports,
- Airports, and
- Census population and employment data.

In the future, the following databases will be added:

- Additional county attributes including manufacturing and agricultural data,
- Network link AADT, and
- Interstate bridges.

This comprehensive data base in a GIS allows the FHWA to respond quickly to congressional questions, analyze the impact of proposed changes in policy, and integrate many data bases for timely analysis (Figure 4).

As part of the evaluation process of the post-Interstate Federal role, the FHWA Office of Policy GIS system is currently being used to identify each state's defined "System of National Significance." In the future, this system will be used to determine priority routes. Criteria will be developed to determine a route's importance on the basis of such items as population, employment served, and proximity to ports. In addition, network analysis to find alternative routes on the basis of link impedances between specific points will be explored. This GIS will be enhanced constantly to allow the FHWA to respond quickly to policy issues and to evaluate in more detail the impact of changes in highway policy as new legislation is being proposed for the post-Interstate period.

A FEW RECENT GIS ACTIVITIES FOR MANAGING PAVEMENTS

Several technical applications have used the ORNL 320,000-mi geocoded network of Federal Aid Interstate and Primary highways. These systems include the Pavements Databank, a gateway data base manager to several collections of pavement research results and pavement management information

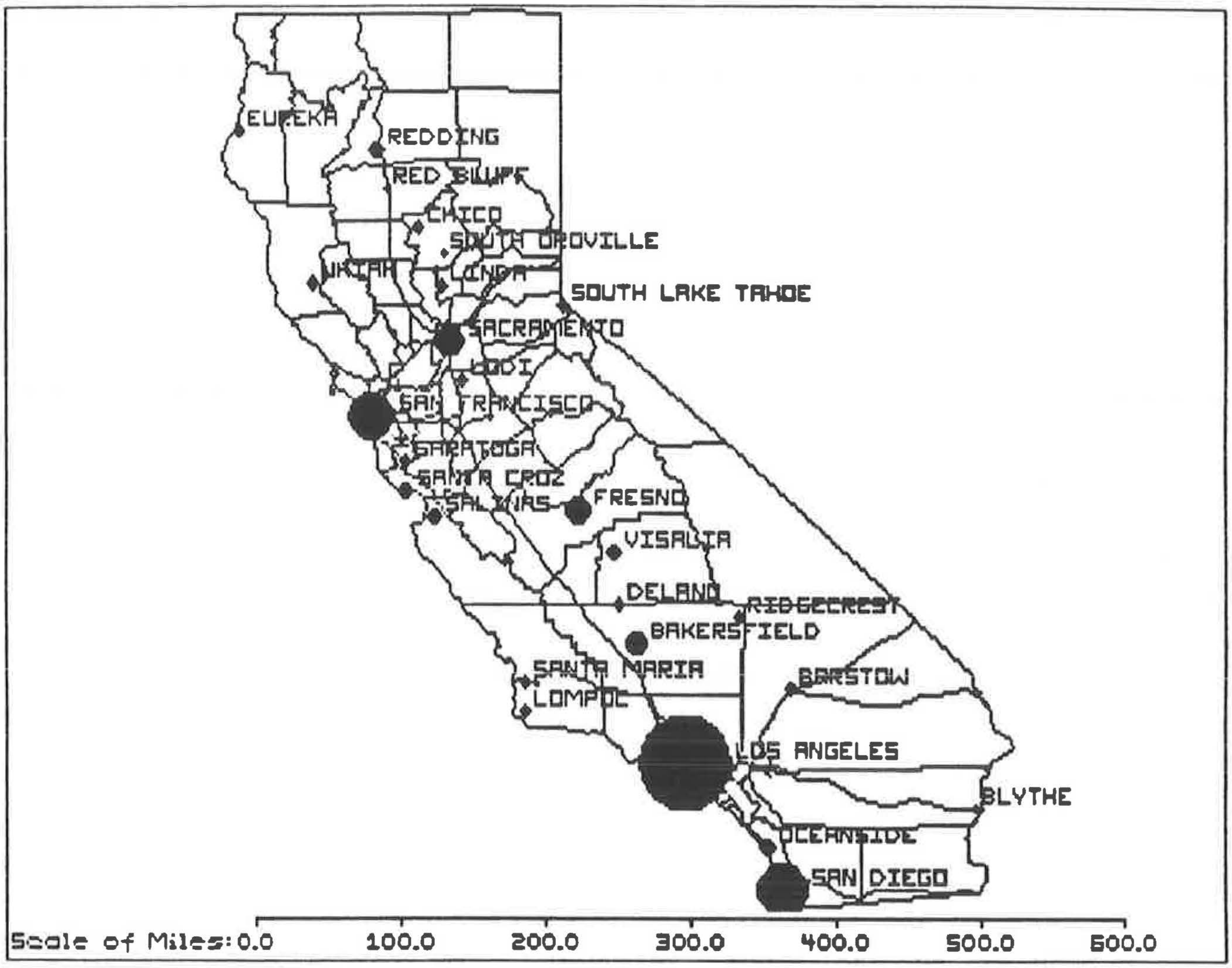

FIGURE 3 GRIDS—California.

systems, as well as several state pavement management information and feedback systems.

The Pavements Databank pilot project is complete. Diverse files containing detailed pavement information for roadways in Minnesota—HPMS, Concrete Pavement Evaluation System (COPES), and the state's own pavement management system have been converted to compatible formats. Field site location codes have been placed in the proper order for display on a map of the roadway network. The map display also includes the U.S. National Oceanographic and Atmospheric Administration (NOAA) first-order weather stations (*8*). Documentation has been prepared describing the application's use of ORNL's highway network file at the NIH computer facility, as well as techniques for conversion of the individual source data. A potential application for the Pavements Databank is to provide a ready source of information on soil types for preliminary road and airfield design in remote areas when there is insufficient time to prepare detailed soil studies.

The Strategic Highway Research Program (SHRP) long-term pavement performance (LTPP) study will assemble a massive library of pavement inventory and condition data over the next 20 years (*9*). Locations are coded by beginning and ending milemarks and stations in the inventory section. The environment section includes the latitude and longitude to place the section in a climate zone defined for highway technology (Thornwaithe Index).

Several states are exploring GIS technology as a tool in highway research and pavement management. Texas and California base their statewide highway information management systems on the HPMS model; California explored the GRIDS system. Illinois is developing a so-called "Pavement Feedback System," which uses a highway network digitized by the State Department of Natural Resources. Texas, California, and Tennessee use global positioning system (GPS) satellite referencing in surveying and mapping. Ohio, New Mexico, and Louisiana may explore the same technology.

STATE AND LOCAL GIS PILOT STUDIES

Wisconsin

The Wisconsin DOT is implementing a GIS using the Arc/Info software and the 1:1,000,000 digital line graphs from the U.S. Geological Survey. The first area selected for implementation was a statewide pavement management system using

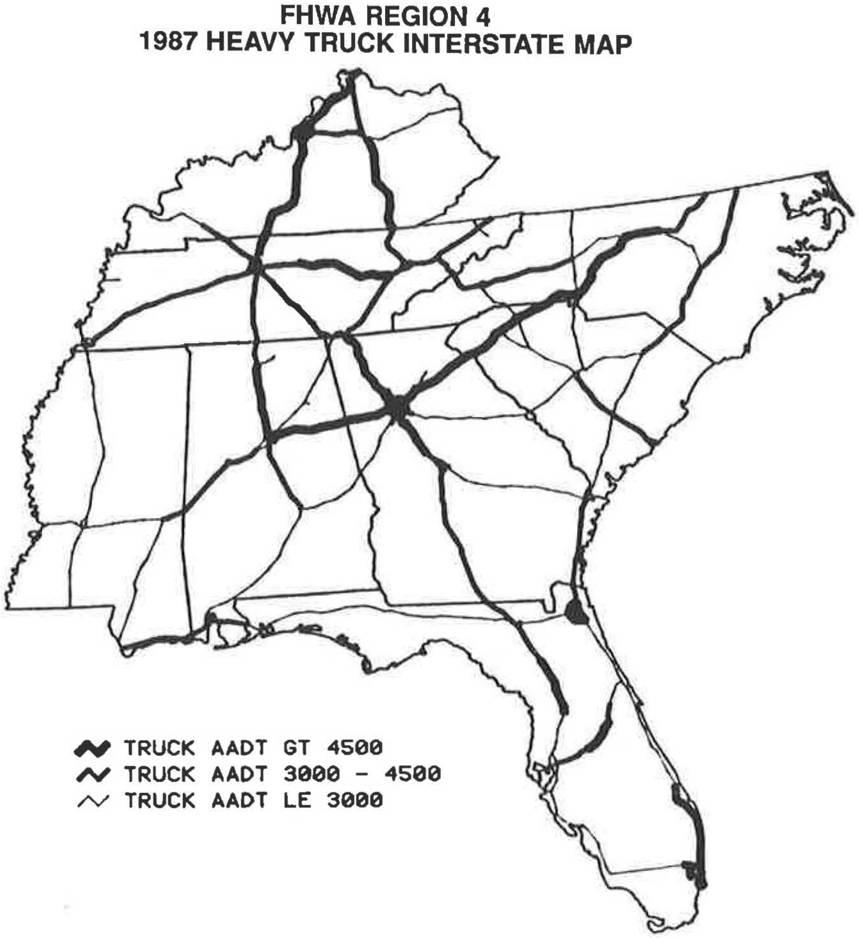

FIGURE 4 GIS for policy analysis.

expert system techniques. The GIS will store and access the wide range of data (materials, traffic, design, maintenance, rehabilitation, etc.) needed in pavement management and graphically display the system's current pavement condition, proposed projects, and future condition projections.

In the Green Bay district, a full-scale pilot of the system is underway and scheduled for completion in February 1990. At that point, the system will be expanded to include all districts using UNIX-based engineering work stations.

An innovative feature of the Wisconsin GIS is the integration of photolog information (video images) on laser discs directly into the system. By using laser discs, the GIS system can access both digital and image data (raster data). This feature will allow photologs, as-built plans, inspection reports, and any other information suited to a photographic or scanned image to be included.

The Wisconsin DOT sees GIS as a tool to build many applications that deal with geographic information (*10*). Over the long-term it would also seek to

- Integrate data bases,
- Reduce repetitive data entry,
- Integrate new technology,
- Improve analysis results, and
- Develop applications more quickly.

North Carolina

In February 1988, the North Carolina DOT formed a GIS task force to determine the feasibility of developing a GIS system for transportation (*11*). They thoroughly reviewed existing GIS technology, GIS application in other states, and their existing computing environment. The conclusions of the task force report were

1. A GIS is feasible;
2. Initial implementation should be pavement management, traffic engineering, planning, bridge maintenance, map publishing, and field support;
3. The GIS should be based at a mainframe with the ability to run on workstations and PCs;
4. The GIS should function on a wide range of hardware platforms to make maximum use of installed systems; and
5. A permanent staff to develop the GIS would be needed.

As a result of these recommendations, the GIS task force was asked to prepare a formal implementation plan. The implementation plan was to address

- Software recommendations,
- Hardware recommendations,

- Training needs,
- Pilot GIS system—pavement management and traffic engineering, and
- Phased implementation plans.

The implementation plan was presented to upper level management in draft form on July 17, 1989. The presentation included pilot GIS demonstrations for pavement management and traffic engineering at the 1:2,000,000 and 1:100,000 scale. Based on the final version of the plan, a full-scale implementation effort began to develop a comprehensive GIS for transportation management in the fall of 1989.

Columbia, Missouri, TIGER Demonstration

In March 1988, FHWA and the Bureau of the Census approached the City of Columbia, Missouri, with a proposal to demonstrate the newly released TIGER files. The Bureau of the Census developed the TIGER files for the 1990 census. The files are the product of the merging of digitized map information from the U.S. Geological Survey 1:100,000 scale maps and the 1980 GBF/DIME files, including geographic features, feature names, address ranges, and political and statistical boundaries. The object of the TIGER file demonstration in Boone County was to assess the value of TIGER as the base map for a geographic information system for transportation (*12*).

TIGER files provided by the Bureau of the Census contained (a) political boundaries, (b) feature names and classification codes, (c) alternate feature names, (d) latitude-longitude coordinates (shape records), and, within the Columbia urban area, (e) address ranges with the associated ZIP codes for streets (Figure 5). The Boone County TIGER file contained 13,533 line segment records and a total of 36,671 records. The file size was 4.5 MB.

The City of Columbia Department of Public Works selected the data bases to be used in the demonstration consisting of a street sign inventory and accident location file. The street sign inventory was created to better manage sign installation, replacement, and maintenance. The inventory used dBase III+ and the individual signs were identified by (a) quadrant of the city, (b) side of the street (N, S, E, W), (c) direction the sign is facing (N, S, E, W), (d) the name of the nearest cross street, (e) number of feet (N, S, E, W) from the cross street, and (f) street name on which the sign is located.

The accident file was also built using dBase III+. Accidents were located on the basis of (a) street name on which the accident occurred, and (b) name of nearest intersecting street.

Latitude and longitude were attached to the Columbia data files by matching the common element in the Columbia data files with the TIGER files. The common element used was

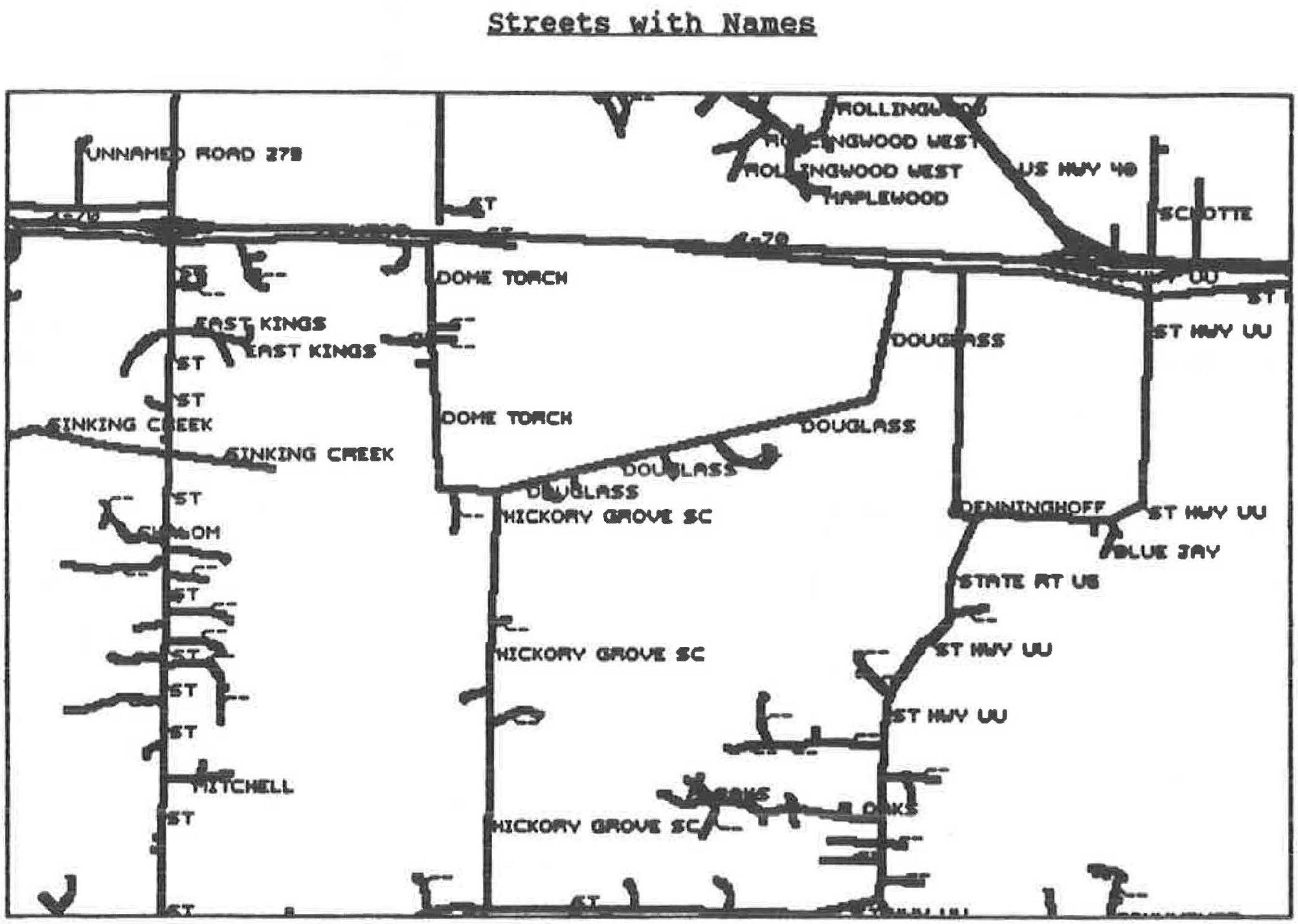

FIGURE 5 TIGER—Columbia, Missouri.

street names. Latitude and longitude for each intersection was obtained by matching street names. The distance from the intersection was then used to locate both signs and accidents and obtain their coordinates.

TransCAD GIS software was used to match TIGER line files street names with street names in the Columbia data base. The result demonstrated the ability to cross reference and integrate sign and accident inventory and to display this information on the TIGER line file within a commercially available geographic information system software.

The Columbia, Missouri, demonstration shows the usefulness of TIGER for infrastructure management by its ability to

1. Create quickly a base map for a geographic information system for transportation,
2. Convert existing data base reference system to latitude and longitude,
3. Integrate data bases, and
4. Create a GIS inexpensively.

As a result of this demonstration, Columbia's Department of Public Works plans to use TIGER line files in its GIS applications. Future GIS applications being considered are

- Pavement management,
- Transit route planning,
- Traffic signal controller inventory,
- On-street parking management,
- Traffic volume mapping,
- Areawide and subarea modeling, and
- Traffic impact analysis.

CONCLUSIONS

As the highway infrastructure matures, the issues change from where to build a new highway to how to maintain and improve existing facilities. Infrastructure managers today are faced with complex and multidimensional problems. Every level of government is expected to do more with less resources and time. Moreover, many valid claims are made for these scarce resources. Today, there is no room for inefficient decision making. An infrastructure manager must have access to information quickly and in a form that presents a multifaceted view of the network and its surroundings.

These five examples show that various levels of government look to GISs to efficiently access large volumes of available data. The GIS permits the user to obtain information in a familiar form that relates directly to the highway system, a map. The benefits of the GIS often given are as follows:

- *Integration of Data.* By using a common reference system, data from both typical highway sources and those outside the highway area (e.g., demographics, economic data, land use, weather, geology) can be used.
- *Spatial Display of Data.* Allows data to be displayed on maps that are easy to understand.
- *Innovative Analysis.* Allows for new ways to look at old problems by combining models with "what if" analysis to provide answers to complex, multidimensional questions quickly.

The key to GIS implementation is a specific application that can use the ability to perform spatial analysis. Given the nature of the highway system, almost all application areas could benefit. Although the potential for GIS applications in highway infrastructure management is tremendous, users must understand the technology, develop specific applications, and pool limited resources to make GIS an effective tool both for decision making and technical applications.

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