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Foreword

The Geographic Information System (GIS) can perform two major functions useful to administrators, design and operating engineers, and planners. These include (a) computerized visual map displays for accessing, interrogating, and presenting data from a wide variety of sources, and (b) integration (linking) of data on a common location system. Infrastructure management is emerging as a strong application of the GIS. The eight papers in this Record deal with the technical development and applications of the GIS.

Four papers are concerned with applications of the GIS. Petzold and Freund offer potential extensions of GIS to highway infrastructure applications such as transit route planning, traffic signal control inventory, parking management, and traffic volumes and impacts; they discuss issues to be addressed, referencing systems, software and hardware tools, and recent activities. Simkowitz discusses essential components of a pavement management GIS and its implementation.

Abkowitz et al. illustrate how data in a GIS can be used to plan shipment routes for hazardous materials. VanBlargan et al. explain the applications of GIS to hydrologic analyses, specifically automatic delineation of watershed areas and estimation of hydrologic parameters.

Four other papers are concerned with the technical development of GIS techniques and tools. Von Essen et al. provide information relevant to the selection of GIS workstation vendors, development of performance criteria and tests, evaluation, and recommendations for procurement. Paredes et al. present the results of a study in which the analysis routines in MICRO-PES (a series of programs used for pavement management activities in the Texas SDHPT) are used to generate maps for highlighting substandard pavement sections.

O'Neill and Akundi describe the development of a microcomputer model for the conversion of milepoint data to intersection/link format. Wigan discusses the potential of using optical storage media (laser disks) for solving the problems of handling massive amounts of data in integrated GIS systems.

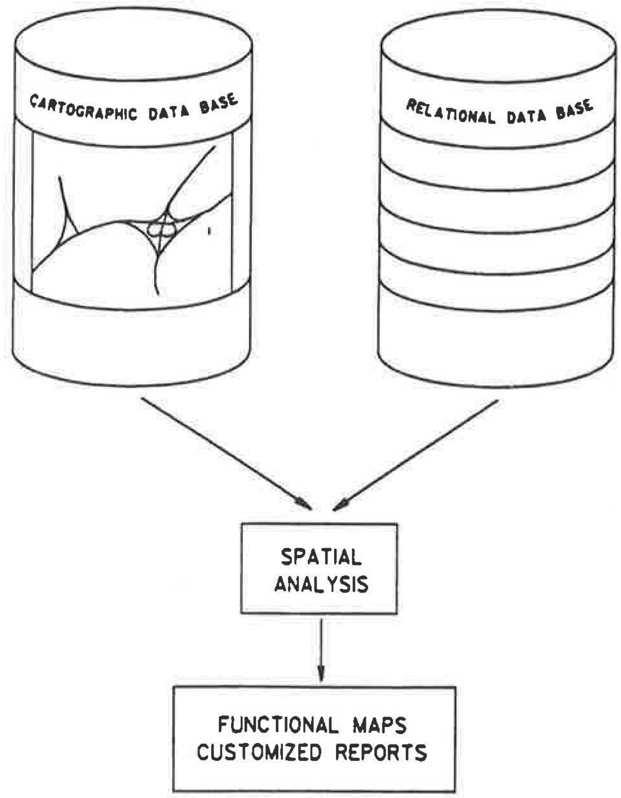
Potential for Geographic Information Systems in Transportation Planning and Highway Infrastructure Management

ROGER G. PETZOLD AND DEBORAH M. FREUND

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.

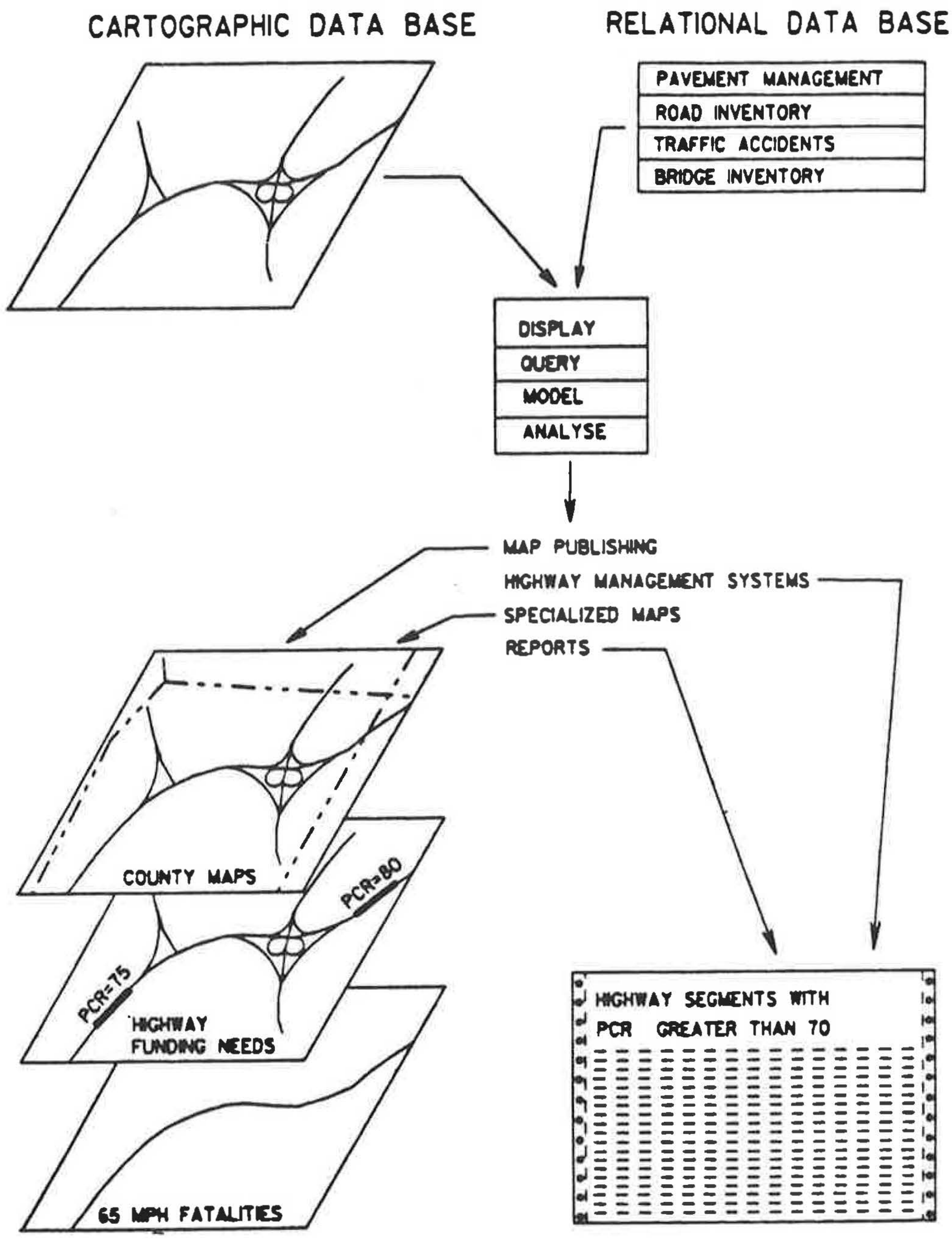
Once an organization has committed itself to a specific tool, it may then be restricted to selecting applications that fit the tool's requirements. It is preferable to select the application first and then find a tool with a range of functions best suited to addressing its needs. Granted, a balance should 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
GDS
GRASS
IDRISI
IGDS/DMRS
IMAGE
Infocam
Informup
LandTrak
Laser-Scan
Mac GIS
Mac Atlas
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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

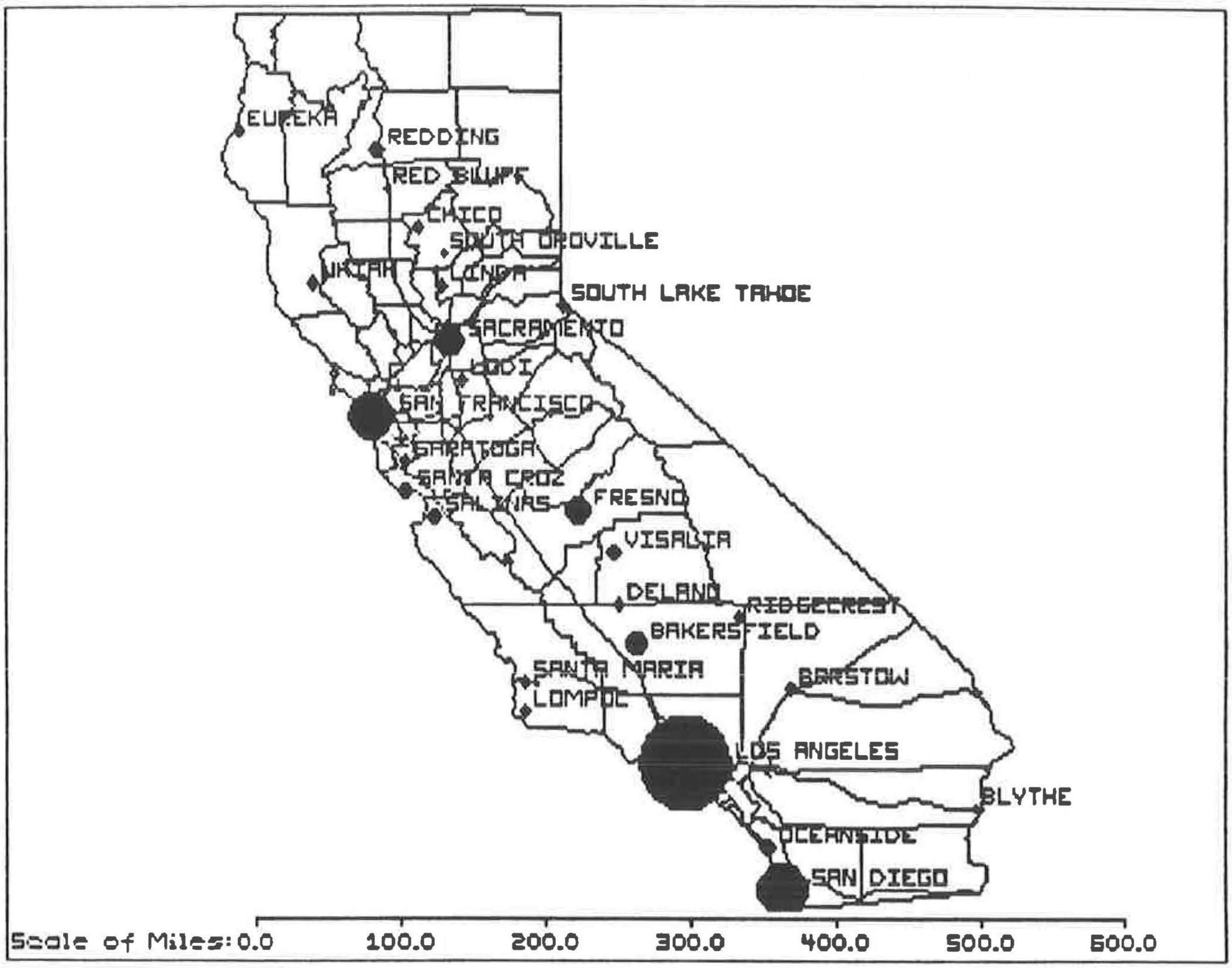

FIGURE 3 GRIDS—California.

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

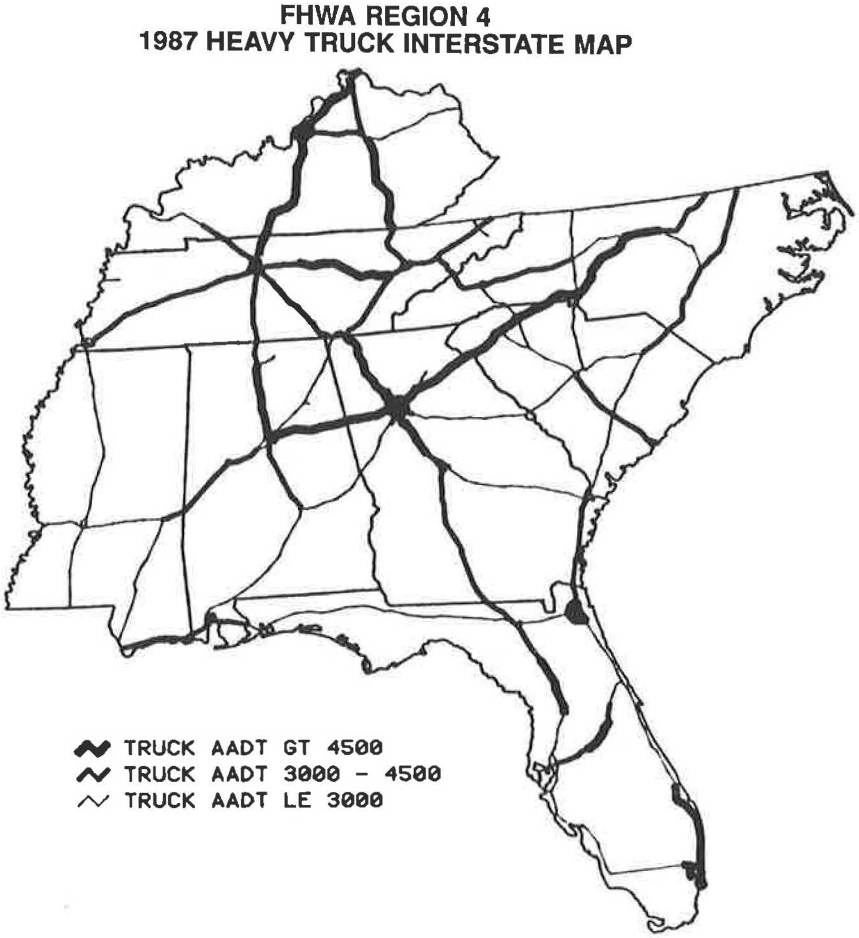

FIGURE 4 GIS for policy analysis.

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

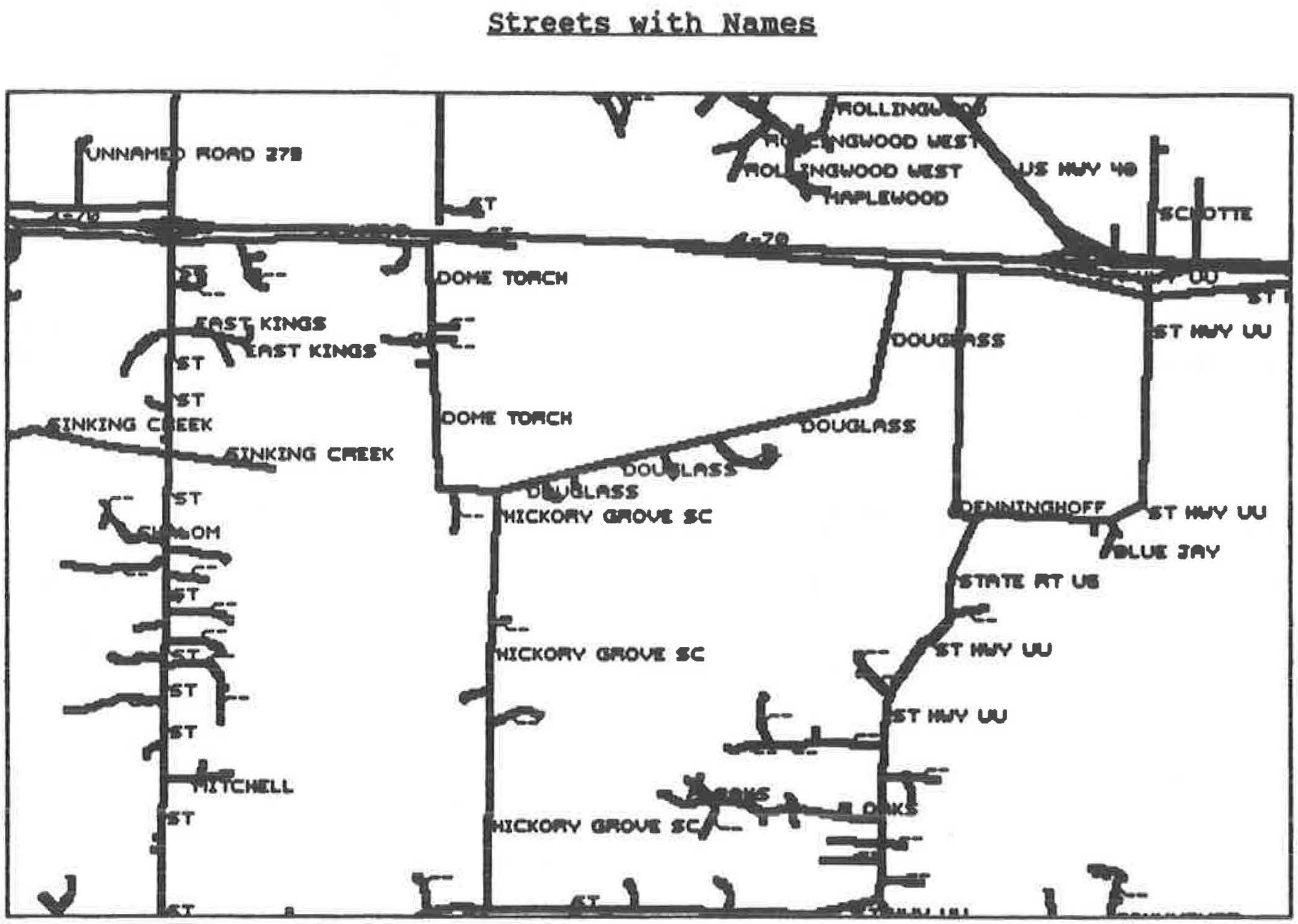

FIGURE 5 TIGER—Columbia, Missouri.

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.

REFERENCES

1. H. J. Simkowitz. *Geographic Information Systems: An Important Technology for Transportation Planning and Operations.* Office of Planning, FHWA, U.S. Department of Transportation, Aug. 5, 1988.
2. *Federal Register.* Pavement Policy for Highways (23 CFR Part 626). Docket No. 87-16, Final Rule, FHWA, U.S. Department of Transportation, Jan. 13, 1989.
3. T. Henderson. *A Comprehensive Proposal For The Acquisition, Use, and Maintenance of Geographically Related Information in the New Mexico State Highway and Transportation Department.* New Mexico State Highway and Transportation Department, Santa Fe, Jan. 19, 1989.
4. T. L. Nyerges and K. J. Dueker. Geographic Information Systems In Transportation. Office of Planning, FHWA, U.S. Department of Transportation, July 16, 1988.
5. Special Report GIS Technology 89. *GIS WORLD*, GIS World Inc., July/Aug. 1989.
6. *The Status of The Nation's Highways and Bridges: Conditions and Performance and Highway Bridge Replacement and Rehabilitation Program 1989.* Report of the Secretary of Transportation to the United States Congress, U.S. Department of Transportation, June 1989.
7. B. Peterson. *Description of the National Highway Planning Network, Version 1.0.* Oak Ridge National Laboratory, Oak Ridge, Tenn., Jan. 6, 1989.
8. D. Freund and C. Conley. The Pavements DATABANK, A Research Application of a Geographic Information System. In *Proc., 26th Annual URISA Conference*, Vol. 4, Los Angeles, Calif., 1988, pp. 42–49.
9. *Strategic Highway Research Program, Research Plans, Final Report.* TRB, National Research Council, Washington, D.C., May 1986.
10. M. L. Bacon and D. D. Moyer. *Geographic Information Systems (GIS) For Transportation Symposium, Final Report.* AASHTO, FHWA, and Highway Engineering Exchange Program, Washington, D.C., 1989.
11. *Geographic Information System Task Force, Feasibility Report.* North Carolina Department of Transportation, Division of Highways, May 1988.
12. J. Fleck and H. J. Simkowitz. Using the Census TIGER File for Transportation Planning: Results from an FHWA Demonstration Project. In *Proc., 2nd Conference of Transportation Planning Methods*, FHWA, U.S. Department of Transportation, 1989.

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Using Geographic Information System Technology To Enhance the Pavement Management Process

HOWARD J. SIMKOWITZ

A pavement management system (PMS) should address all aspects of the pavement management process from planning and programming through project development and implementation. Geographic information system (GIS) technology can be used to expand and enhance each of these PMS components. A GIS can be designed as a platform on which the PMS is built and operated. Such a system is designated a PMS/GIS. The importance of a variety of spatially integrated data to pavement management decision making is examined. Each component of the PMS process is explored and the applicability of GIS technology to this particular component is discussed. This process results in the identification of a set of functions required for an effective PMS/GIS. These functions include thematic mapping, flexible data base editing, formula editing, statistics, charting, matrix manipulations, network generation, and integrated models and algorithms. The results are based on research for integrating GIS technology and pavement management models. All reported concepts and results have been incorporated into TransCAD, the GIS for transportation software.

Pavement management has captured the hearts, minds, and pocketbooks of the FHWA and the state highway agencies. This was made clear by FHWA regulations requiring that a pavement management system (PMS) be in place in all states by 1991 and the focus of the Strategic Highway Research Program (SHRP) on asphalt and concrete materials, pavement performance, and other PMS-related topics (*1*). A PMS should be comprehensive in covering all aspects of the process from planning and programming to project development and implementation. For a PMS to be successful, these interrelated steps must make significant requirements on the collection of specific pavement condition data, require the assessment of related data such as accidents and traffic volumes, utilize life cycle costing (LCC) and other analytic models, and take into account other construction and maintenance projects already scheduled or being considered by the agency.

A well-designed geographic information system (GIS) provides a platform on which all aspects of the PMS process can be built. The resulting system, a PMS/GIS, represents a significant enhancement to all aspects of the PMS process. A variety of spatially integrated data are important to pavement management decision making. GIS technology, as defined and explored, is shown to be the most logical way of relating these diverse, but relevant, data. Next, each component of the PMS process and the applicability of GIS technology are discussed. The components include data collection, preliminary data analysis and interpretation, system assessment, determination of strategies, project identification and development, and project implementation. Each of these stages in the PMS process is enhanced by GIS technology. Looking at the PMS process in its entirety leads to the enumeration of a set of functions to be embedded in the GIS platform that is required for an effective PMS/GIS. These functions include thematic mapping, a flexible data base editor, formula editing, statistics, charting, matrix manipulations, network generation, models and algorithms, and hooks to external procedures.

Research is being conducted on integrating GIS technology and transportation models. This research has resulted in the development of TransCAD, a transportation GIS. TransCAD provides all the tools that the pavement management analyst needs, at the same time supporting complex transportation models and algorithms in a comprehensive and cohesive structure. All reported concepts and results have been incorporated into the TransCAD software.

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THE ROLE OF SPATIALLY INTEGRATED DATA IN A PMS

Spatial considerations are fundamental to most transportation activities, including pavement management. A transportation system consists of nodes, links, and entities distributed in two- or three-dimensional space. Events happen within this system at a point (an accident, a signal location), along a segment (pavement deficiencies, vehicle volumes), or within a geographical area (people living in one neighborhood who wish to commute downtown).

Comprehensive pavement management models require a diverse collection of highway-related data including pavement condition surveys, skid resistance measurements, traffic counts, bridge inspections, sign inventories, photologging, accident investigation, construction and maintenance records, and inventories of signs and roadside obstacles. Although these data may be available in digital format, they are typically unrelated to each other, duplicative, and inconsistent. The various files may have been created independently of one another, using different referencing systems or computer formats. Popular referencing systems include milepost, reference post, paper document methods, state plane, and latitude-longitude. In the worst case, some of the data required for analysis may not be spatially referenced at all. As a result, they are difficult to use in a consistent and efficient manner as inputs to a PMS. In the next section, GIS technology is

proposed as a framework for data integration because it provides a means of relating data collected under various referencing systems.

GIS TECHNOLOGY AND BENEFITS

A GIS is a computerized data base management system for the capture, storage, retrieval, analysis, and display of spatial (i.e., locationally defined) data. A GIS contains two broad classifications of information, geocoded spatial data and attribute data. Geocoded spatial data define objects that have an orientation and relationship in two- or three-dimensional space. Each object is classified as either a point, a line, or a polygon and is tied to a geographic coordinate system. These objects have precise definitions and are clearly related to each other according to the rules of mathematical topology.

In addition to topological information, a GIS contains the same attribute data that is found in traditional data bases. Attributes associated with a street segment might include its width, number of lanes, construction history, pavement condition, and traffic volumes.

An accident record could contain fields for vehicle types, weather conditions, contributing circumstances, and injuries. What distinguishes a GIS from a traditional data base is that this attribute data is associated with a topologic object (point, line, or polygon) that has a position somewhere on the surface of the earth.

A well-designed GIS permits the integration of these data. The sophisticated data base in a GIS has the ability to associate and manipulate diverse sets of spatially referenced data that have been geocoded to a common referencing system. To permit this, it might be necessary, for example, to use software that transforms state plane coordinates and milepoint data to latitude-longitude data, and vice versa.

A GIS can lead to new ways of thinking about and dealing with the pavement management process. It can expand the decision making on repair strategies and project scheduling by incorporating such diverse data as accident histories, economic needs, hazardous materials shipments, and vehicle volumes.

Rather than being limited to textual queries, a GIS can perform geographic queries in a straightforward, intuitive fashion. A GIS/PMS can display deficient sections, can group sections by deficiencies, can be used to build projects through spatial selection, can compute traffic impacts of various PMS plans, and can incorporate the results of life cycle forecasts into measurements of future mobility.

The following sections explain how GIS technology can be used in all aspects of the pavement management process.

DATA COLLECTION

The first step in the pavement management process is to collect and record the condition of the roadway segments. Typically, the roadway deficiencies are coded on a segment-by-segment basis and the results printed in tabular form. A series of computer displays showing the segments color-coded by the various attributes would greatly facilitate the process of data entry and editing. Omissions in the data collection effort would be immediately apparent from segments in the roadway showing no data. Errors in measurement or coding would also be readily apparent. One such example would be a case in which a long stretch of roadway had recently been resurfaced and a segment in the middle was coded as having severe transverse cracking (Figure 1). With a GIS, this series of map displays can be quickly produced and assimilated.

Recent developments in electronic data collection equipment make it feasible to scan a roadway from a moving vehicle and automatically record pavement distresses on a microcomputer. If the data were to be entered directly into a GIS data base, this procedure could produce an instant map display of the road condition.

PRELIMINARY ANALYSIS AND INTERPRETATION

In the traditional PMS, the highway engineer transfers some of this tabular information to a base map by hand as a step in understanding the data. For example, he might construct a map showing the severity of rutting or block cracking or create a map indicating the overall performance index. As in the situation for data editing, a GIS that integrates the data base attributes describing the pavement condition with a cartographic display of the road network can be used to create any number of illustrative visual displays of the status of the road system. In Figure 2, all segments with block cracking greater than six are highlighted. In Figure 3, the segments have been grouped by the amount of excess asphalt and a different color assigned to each group.

SYSTEM ASSESSMENT

Although these visual representations of the segment-by-segment status of the roadway are a valuable addition to the pavement management process, it is necessary to add analytical capabilities to assess the current status of the system, compare it with previous periods, and make predictions about the future. To do so requires basic formula manipulations, spatial and conditional query capabilities, statistical procedures, and charting for graphical representation of the data. For example, suppose that 10 deficiencies are rated on a scale from 0 to 10, for which 10 is the worst. To obtain an overall rating of each segment, it might be appropriate to add these 10 ratings and place them in a computed field in the road segment data base. The segments could now be sorted in descending order so that the most deficient segments are at the top of the list. Or one might prefer to compute the present serviceability ratings or the serviceability index as defined in the *Pavement Condition Rating Guide* (*2*) as a summary measure of condition. Assuming a rating system of 0 to 100, each segment could be placed in 1 of 10 groups (0–10, 11–20, . . . , 90–100).

A good PMS/GIS should make it possible to perform statistical analysis of the data. Here are some examples: query the data base by condition to find out how many miles of roadway have a deficiency rating greater than 90; query the data base by road type to find out how many miles of Interstate highway have a deficiency rating greater than 90; query the

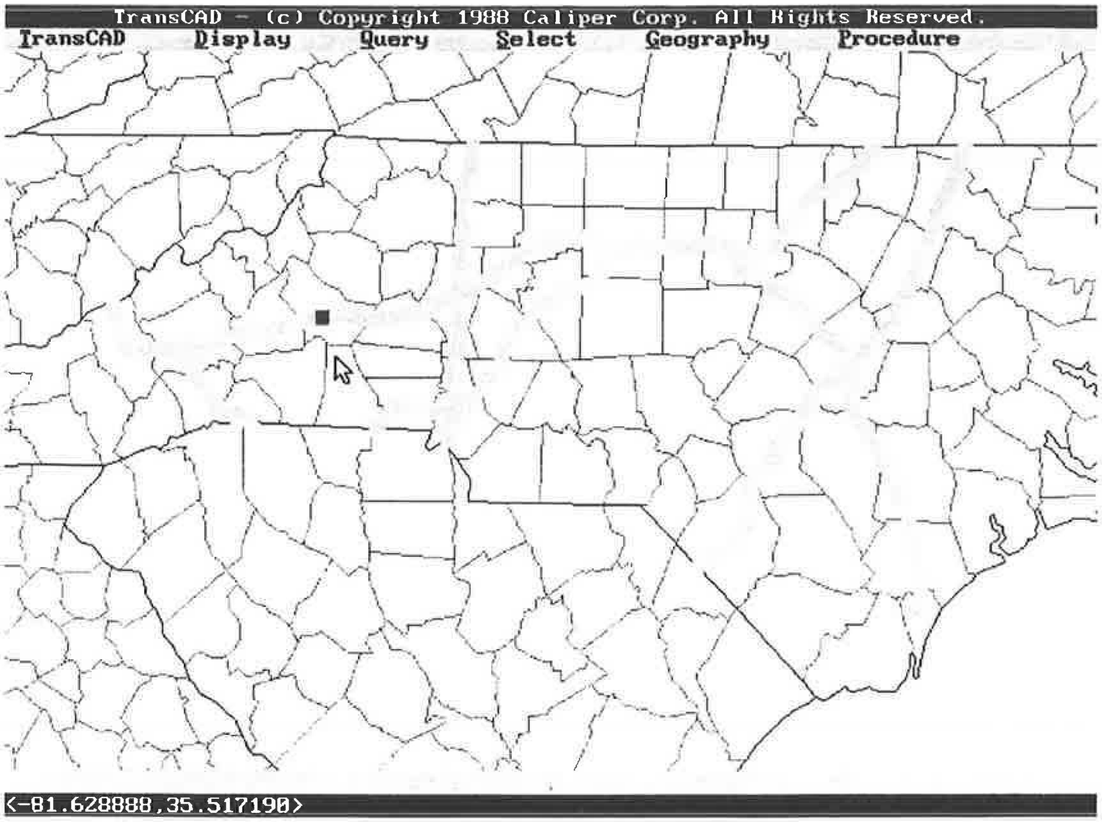

FIGURE 1 Miscoded data.

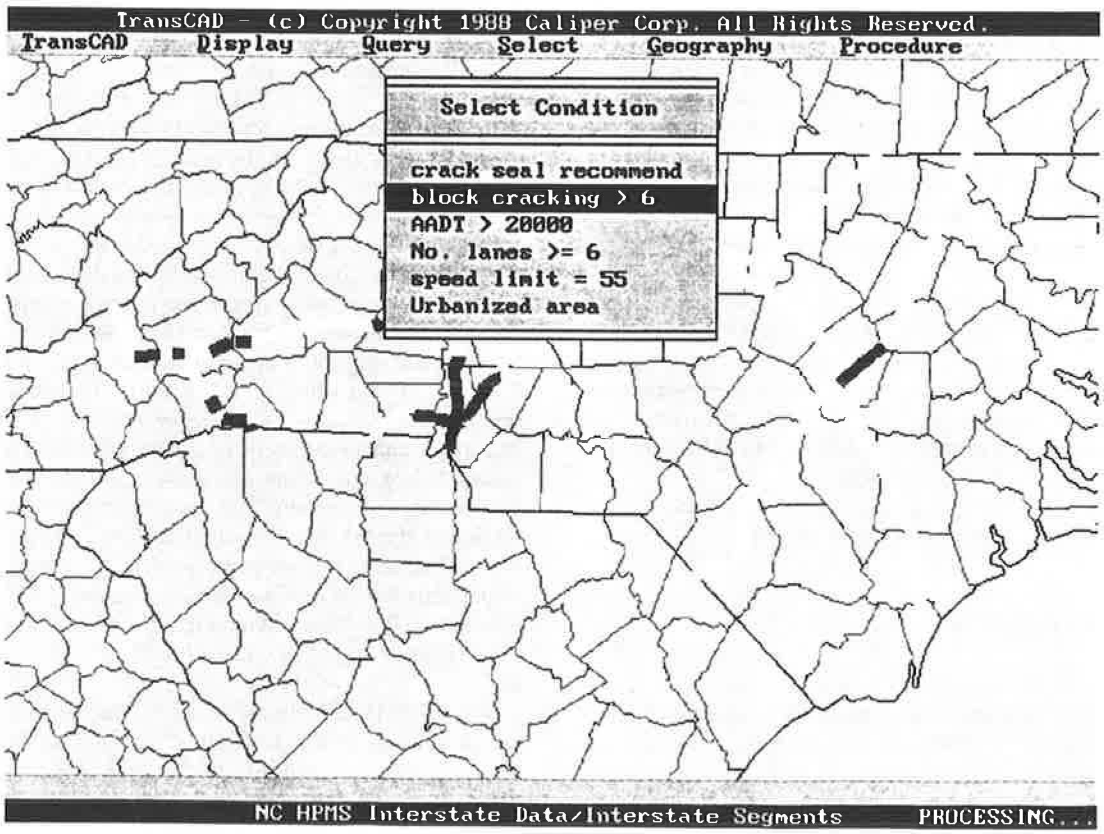

FIGURE 2 Highlighting of segments with block cracking greater than six.

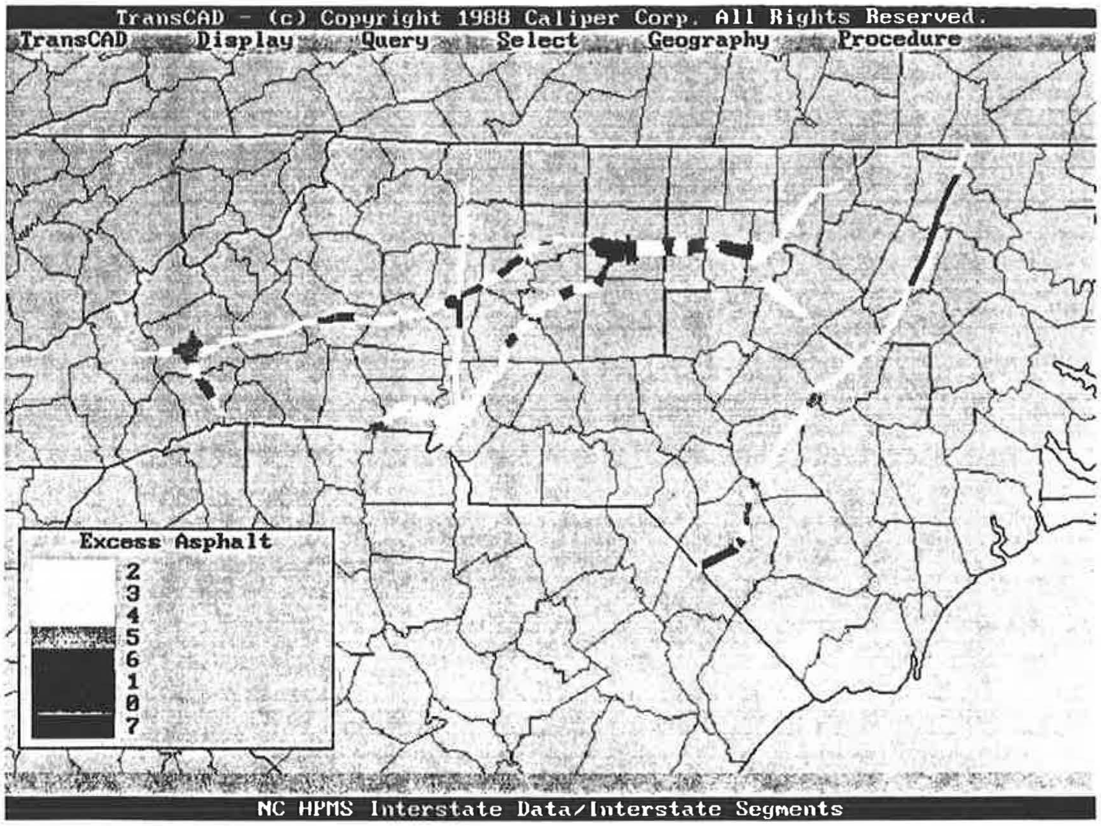

FIGURE 3 Segments grouped by the amount of excess asphalt.

data base spatially to find out how many miles of roadway within 15 mi of the center of a major urban area have a deficiency rating greater than 90 (Figure 4) or how many miles are deficient within an engineering district.

The statistical procedures could also be used to obtain the condition of the average road segment, or the variation in segment conditions throughout the system. Charting could be used to create a pie chart showing the relative proportion of road miles in each condition group. By combining traditional conditional query capabilities with spatial queries and adding mathematical manipulation, statistics, and charting, a full assessment of the road system is possible from within the PMS/GIS. The graphical products produced as part of the assessment could be easily comprehended by management, politicians, and citizen groups, helping to clarify issues and obtain needed support.

DETERMINATION OF STRATEGIES AND ASSIGNMENT OF RESOURCES

The next step in a PMS is the determination of appropriate strategies to deal with the pavement deficiencies over a time horizon and the corresponding assignment of resources to implement these strategies. The determination of strategies could imply a series of decision rules that match deficiency ratings with appropriate actions (Figure 5), or the process could involve a more elaborate calculation of LCC and the appropriate timing of preventive and restorative measures.

The former approach is used in the Pennsylvania DOT STAMPP PMS, in which, for example, rutting plus serious raveling plus average daily traffic greater than 2,000 imply the need for resurfacing (*3*). The Florida DOT recommends LCC as part of an economic analysis that includes initial cost, follow-up maintenance and rehabilitation costs, inflation, and the time value of money for each pavement type that is considered (*4*).

Whichever approach is taken, a well-designed PMS/GIS should have direct links to decision models so that the strategies can be readily determined. In other words, the strategy models should have direct access to the PMS/GIS data base, and the model results should be entered directly into the data base.

In addition to the traditional elements contained in a PMS, a GIS would make it possible to enrich the decision-making process by incorporating other types of data that could not easily be brought into the process without the ability to relate data spatially. One important example is being able to use accident analysis in the decision-making process. Accident analysis requires the correlation of a number of explanatory roadway and environmental variables such as roadway geometrics, weather conditions, traffic volumes, signage, signalization, lighting, and pavement condition (Figure 6). A GIS can serve as the integrator of all transportation activities (e.g., pavement management, accident analysis, sign and signal inventories, planning, and hazmat), as well as the link to other agencies with overlapping data needs (e.g., planning, environmental resources, utilities) (*5*).

Another important component in a PMS is good traffic estimation procedures. It has been pointed out that classification counts are not always representative of actual traffic conditions because of overloaded trucks avoiding weighing

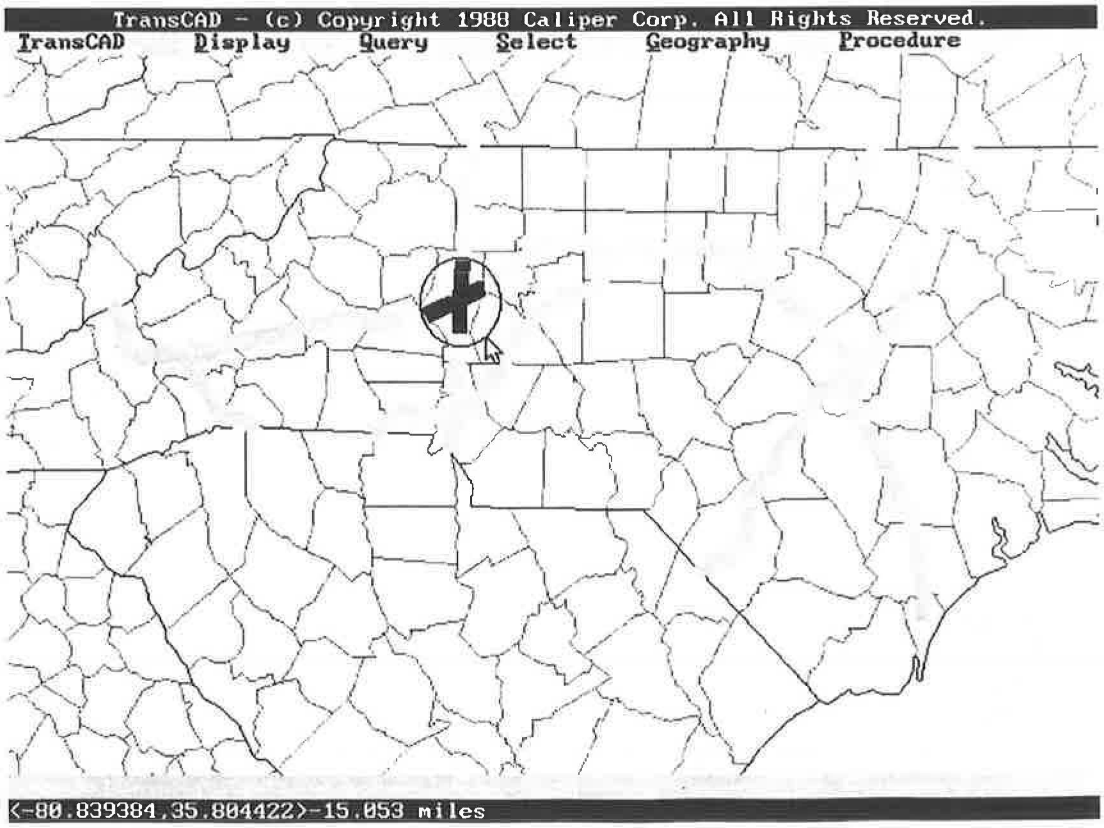

FIGURE 4 Selecting road segments within a 15-mi radius of the center of an urban area.

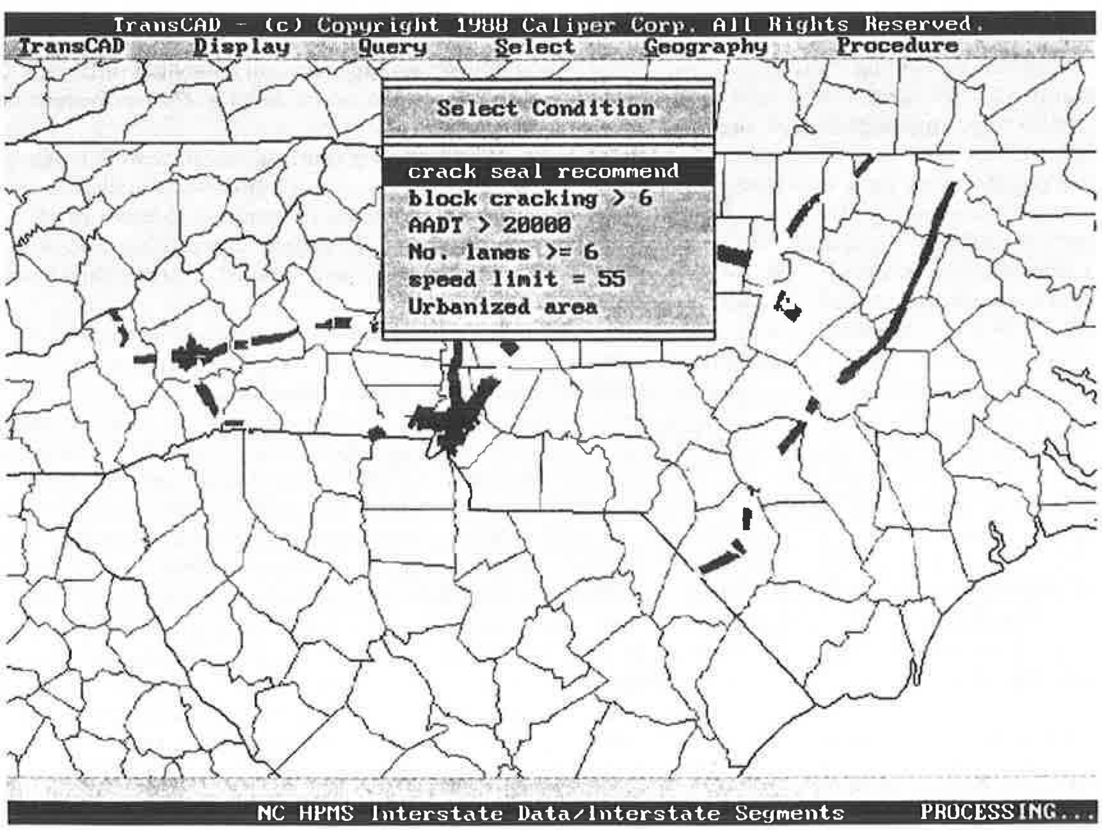

FIGURE 5 Decision rules recommend crack seal.

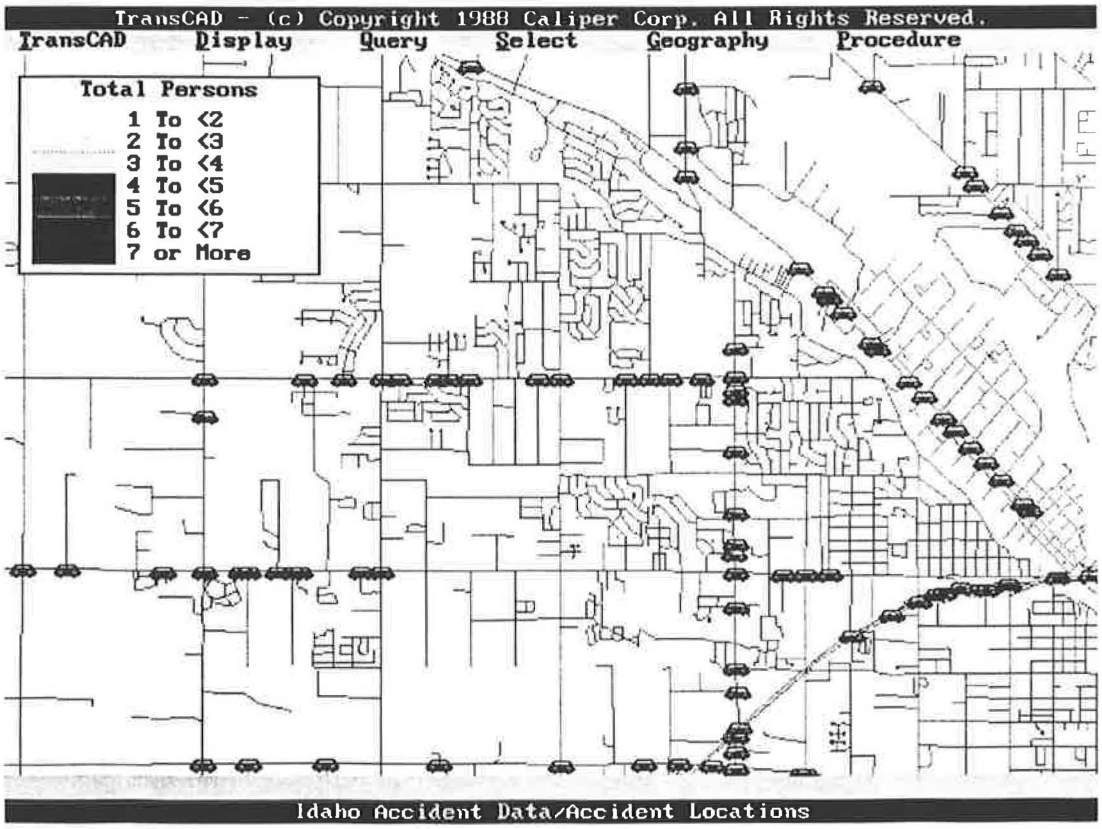

FIGURE 6 Accidents correlated with pavement condition.

scales and insufficient traffic sampling programs (*6*). A PMS/GIS, with an appropriate assignment model, could test for discrepancies between estimated volumes and actual counts.

PROJECT DEVELOPMENT

Once the strategies have been defined and the budgets assigned, it will most likely be the responsibility of the district engineer to implement the strategies through a series of projects. Using the same set of visual and analytical tools that was used for system assessment, the district engineer can group road segments into homogeneous projects on the basis of spatial proximity and resource constraints (Figure 7).

PROJECT IMPLEMENTATION

Individual projects are typically scheduled on the basis of the availability of resources. By encapsulating the PMS within an overall GIS, it would also be possible to schedule projects so that they have minimal impact on the efficiency of the network. Employing demographics and journey-to-work data, a transportation model linked to the GIS could compute traffic assignments on the network. Negative interactions of multiple projects would be readily apparent. User costs resulting from delays could be determined. Shortest path analysis could be used during project implementation to identify optimal diversion routes around segments with the highest volume/capacity ratios (Figure 8).

NETWORK SEGMENTATION IN A PMS/GIS

A transportation system can be viewed as a connected network with segment boundaries (nodes) defined not just by road intersections but also by changes in the particular attribute or attributes under consideration. Some segmentation schemes could result in long segments. For example, the number of lanes of an Interstate highway might not change for 100 mi. Other data-delimited elements, such as road condition and vehicle volumes, usually change at more frequent intervals. Finally, other data, such as an accident record, might be tied to a discrete point.

The following represents a hypothetical, but realistic, situation. The first 3 mi of a road are two lanes, at which point the road widens to four lanes. But after the first mile, the concrete surface has been covered with a layer of asphalt for 1½ mi. Accidents seem to cluster around intersections, but there are two curves that also have a large number of accidents. Five miles down the road, a major highway joins this road, doubling the traffic volume for the next 3 mi. A large number of trucks enters the roadway 2 mi further at a freeway interchange. Suddenly, the amount of edge deterioration increases dramatically.

These observations lead to the question, "When designing a PMS/GIS, how should the network be segmented?" Too

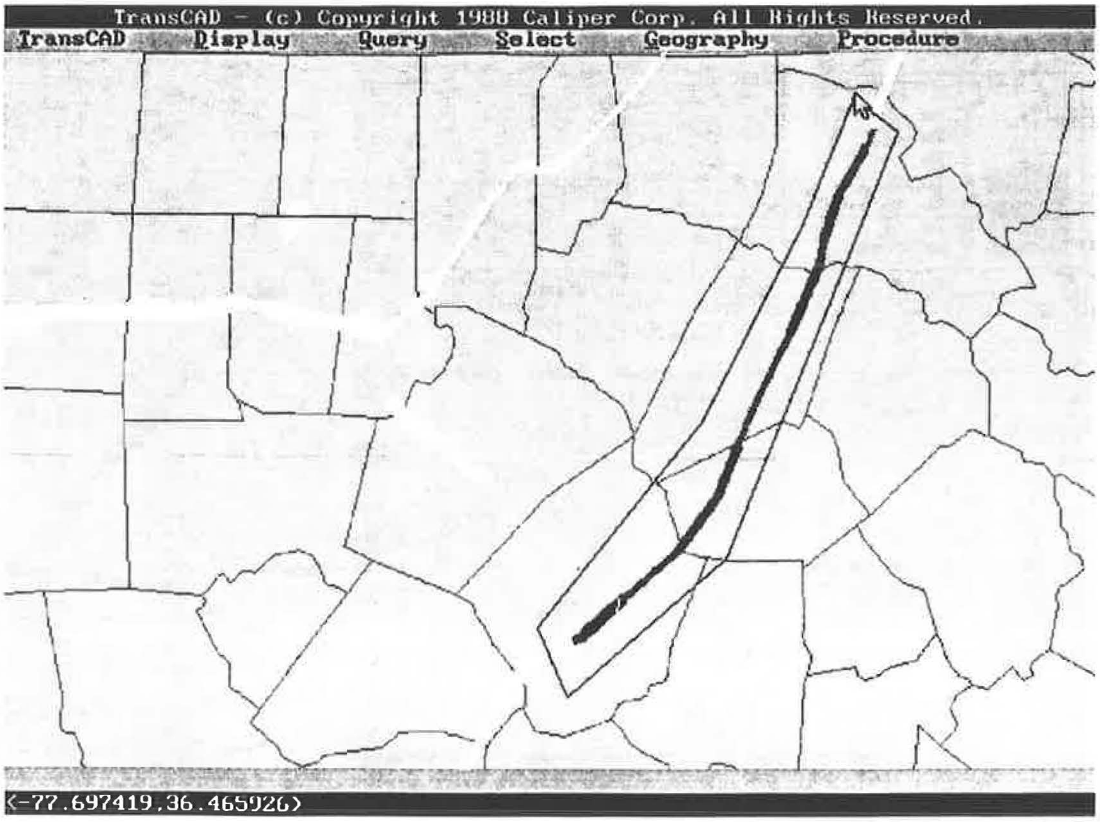

FIGURE 7 Selecting the segments to include in a project.

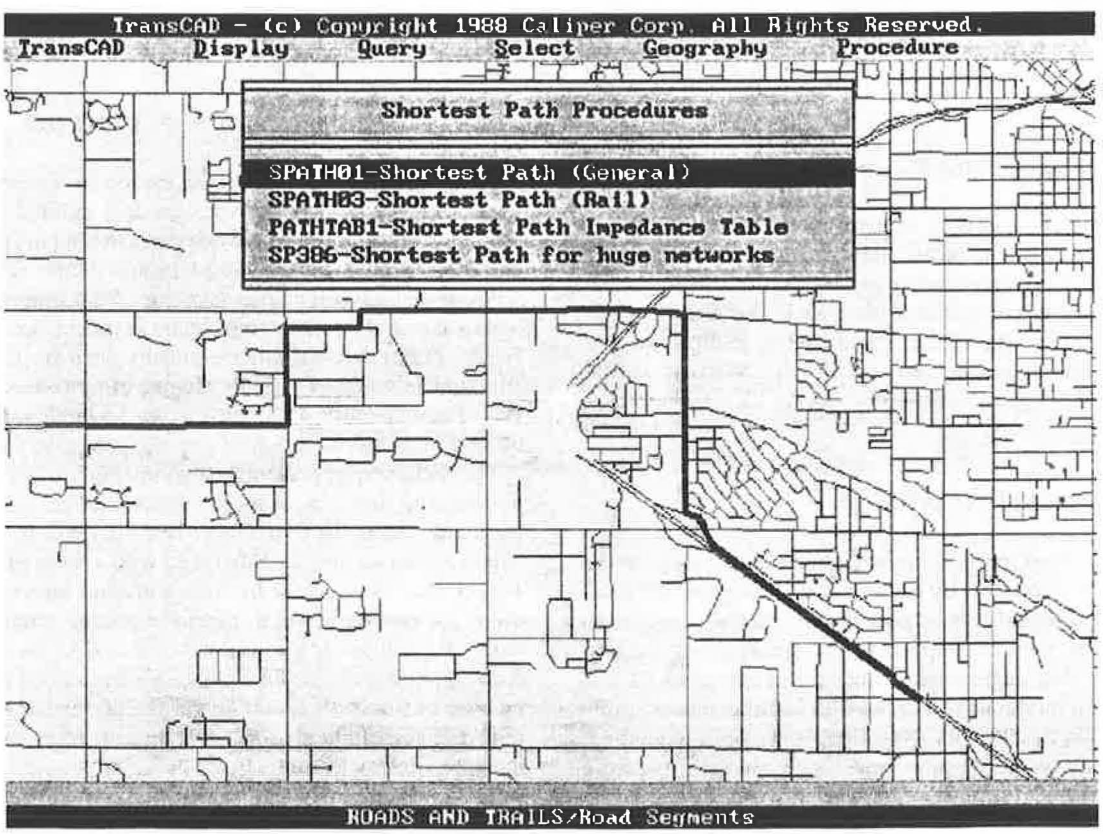

FIGURE 8 Shortest path detour around construction site.

few segments means that changes in data will be lost. Too many segments will leave the system awash in repetitive detail. Nyerges (*7*) discusses the pros and cons of fixed length and variable length segmentation schemes.

Fletcher (*8*) develops the idea of dynamic segmentation of the highway. He proposes that each attribute be stored in its own representation of the network, separate from the base configuration. Segment boundaries in each thematic network would be defined by the variability of each attribute. The network containing pavement widths would probably contain fewer segments than the ones for vehicle-miles of travel or road conditions. Such a construct would minimize data redundancy while capturing data at any desired level of detail. For a particular analysis, only networks of required data elements would be used.

Algorithms have been developed for dynamically segmenting the road network on the basis of changes in the underlying attributes of interest. For example, TransCAD can store attributes in files where each record contains the new attribute value and the beginning milepoint. The analyst selects a subset of attributes of interest and the software automatically inserts nodes in the network wherever one of these attributes changes.

SOURCES OF MAP DATA FOR A PMS/GIS

There are two primary sources of digital map data that are appropriate for use in a PMS/GIS. The Bureau of the Census, in cooperation with the U.S. Geological Survey, has created a topological data base containing every street and block face in the United States for use in the 1990 census. Called TIGER, it combines the 1980 GBF/DIME files in the central cities with the U.S. Geological Survey 1:100,000-scale digital line graphs (*9,10*). TIGER would be appropriate for city and county PMS/GISs (Figure 9). Each road segment in the TIGER file has a street name associated with it, and segments in the urbanized areas also have address ranges identified. Other fields required by a PMS, such as deficiencies and traffic volumes, would have to be added. In addition, TIGER includes all census geography such as census blocks and tracts. This information makes it possible to associate census data from the standard tape files of the decennial census, making TIGER a suitable basemap for all types of planning and analysis (*11*).

A demonstration project funded by FHWA illustrated how TIGER, combined with GIS technology, could be used for transportation planning and PMS analysis (*12*). The report explains how a windowed network could be created for all TIGER road segments within a band along the construction site. This network could then be used to develop optimal detour routings as shown in Figure 8.

The second source of inexpensive digital data is the digital line graph (DLG) series from the U.S. Geological Survey. Files at 1:100,000 scale are available for the entire United States. Some files are also available at the 1:24,000 scale (*13*). DLGs are appropriate for state PMS/GISs, particularly when the state has not already digitized its road network (Figure 10). Unlike TIGER files, only the interstate and primary segments have names identified, and address ranges and census geography are not included.

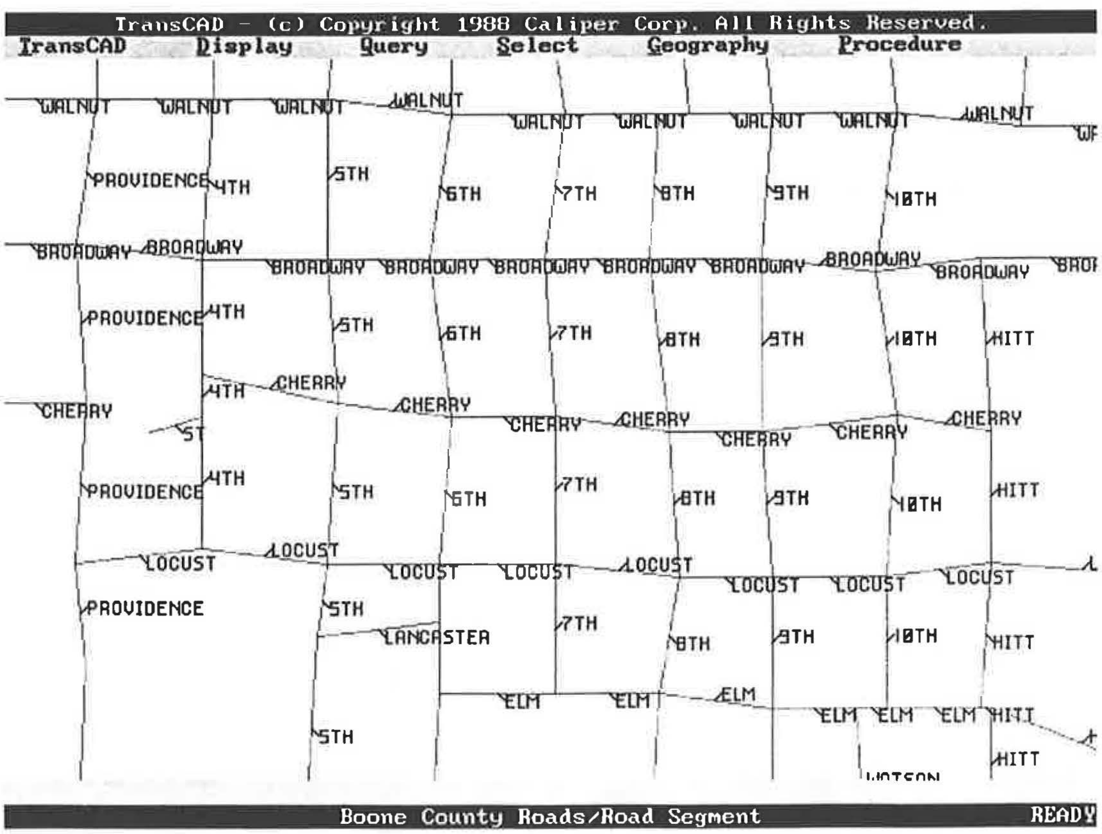

FIGURE 9 Census TIGER file street map.

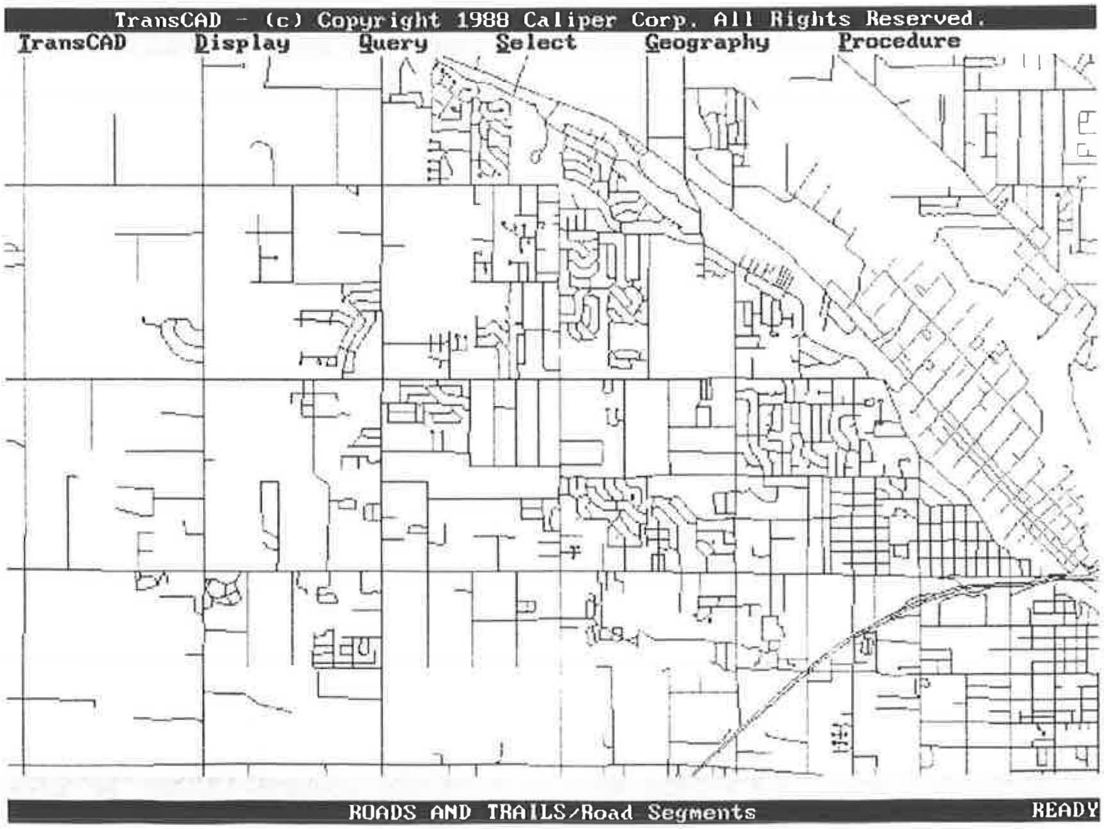

FIGURE 10 U.S. Geological Survey digital line graph at 1:24,000 scale.

ESSENTIAL COMPONENTS OF A PMS/GIS

The preceding discussion has identified a number of essential analytical capabilities that should be included in a comprehensive PMS/GIS:

- Flexible data base editor for storing and editing pavement condition data and other data to be used in the analysis;
- Formula editing of data base fields that facilitates the computation of new relationships such as an overall condition rating;
- Univariate statistics (min, max, sum, mean, and standard deviation), e.g., to compute the total lane miles with a deficiency rating greater than 90; multiple regression to compute deterioration equations; correlation to compute dependence between possible explanatory variables such as truck volumes, weather, and soil conditions and pavement condition;
- Charting (e.g., pie charts and bar charts) to enhance the understandability of the data and make it easier to communicate results to decision makers, politicians, and citizen groups;
- Matrix tools for creating and manipulating origin-destination tables, travel time matrices, and other one- and two-dimensional matrices used in transportation models for shortest path detour determination and traffic assignment;
- A set of useful transportation models and algorithms including shortest path, traffic assignment, vehicle routing (for efficient reallocation of trucks and equipment), and traveling salesman (for the delivery of materials to several construction sites); and
- Links to external procedures such as LCC, decision analysis, shortest path, and traffic assignment.

By including these features, PMS/GIS becomes a tool the applications of which are limited only by the sophistication of the hardware and software, the quality of the data, and the imagination of the users.

CONCLUSIONS

The transportation community is placing a major emphasis on improved pavement management procedures. At the same time, GIS technology is being explored by transportation professionals at all levels of government, in the private sector, and at research facilities. The coupling of appropriate GIS technology with stand-alone PMS can result in a greatly enriched PMS process.

Although the traditional strengths of the GIS formulation are in mapping display and polygon processing, a transportation GIS requires new data structures, data objects, interfaces, and procedures to fulfill its potential. Research into data base design, transportation objects, and user interface has resulted in the development of TransCAD, a transportation GIS that is fundamentally different from the traditional environmentally oriented GIS. TransCAD provides all the tools listed in the previous section essential to a comprehensive PMS/GIS.

Computer hardware continues to become less expensive and more powerful. Software continues to grow more sophisticated. Public agencies and private companies are developing more and better geocoded data. The end result is that cost-effective GIS-based PMSs will become more and more common within the transportation community.

REFERENCES

1. D. J. Kulash. SHRP Research Products Expected by 1993. *TR News*, No. 143, July–Aug. 1989, p. 5.
2. J. P. Zaniewski et al. *Pavement Condition Rating Guide.* FHWA, U.S. Department of Transportation, Office of Highway Planning, Washington, D.C., 1985.
3. PennDOT. *Systematic Technique to Analyze and Manage Pennsylvania Pavements.* Special Task Force on Pavement Management, Harrisburg, Pa., Oct. 1983.
4. D. E. Peterson. *NCHRP Synthesis of Highway Practice 122: Life-Cycle Cost Analysis of Pavements.* TRB, National Research Council, Washington, D.C., Dec. 1985.
5. L. B. Stephens, Jr. The Integration of a City's PMS with other Street Management Systems. Second North American Conference on Managing Pavements, Proceedings, Vol. 1, FHWA, U.S. Department of Transportation, Washington, D.C., 1987.
6. Desai, et al. *Traffic Forecasting for Pavement Design.* Federal Highway Administration, Office of Implementation, McLean, Va., 1988.
7. T. L. Nyerges. Design Considerations for Transportation GIS. Presented at the Ninth International Symposium on Computer-Assisted Cartography, Baltimore, Md., 1989.
8. D. Fletcher. *Modeling GIS Transportation Networks.* URISA 24th Annual Conference Proceedings, Fort Lauderdale, Fla., 1987.
9. R. A. LaMacchia, S. G. Tomasi, and S. K. Piepenburg. The Tiger File: Proposed Products. Geography Division, Bureau of the Census, Washington, D.C., 1987.
10. L. Batten. *Geographic Information Systems Research Utilizing 1:100,000 Digital Line Graph Data.* U.S. Geological Survey, Reston, Va., 1988.
11. H. J. Simkowitz. Using the Census TIGER/Line Files for Transportation Planning. Presented at the National Conference on Effective Planning Techniques for Small and Medium-Sized Areas, Phoenix, Ariz., 1988.
12. J. Fleck and H. J. Simkowitz. Using the Census TIGER Files for Transportation Planning: Results of an FHWA Demonstration Project. Presented at the Second Conference on Transportation Planning Applications, Orlando, Fla., 1989.
13. U.S. Geological Survey. *Guidelines for Acceptance of Digital Cartographic Data into the National Digital Cartographic Data Base.* Digital Cartography Program Office, Reston, Va., 1987.

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Pavement Management Applications of GIS: A Case Study

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Despite ever-increasing budget limitations, more effective ways of establishing maintenance and rehabilitation requirements are needed to optimize the use of available highway funds. Like many other state transportation agencies, the Texas State Department of Highways and Public Transportation (SDHPT) already has in-place, analytical tools for assisting state highway engineers in the management of their roadways. The MICRO-PES package, for example, is a suite of computer programs developed to assist state district engineers with their network level pavement management activities. This analysis package, as the name implies, is implemented on a microcomputer. Because the MICRO-PES system is modular, it can be expanded to include other PMS analysis tools for which the Texas SDHPT may have need. A recent survey has revealed an urgent need by the districts for an automated procedure to generate maps highlighting substandard pavement sections. Currently, the production of these maps is a tedious process, accomplished by manually color-coding maps using pavement condition information from the Pavement Evaluation System (PES) data base. A computerized procedure would assist the engineering districts in the management of their roadways. In this regard, a small-scale study was conducted to evaluate the potential of using geographic information system (GIS) technology within the MICRO-PES environment to satisfy the need of the districts for graphics output capability. A prototype GIS module was developed that provided the capability for graphically displaying the output from the existing MICRO-PES analysis subsystems. The study demonstrated the applicability of GIS as a tool for pavement management.

Many transportation agencies in the United States have operational Pavement Management Systems (PMSs) in one form or another. The past decade has witnessed growth in developing pavement inventories and associated models that assist state departments of transportation (DOT) in prioritizing projects and anticipating future needs. Most agencies are experiencing increasing competition for available state and federal funds. PMSs have become important tools in quantifying overall needs and in evaluating the consequences of budget limitations. FHWA, in recognition of the increasing importance of PMS, has published its pavement initiative, a key element of which is that each state DOT must have in operation an approved PMS no later than February 1993.

The federal policy has prompted several states to accelerate their PMS development. Resulting improvements often mean upgrading of existing systems to meet federal guidelines and to provide additional capabilities for system users. The Texas State Department of Highways and Public Transportation (SDHPT) has recently completed a review of its existing PMS activities (*1*). One aspect of this study was a questionnaire sent to each of the 24 Texas districts that asked the district staff to rank PMS output requirements. By far the most urgent current need identified was for "maps highlighting substandard pavement sections." Many districts are manually color-coding maps using PMS data available only in standard tabular format. The need to evaluate the potential for geographic information systems (GISs) to support PMS activities is obvious. Initial efforts have been made to implement this technology within the Texas SDHPT.

Initial efforts to implement GIS technology to assist pavement management activities involved the incorporation of a prototype GIS module into the MICRO-PES system (*2*). This microcomputer-based system, which was developed by the Texas Transportation Institute, provides Texas SDHPT personnel with tools for analyzing the information stored within the network level Pavement Evaluation System (PES) data base. For each 2-mi section in the highway network, the following data items are available from PES:

1. Width and number of lanes;
2. Functional class;
3. Current condition in terms of
   a. Surface distress (e.g., rutting, cracking);
   b. Roughness;
   c. Structural strength;
4. Annual average daily traffic; and
5. Estimated traffic loads (in 18-kip ESALs).

Included in the MICRO-PES package are the following three analysis subsystems for network level pavement management:

1. A 1-year maintenance and rehabilitation system that consists of a series of decision trees that were based on the recommendations of experienced highway engineers from the Maintenance and Pavement Divisions of the Texas SDHPT. The decision trees relate characteristics such as pavement distress, roughness, pavement type, and whether the road is rural or urban, to the appropriate maintenance and rehabilitation strategies.
2. The Rehabilitation and Maintenance Optimization System (RAMS–DO1), which selects an optimal combination of projects that maximize benefits at a given budget level. The optimization procedure uses a 0–1 integer programming algorithm to maximize the overall maintenance effectiveness.
3. A routine maintenance estimation system that estimates type, extent, and cost of routine maintenance requirements for any highway or network of highways on the basis of user-specified trigger levels of pavement distress types.

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TABLE 1 RAMS DO-1 OUTPUT FOR ANGELINA COUNTY

Segm Num	Dist Num	County Code	Highway Number	From	To	LN	Strategy	Benefit	Cost	Percent Budget	AADT	18 Kips	Pvmnt. Score	PSI Raw
1	11	003	FM0058	000+00	002+00	R	Seal Coat	12833.	57960.00	1.82	9200	6476	34	4.0
2	11	003	FM0058	002+00	004+00	L	Seal Coat	3964.	23920.00	.75	7000	5827	51	4.2
3	11	003	FM0058	004+00	006+00	R	Seal Coat	3913.	23920.00	.75	2300	1444	69	3.9
7	11	003	FM0304	000+00	000+15	R	L.D. Reconstrt.	20888.	120000.00	3.76	940	591	31	2.2
23	11	003	FM0842	002+00	004+00	L	Seal Coat	3010.	18400.00	.58	870	610	59	3.0
24	11	003	FM0842	004+00	006+00	L	L.D. Reconstrt.	26072.	160000.00	5.01	870	610	24	2.2
25	11	003	FM0842	006+00	008+02	L	L.D. Reconstrt.	31480.	176000.00	5.52	190	119	12	1.9
33	11	003	FM1194	000+00	004+00	L	L.D. Reconstrt.	36408.	240000.00	7.52	2700	1678	9	1.9
43	11	003	FM1669	010+00	012+00	L	L.D. Reconstrt.	41644.	312000.00	9.78	5500	3949	39	2.5
45	11	003	FM1818	002-20	002+00	L	L.D. Reconstrt.	29378.	208000.00	6.52	3300	2073	26	2.4
46	11	003	FM1818	006+00	008+00	L	Thin Overlay	15373.	83580.00	2.62	790	495	70	2.7
50	11	003	FM1818	018+00	020+08	L	L.D. Reconstrt.	34832.	224000.00	7.02	380	238	42	2.1
62	11	003	FM3150	000+00	000+17	R	L.D. Reconstrt.	19291.	144000.00	4.51	1550	1041	32	1.9
68	11	003	SH0094	006+00	008+00	L	Seal Coat	9020.	51520.00	1.61	10900	12941	41	4.3
75	11	003	SH0103	022+00	024+00	R	Thin Overlay	10909.	72436.00	2.27	3500	3791	34	2.8
80	11	003	SH0278	000+00	000+09	R	Thin Overlay	11670.	91341.00	2.86	11000	13915	43	2.2
83	11	003	SH0287	002+00	004+00	L	Seal Coat	7975.	46000.00	1.44	14400	18273	31	3.7
84	11	003	SH0287	004+00	008+00	R	Seal Coat	9222.	55200.00	1.73	12400	15685	48	4.0
91	11	003	SH0287	012+00	014+09	L	Seal Coat	10911.	66700.00	2.09	21000	25762	41	3.3
92	11	003	SH0339	000+00	002+01	S	Thin Overlay	22473.	171936.00	5.39	7300	9386	68	2.3
94	11	003	SH0339	002+01	002+04	L	Thin Overlay	4475.	28656.00	.90	8800	9460	56	2.4
96	11	003	US0059	006+00	006+16	L	Seal Coat	7656.	44160.00	1.38	19400	21079	58	3.6
98	11	003	US0059	010+00	010+12	R	Thin Overlay	34907.	148056.00	4.64	28000	35638	28	2.7
99	11	003	US0059	014+00	016+00	R	Seal Coat	10538.	44160.00	1.38	18400	19565	53	3.5
100	11	003	US0059	014+00	016+00	L	Thin Overlay	31349.	191040.00	5.99	18400	19565	43	2.8
105	11	003	US0069	000+00	000+08	L	Seal Coat	3853.	23552.00	.74	5500	5913	52	3.9
108	11	003	US0069	002+00	004+01	L	Seal Coat	7668.	46368.00	1.45	5500	5913	57	3.5
109	11	003	US0069	004+01	006+00	L	Seal Coat	12343.	55936.00	1.75	6500	6759	43	4.1
110	11	003	US0069	006+00	008+00	L	Seal Coat	12799.	58880.00	1.85	8500	10128	31	4.2
115	11	003	US0069	022+00	024+00	S	Seal Coat	6901.	47840.00	1.50	10500	9778	52	4.0
116	11	003	US0069	024+00	026+00	R	Seal Coat	8294.	47840.00	1.50	10200	10923	41	3.9
117	11	003	US0069	038+00	040+00	R	Thin Overlay	14479.	103480.00	3.24	4900	5304	66	2.5
							TOTALS:	516526.	3186881.00	99.87	260690	284929	1384	99.0

When using MICRO-PES, the user is presented with a menu from which any one of the analysis subsystems can be selected for execution.

Before this GIS study, the output from the MICRO-PES package was in standard tabular format. For example, Table 1 presents a typical output from the optimization program. In order to add graphics capability to the system and thus satisfy the need of highest priority of the engineering districts, a prototype GIS implementation was developed as an additional option for presenting MICRO-PES output. The primary goal was to develop an interface between the GIS and the PMS analysis subsystems of MICRO-PES. This interface was intended to provide the following improvements to the MICRO-PES package:

1. Capability for graphically displaying, on a microcomputer color monitor, a map of a selected highway network and for evaluating the general condition of the selected network through queries on the PES data base using the data base management system (DBMS) of the GIS.

2. Capability for generating the input files for the PMS analysis modules using the GIS's DBMS to extract the relevant input data from the PES data base.
3. Capability for graphically displaying the output from the PMS analysis modules and for generating graphical output on hard copy devices that can be included as material for PMS reports.

Initial GIS implementation efforts led to the development of a prototype GIS that provided the enhancements to the MICRO-PES package. Development of this prototype GIS is described in what follows.

DEVELOPMENT OF A PROTOTYPE GIS MODULE FOR MICRO-PES

The main objective of the research effort described herein was to evaluate the feasibility of using GIS technology to satisfy the requirements of the Texas SDHPT for the production of maps identifying deficient pavement sections. The approach selected for accomplishing this task was to perform a case study in which GIS software would be integrated with the MICRO-PES computer system to support the latter's PMS analysis packages.

The support rendered by the GIS software to the PMS analysis subsystems is viewed as yet another option within MICRO-PES; an option that will allow the user to produce a map display, either in the computer screen or as a hard copy, of an area (e.g., a county or district) that has previously been selected for PMS analysis. The GIS option will eventually allow the user to graphically display the output from any of the PMS analysis subsystems. For example, the user will be able to generate a map that shows highway sections that have been selected for some maintenance and rehabilitation work by the RAMS program. By maintaining the GIS as a separate option within MICRO-PES, as opposed to using its mapping capabilities alone through each of the three PMS analysis subsystems, the user is ensured access to all of the GIS capabilities. This feature means that the GIS could be accessed directly to perform other functions, such as PES data subsetting using the GIS data base manager to generate input files for any of the PMS analysis subsystems, or production of maps based on simple queries to the PES data base.

The framework for developing the case study can be subdivided into five main tasks: (a) selection of a GIS software package, (b) selection of an appropriate county, (c) acquisition of the PES data for the selected county, (d) development of the land base, and (e) development of the interfaces between the GIS and the PMS analysis modules. A detailed description of how these tasks were performed follows.

Selection of a GIS Software Package

The two GIS packages that were available for the development of the case study were Environmental Systems Research Institute's PC ARC/INFO and Caliper Corporation's TransCAD. The final decision for selecting PC ARC/INFO over TransCAD rested on the fact that the latter did not have a digitizing capability in its current version (Version 1.20). This capability was crucial to the case study because the land base was to be created from scratch, by digitizing county highway maps provided by the Transportation Planning Division (D-10) of the Texas SDHPT.

A brief description of the modules and capabilities of PC ARC/INFO is in order. PC ARC/INFO is a software system for managing geographic information. This system integrates geographic analysis and modeling capabilities with a fully interactive system for acquisition, management, and display of spatial data.

PC ARC/INFO consists of a series of modules, including

- Starter Kit—used for map creation and digitization, attribute table creation, topologic data structuring, map plotting system, and host computer communication.
- PC INFO—a stand-alone fully featured data base management system.
- PC ARCPLOT—used for interactive map creation and display, graphical query, and generation of high-quality hardcopy maps.
- PC ARCEDIT—supports sophisticated graphics editing for coverage creation and update.
- PC OVERLAY—supports polygon overlay, line and point-in-polygon overlay, and buffer generation.
- PC NETWORK—handles analytical functions for modeling real networks and performs optimal routing, districting, address matching, and geocoding.
- PC DATA CONVERSION—converts grid cell and vector formats to ARC/INFO or vice versa.

The Starter Kit is the foundation of the system, and as such it has to be installed before any other modules. It provides the basic GIS tools such as

1. Arc Digitizing System (ADS) used to digitize map coverages,
2. CLEAN and BUILD procedures to create topology from coordinates,
3. The TABLES program that directly interacts with PC INFO to integrate attribute data with map entities,
4. HELP menus and screens that provide reference to both ADS and TABLES commands,
5. ESRI's Plot System for viewing maps on the screen or for sending them to a plotter or graphics printer, and
6. The Simple Macro Language (SML) that can be used to create a user interface.

Of the PC ARC/INFO modules, only the Starter Kit PC, ARCEDIT, and PC ARCPLOT were used to develop the case study. Both the Starter Kit and PC ARCEDIT were used to digitize and edit the highway network, county boundaries, and city limits coverages that conformed the base map of the area selected for the study. PC ARCPLOT was used to create the display map; assign colors, line types, line weights, and labels to map entities; perform queries highlighting selected highway sections; and plot maps from various analysis queries.

Selection of an Appropriate County

An appropriate county for the case study had to have

- A representative sample of the Texas highway network, that is, a highway network representing several of the

following functional classes: Interstate highways, state highways, U.S. highways, farm-to-market highways, park roads, and state loops or spurs.

- A complete PES database for the highway network. This requirement meant that each PES highway section in the county's highway network had to have at least one data record in the PES data base.

Of the 254 counties in Texas, several satisfied these criteria. It was decided to use Angelina County in the Lufkin District (District 11) for developing the case study shown in Figure 1. Angelina County was used because it had been the subject of a previous research study aimed at evaluating the effectiveness of the RAMS–DO1 program in optimizing the allocation of limited funds to maintenance and rehabilitation needs (*3*). By selecting Angelina County for the case study, the results from the research project (*3*) could be recreated in graphic form, thereby demonstrating the application of GIS as a PMS tool.

Acquisition of PES Data For The Selected County

The PES data base file was provided by the Safety and Maintenance Operations Division (D–18) of the Texas SDHPT. This data base was the same one that was used for the RAMS research study mentioned previously. It contained data from the 1985 PES survey.

Development of The Land Base

Several sources were available from which an appropriate base map could be obtained. These included various digital and paper map products from agencies such as the Bureau of the Census, the U.S. Geological Survey, and the Transportation Planning Division of the Texas SDHPT. The final decision on the map base was to use the Texas SDHPT General Highway Map product for Angelina County. Besides incorporating the complete highway network for the county, it also included the 2-mi highway sections used by the state to maintain its roadway inventory. In order to gain some experience in map preparation and digitization, it was further decided to use a paper map product instead of a digital one. This procedure ensured that the base map would contain only the elements that were of interest to the case study: county boundaries, highway networks, and city limits.

The creation of the base map for the case study was accomplished in three phases: (a) map digitization, (b) PES attribute data integration, and (c) final base map production. Descriptions of the three phases follow.

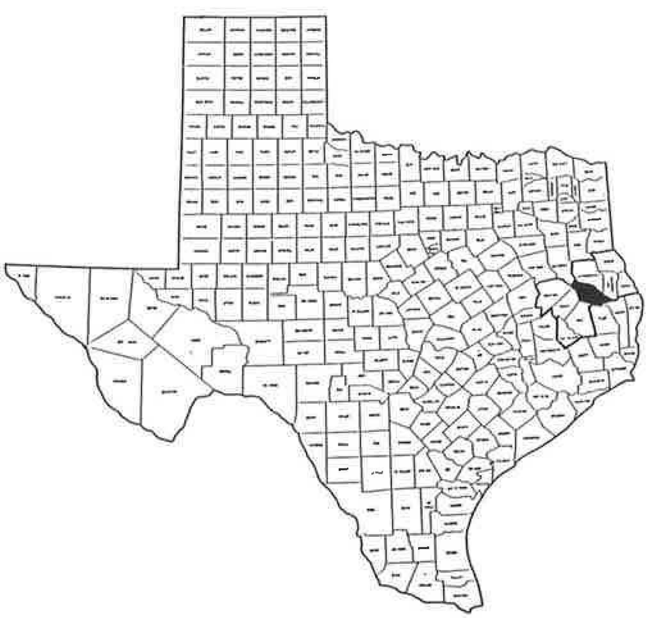


FIGURE 1 Location of Angelina County within District 11 and Texas.

Map Digitization

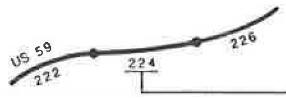
The digitization of all base map coverages was performed with the Starter Kit's Arc Digitizing System (ADS) utility. The Texas SDHPT General Highway Map for Angelina County consisted of two base sheets and one supplementary sheet. Because the base sheets cover the whole county whereas the supplementary sheets show adjacent areas of the county in greater detail, it was decided that the base sheets would be used for the digitizing exercise. Two steps had to be performed before the digitizing process could begin. First, six reference points or tics were marked on the map and labeled 1 through 6. The locations of these tics were arbitrary so they were made to correspond with the intersections of the map's latitude-longitude grid.

The highway network to be included in the land base comprised almost all of the county roadways, with the exception of some short roadways that were considered insignificant to the study. All the roadways were digitized into a single layer or coverage named "HIGHWAYS." The other two coverages, BORDERS and CITYBOUN, that made up the land base, contain the county boundary and Angelina city limits, respectively. These two coverages were digitized using the same set of reference tics as the one in the HIGHWAYS coverage allowing them to be perfectly overlaid, thus generating the complete land base. Because both the CITYBOUN and BORDERS coverages represented only boundaries for visual orientation, no topology was built into them.

In contrast, because the HIGHWAYS coverage represented the highway network, each 2-mi section was digitized as an arc connecting a beginning and an ending node. Thus, the whole network was represented by a series of sequential arcs joined together by nodes. During digitizing, a unique ID number was assigned to each of the arcs representing highway sections. Once the digitizing of this coverage was complete, the BUILD utility was used to make an arc attribute table (AAT), which contained the topological relationships of the arcs that formed the highway network (Figure 2).

PES Attribute Data Integration

The data base used for the case study was a subset of the 1985 PES data set for District 11. The Angelina County data were extracted from this subset using Option 1 of the MICRO-PES program. Furthermore, because PES records contained 47 variables and many of them were not relevant to the study,



HIGHWAYS.AAT

FROM NODE	TO NODE	L POLYGON	R POLYGON	LENGTH	HWY #	HWY ID
2	3	0	0	1.012	2	222
3	4	0	0	1.005	3	224
4	5	0	0	0.918	4	226
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.

HWY ID	PRE	NUM	LANE	RUTT	BLOCK	PAT	FAIL	ALLIG	LONG	TRANS	PSI	SPEED	PTYPE	FC	WIDTH	AADT	18KIPS	STRATEGY	BENEFIT	COST	BUDGET%
222	US	59	S	100	0	0	0	100	10	0	42	65	5	1	36	0920	30126	0	0	0	0
224	US	59	S	100	0	0	0	0	100	0	40	65	5	1	36	9166	38809	0	0	0	0
226	US	59	R	100	0	0	0	0	100	0	40	65	5	1	36	16666	55456	0	0	0	0
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

FIGURE 2 The Arc Attribute Table is linked together with the HIGHWAYS database through the HWY–ID variable, which was used as the key.

only the variables that were the most applicable to the problem at hand were used. Table 2 lists the 22 variables that were selected for the PES attribute data base. The first variable in the table, HWY–ID, does not belong to the PES data set. It was added to it to store the highway section ID number that was used to link the attribute data with the topological data in the AAT created during the digitizing process just described. The four variables STRATEGY, BENEFIT, COST, and BUDGET % (following the KIPS variable) were also added to the HIGHWAYS data base to accommodate output values from the RAMS–DO1 analysis module.

The TABLES utility from the STARTER KIT was used to create an INFO template with the 22 variables that formed the attribute data set and to input the data. Special care was taken to ensure that the HWY–ID variable in the attribute data set matched the HWY–ID variable of its corresponding highway section in the AAT. Once this match was accomplished, the records in these tables were linked together using the common HWY–ID variable as the key (Figure 1), resulting in a fully relational geographic data base for the highway network.

Base Map Production

Once the geographical data base was complete, the next step was to produce the base map that would be used as a basis for displays and queries. This step was accomplished by using the map composition features of PC ARCPLOT. PC ARCPLOT allows the user to display maps created from a number of coverages using different colors, line types, line widths, text annotations like labels and titles, legend and title boxes, and frames.

Map composition in PC ARCPLOT is a process that is performed one step at a time. For instance, the creation of the base map for the case study was done by first defining the map extent (boundaries); then, each of the coverages (BORDERS, HIGHWAYS, and CITYBOUN) were drawn, one at a time, using desired colors and line types until the map was completed. Next, all text (i.e., labels and titles) was added to complete the base map (Figure 3). This step-by-step process had to be repeated every time the map was displayed. In order to avoid such a tedious task, PC ARCPLOT included SML, which could be used to create a batch type file that executed all steps for creating the base map so that map composition could be performed by typing in a single command. For the case study, the macro ANGELINA.SML was created to display the complete base map.

Developing the Interface Between the GIS and the PMS Analysis Modules

Interaction of the MICRO-PES software package and the PC ARC/INFO GIS can be accomplished at the following two levels:

- *Level 1 Integration*—Basic, and entails the exchange of data files while running both packages independently of each other. An example of Level 1 integration would be the case in which the user first selects to run the RAMS–DO1 program and then to run the GIS to display a map of the highway sections that were selected for maintenance or rehabilitation by the RAMS–DO1 program. The user starts MICRO-PES and then the RAMS analysis subsystem. Then, when RAMS is done the user terminates the MICRO-PES session and exits to DOS. From DOS, a PC ARC/INFO session is initiated by entering the ARCPLOT module and by querying the system on the basis of any of the four RAMS–DO1 output variables (STRATEGY, BENEFIT, COST, and/or BUDGET%) to produce the desired map display.
- *Level 2 Integration*—Although Level 1 integration is straightforward, it also involves several steps that require a sound knowledge of PC ARC/INFO operation and principles. In Level 2 integration, the user will not have to be concerned with the operating principles of PC ARC/INFO because the interface makes the communications between PC ARC/INFO and MICRO-PES totally transparent. That is, the user will

TABLE 2 VARIABLES USED TO CREATE THE HIGHWAYS DATABASE

Column	Item Name	Width	Output	Type
1	HWY-ID	3	4	I
4	PRE	2	3	C
6	NUM	3	4	I
9	LANE	1	2	C
10	RUTT	3	4	I
13	BLK	3	4	I
16	PAT	3	4	I
19	FAIL	3	4	I
22	ALLIG	3	4	I
25	LONG	3	4	I
28	TRANS	3	4	I
31	PSI	2	3	I
33	SPEED	2	3	I
35	PTYPE	2	3	I
37	FC	1	2	I
38	WIDTH	2	3	I
40	AADT	5	6	I
45	KIPS	5	6	I
50	STRATEGY	2	2	I
52	BENEFIT	7	7	N
58	COST	11	11	N
69	BUDGET %	6	6	N

Columns 10 thru 30: Pavement distress types
31 thru 32: Pavement roughness
40 thru 44: Annual average daily traffic
50 thru 51: Recommended rehabilitation strategy from RAMS-D01
52 thru 57: Benefit of applying strategy
58 thru 68: Cost of rehabilitation strategy
69 thru 74: Percent of budget spent by applying said strategy

enter the GIS environment to either select highway sections to be analyzed through MICRO-PES analysis subsystems, or to display output from them, by means of an option in the MICRO-PES menu screen. Once the GIS options are executed, the interface will return program control back to the same menu so the user can either perform a new analysis or terminate the session.

The main concern of the present case study is to demonstrate the feasibility of attaining Level 1 integration. Level 2 integration, although it presents an ideal final product, requires more time and resources than those allotted to the study.

SUMMARY AND RECOMMENDATIONS

A GIS is a computerized data base management system for managing spatially defined data. Applications of a GIS are varied, and the capability for presenting information visually, in a form that the user can readily comprehend, is a distinct advantage over conventional data base management systems that present information in tabular form.

Using a GIS has potential to satisfy the need of the engineering districts in Texas for an automated procedure to generate maps highlighting substandard pavement sections. The development of a prototype GIS option for graphically

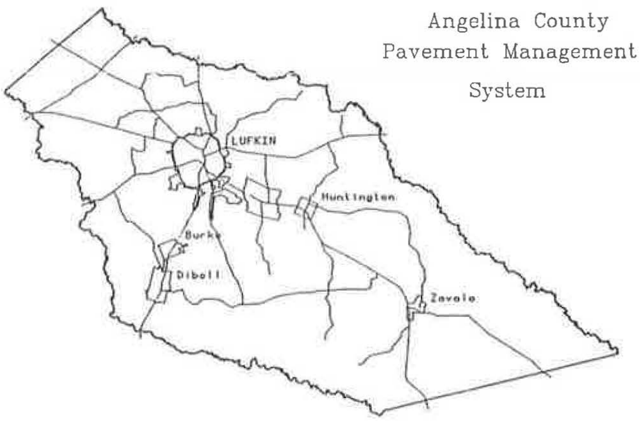


FIGURE 3 Base map for the case study.

displaying output from the existing MICRO-PES analysis subsystems is a significant step toward satisfying the need by the engineering districts for graphics output capability. Although this prototype GIS is at the basic level of integration with the existing MICRO-PES analysis subsystems, it nevertheless has demonstrated the applicability of this technology as a tool for pavement management. Undoubtedly, improvements can be made later on so that the operation of the GIS within the MICRO-PES environment will be more transparent to the user. These improvements in the level of integration of the GIS with the PMS analysis subsystems in MICRO-PES will require the investigation of alternative methods of getting around the 640K memory address limitation of the current DOS environment.

The prototype GIS module for MICRO-PES developed in this study shows the potential of the GIS as a tool for pavement management. Consequently, the development of PMS and other transportation applications of GIS should be pursued, and the following recommendations for future studies are hereby made:

1. A survey of user requirements for a departmentwide GIS should be conducted.
2. The applicability of using existing digitized maps from the department and elsewhere to develop the land base for a GIS should be investigated.
3. An implementation plan for GIS should be developed.
4. Technical issues remain to be resolved, such as the incorporation of dynamic segmentation that would provide different alternatives for reporting highway-related data, i.e., by 2-mi section, from intersection to intersection or at user-supplied limits.

The prototype GIS developed in this study addresses applications of GIS specific only to the pavement management area, and many other applications exist for which a GIS may be used within a transportation agency. With this broader perspective, the recommendations set forth have been made.

ACKNOWLEDGMENT

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REFERENCES

1. T. Scullion. *Pavement Management: Where Do We Go From Here?* Research Report 930-1, Texas Transportation Institute, Texas A&M University, College Station, Tex., 1989.
2. M. Paredes, T. Scullion, J. Fowler, and E. G. Fernando. *The MICRO-PES Release 1.0 User's Manual.* Research Report 930-2, Texas Transportation Institute, Texas A&M University, College Station, Tex., 1989.
3. E. G. Fernando, J. Fowler, and T. Scullion. *RAMS–DO1 as a Decision Analysis Tool.* Research Report 930-3, Texas Transportation Institute, Texas A&M University, College Station, Tex., 1988.

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Automated Conversion of Milepoint Data to Intersection/Link Network Structure: An Application of GIS in Transportation

WENDE A. O'NEILL AND BALAKRISHNA AKUNDI

Restructuring or converting network data is an essential function of the geographic information system (GIS) when adapted to transportation. Implementing effective data restructuring models in the GIS allows users to collect and maintain data in the format with which they are most familiar while allowing others to use it in a format they require. Milepoint referenced data in road inventory files provide valuable network information for transportation research. Individual records in these files represent variable-length sections of roads. A new record is created each time a highway attribute changes. Consequently, a segment of road between two intersections may be represented by one or more records in a road inventory file. Further, all attributes in these records are associated with both directions of travel along a section of road. Many transportation analysis models require networks to be represented by a node-link data structure in which nodes symbolize an intersection of two or more roads. Additionally, if a road is two directional, it is represented by two links, each of which has its own set of attributes. To utilize road inventory data in these analysis models, network information has to be converted from milepoint to an intersection/link format. This process involves aggregating and disaggregating attribute data to represent longer and shorter road segments, and also disaggregating data into bidirectional information. Data conversion efforts are needed to produce intersection/link network representations from milepoint data. A microcomputer model for data conversion is developed and application issues and model sensitivities are addressed.

Many transportation agencies currently are investigating adaptation of the geographic information system (GIS) to transportation. One issue for consideration relates to data structures, specifically representation of transportation networks in digital data bases. Data base design solutions that require distinct groups within planning agencies to conform to one specific structure are unrealistic and unsatisfactory. A model developed here demonstrates that different network structures may be maintained by individual groups. Further, various data bases may be shared among groups, thus increasing information utilization and lessening redundancy.

Road inventory files represent an extensive data base containing highway attribute information. Records in these files represent sections of roadways such that a new record is created each time an attribute changes. The data structure in road inventory files is represented by variable length segments representing several network attributes simultaneously within a segment. Consequently, there is a great deal of data redundancy in these files. The spatial component in this data base limits queries to identification of the district, county, city, or town to which a highway belongs. Milepoint information is provided for each road segment terminus that does not represent a highway intersection. Additional milepoint information in each record gives the distance, in miles, from a set reference point to the beginning of the highway segment represented by the data record.

A dynamically segmented data base structure may be addressed using the model. In this structure, each network attribute is associated with variable-length segments defined by occurrences of changes in the attribute. When several attributes are overlayed, the intersection of segments represents the milepoint data structure found in the road inventory files.

Transportation planning models typically require a network data structure in which links represent one-directional sections of roads. Nodes distinguish the beginning and end of each link and represent an intersection in which change in travel direction may occur. Attributes, such as those found in road inventory files, are associated with each link. Depending on the nature of the application, an intersection/link network may encompass every road in a region or simply a subset of roads.

To make use of road inventory or milepoint attribute information in studies requiring an intersection/link data structure, aggregation and disaggregation of network data must take place. The manual process for performing this task is labor intensive and error prone. An automated procedure has been developed to simplify this data structure conversion process. As a result, road inventory files may be utilized in a broad range of applications.

This paper describes theoretical and practical issues related to conversion from one network data structure to another. Aggregation and disaggregation impact the accuracy of information. Simple rules are defined in the model to achieve an intersection/link data base.

NETWORK DATA AGGREGATION, DISAGGREGATION ISSUES

Aggregation and disaggregation of spatial data have been addressed primarily by geographers for polygonal data structures. In transportation, sketch planning and network abstraction issues are relevant to aggregation and disaggregation of lineal data. Literature on GIS applications in transportation discusses data base design, methodologies for attaching attribute data to lines, and the need for flexibility in transportation

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data bases to meet a variety of objectives (*1–4*). Recently, Kuykendall (*5*) has addressed the capabilities of ARC/INFO to utilize data captured using a variety of location-referencing methods. However, no consideration is given to errors induced by converting data from one structure to another. Unfortunately, few have researched the types of errors produced by aggregating and disaggregating network data and sensitivity of transportation models to these errors.

Some network attribute data are used in transportation analysis to represent available travel supply. These values determine the level of service of a network, which, in turn, influences the amount of travel predicted, as well as the distribution of travel demand through the system. Certain transportation applications, such as evaluating the impact on travel demand of increasing capacity on network links, require models to be sensitive to changes in network attributes, like increases in the number of lanes. Other applications strive for the opposite effect. For example, when investigating a subregion of a network, an abstracted representation of the infrastructure outside the study area is desired. To achieve this abstraction, several links will be replaced by one link which, ideally, represents the same amount of supply available in original data. This approach of minimizing the effects of altering a network is also required for converting data structures. A new network representation should accurately reflect transportation supply found in the existing structure.

A pilot survey of state departments of transportation (DOTs) has been conducted to determine methods used for data structure conversion. The Virginia DOT is working with consultants to convert milepoint data to an intersection/link structure. All data are being stored as offset information and pointers are used to indicate direction of travel to which some attributes apply. It is left to the user to aggregate and disaggregate information to fit the particular application (unpublished data). The Maryland DOT has developed a data base structure that accommodates both milepoint and intersection/link queries. The Florida DOT recently completed conversion of milepoint data to an intersection/link structure (unpublished data). More information on these systems is forthcoming. The Wisconsin DOT has written Fortran routines to convert data structures. Smoothing algorithms used within these routines are currently being analyzed (unpublished data).

Although data base conversion is taking place in transportation agencies, the underlying issue of how to attach attributes to a new structure without compromising accuracy of existing information has not been sufficiently researched. A typical example of the situation faced in data structure conversion is shown in Figure 1. These roads are in James City County, Virginia. Note that a single line has been indicated for the link structure when in fact each line represents two links, one for each travel direction. Only three geographical locations of intersections and milepoint terminus correspond. Consequently, network attribute information found in Segments 1, 2, and 3 must be mapped to Links 1 and 2. Data relevant to Segment 5 must be reflected in attributes of Links 3, 4, and 5. A few milepoint segment attributes found in road inventory files are presented in Table 1. For this network segment, a decision must be made on how to determine the number of lanes and surface width for Link 1. This decision impacts link capacity, which, in turn, affects travel demand assigned on the link. The model developed here for data conversion allows sensitivity testing of aggregation/disaggregation

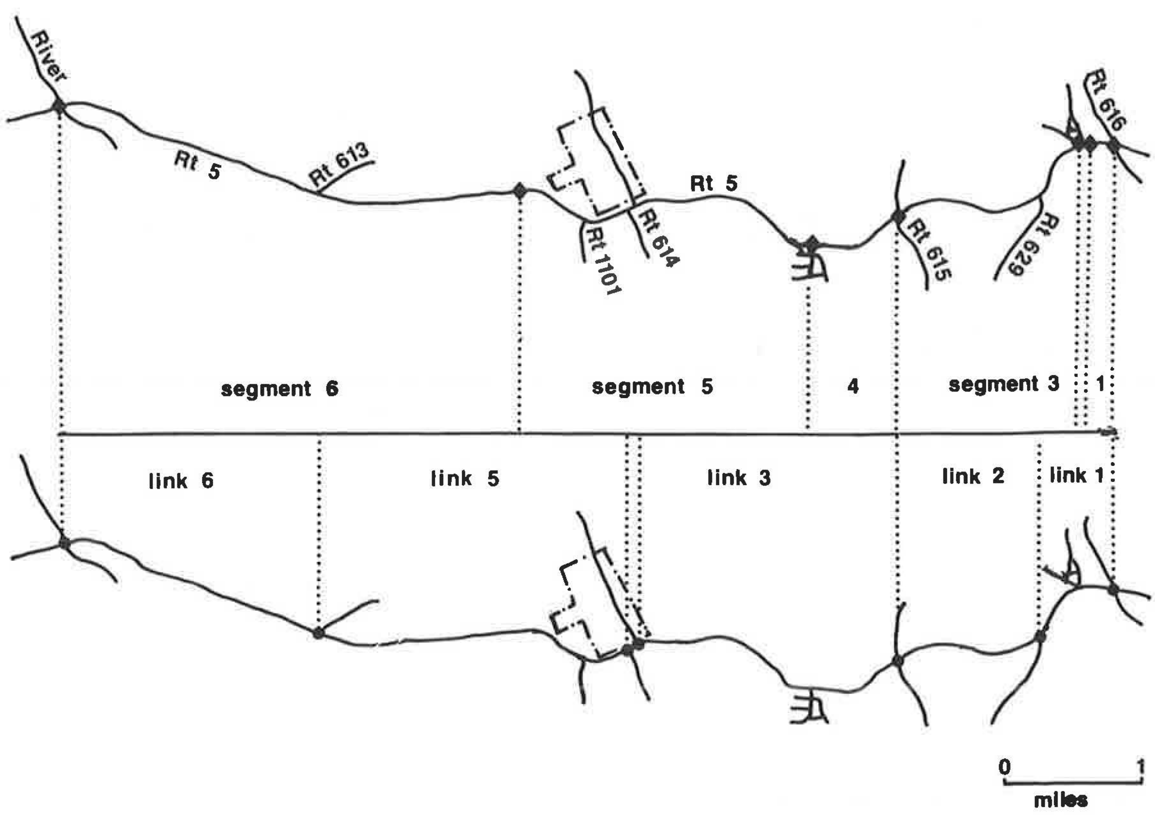

FIGURE 1 Network link and milepoint road segments in James City County, Virginia.

TABLE 1 SAMPLE MILEPOINT SEGMENT ATTRIBUTES

Rt.	From	To	Length	SW	ShW	Lanes	AADT	ST	MP
5	Rt199	18MWRt199	0.18	50	6	4	6260	6	5.01
5	18MWRt199	24MWRt199	0.06	24	6	2	6260	6	5.19
5	24MWRt199	Rt615	1.55	24	6	2	6260	6	5.25
5	Rt615	Rt1438	0.67	24	6	2	4590	6	6.80
5	Rt1438	53MWRt1101	2.28	24	6	2	4590	6	7.47
5	53MWRt1101	Chickahominy	3.43	24	6	2	4590	6	9.75

SW = Surface Width, ShW = Shoulder Width, ST = Surface Type, MP = Milepoint

rules so that accuracy in characterizing network supply is maximized.

DATA STRUCTURE CONVERSION MODEL

Input Requirements

Graphic display of a network is becoming commonplace in many transportation analysis models. Inherent in the definition of GIS is the ability of a system to graphically display and manipulate data. To enhance user-friendliness and simplify computational complexity of the conversion procedure described here, graphic images of highway networks are used by the microcomputer model. However, road inventory files contain highway attribute or descriptive data from which it is difficult to construct a map. Locational information found in road inventory files is summarized as follows. Each record contains (a) district, county, city or town identifiers, (b) the route number of the road segment, and (c) 12-character labels identifying termini-from and termini-to locations of the segment. No digital coordinates are provided in these files. Consequently, visual representation of the underlying network is not easily obtainable from this information.

A digital data base representing a map of the study area network is used to simplify data conversion. This digital representation conforms to an intersection/link network structure. Information on route number or name of each link accompanies the *x,y* coordinates of each node. Route numbers of links intersecting at the beginning and end node of each link are necessary. Depending on the nature of the application, other locational information may include county and analysis zone identifiers.

Several options are available for creating or obtaining a digital map to be used in the conversion process. Two procedures are described. If the study area is small and a digitizing table is available, software is provided in the data conversion system to create the required data base. Several base maps, such as county highway maps and U.S. Geological Survey 7.5-min quadrangle maps, may be used to identify an intersection/link structure that is matched with the location referencing method applied in road inventory files. Users may capture *x,y* coordinates for network nodes alone or digitize several shape points to represent curves in each link. A label, entered during digitizing, is associated with each link in the file. This label is similar to identifiers found in road inventory files. It indicates route name and the names of intersecting routes. Providing names of intersecting routes during digitizing is not necessary but may easily be done when the study area is small. Otherwise, this information can be constructed from the data base, assuming each link has been labeled. Finally, a county code may be entered that matches county code numbers found in road inventory files. County codes are used in the search process to eliminate sections of a road outside the area of interest.

An alternative method for obtaining a digital representation of the study area is to use an existing data base such as highway network (HNET) files [generated in Urban Transportation Planning System (UTPS)] containing link and node information, or TIGER files created by the Census Bureau, or possibly Digital Line Graphs (DLGs) produced by the U.S. Geological Survey. Any existing data base will require editing to incorporate link label information and county codes if this information is not currently present. In urbanized study areas, HNET files represent an ideal source as long as network information has been maintained. However, in many instances HNET files are incompatible with road inventory files that contain statewide data on primary and secondary roads, Interstates, and any road with a federal project number. In this event, TIGER or DIME files or DLGs may be used. These files require some restructuring to achieve an intersection/link highway network data structure. Further, users should be aware that a common criticism of purchased or externally acquired data bases is that information often is outdated, so, for example, newly constructed roads may not be in the file.

Data Structure Conversion

A two-step process is undertaken for converting milepoint information to an intersection/link structure. The first step involves variable or attribute definition. The second step

converts data based on rules defined in the previous step. Details on each of these procedures follow.

Variable Definition

Two types of variables found in road inventory files may be classified as measured and descriptive. A measured variable is one that may be aggregated or disaggregated using mathematical equations without significant loss in accuracy. This assumption is not valid for descriptive variables. With descriptive variables, aggregation of information will result in unacceptable loss in accuracy.

An example will clarify the variable classification methodology required to distinguish data types. Figure 2 shows a link that comprises three milepoint road segments. Each segment has a variable or attribute associated with it that takes on values *A*, *B*, and *C*. Suppose the variable is system domain and a value of *A* represents private land, *B* represents state agencies, and *C* represents national park service. If this information is aggregated on the basis of weighting formula, the value of the variable stored in the intersection/link structure is *C* because it is the value associated with the longest segment. When the new data base is queried to identify all links with value *A*, this link would not be selected because this information is lost from the system. However, if for each of these segments, the values for *A*, *B*, and *C* represent the number of structures within a certain distance from the shoulder, these values may be summed into a single link value without loss of accuracy.

Examples of measured data in road inventory files include length, number of at-grade railroad crossings, and number of structures. Descriptive data include surface and base type, route signing, and functional class. A group of variables, like surface and shoulder width, number of lanes, and average annual daily traffic (AADT) cannot be classified strictly as measured or descriptive. Mathematically aggregating values of these variables over a link is appropriate for some applications and inappropriate for others. A complete list of variables in road inventory files may be found in Table 2. Each variable has been labeled as descriptive or measured. Some records in road inventory files represent sample sections for the FHWA's Highway Performance Monitoring System (HPMS). For these sample sections, much more comprehensive data are maintained. A list of additional variables found in HPMS sections is provided in Table 3 as well as default classifications as measured or descriptive variables.

In the data conversion computer model, users are allowed to select which variables in road inventory files to convert to an intersection/link structure. The specific application for which data are required will dictate this selection process. For instance, applications using data to calculate link capacity from the *Highway Capacity Manual* formulation may use lane and shoulder width, number of lanes, and percent trucks attributes in road inventory files. However, applications that derive link capacity from the UTPS look-up table use facility and area type data.

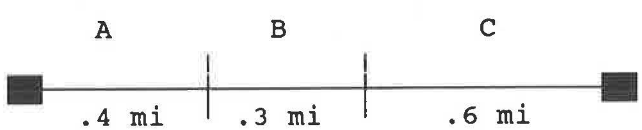

FIGURE 2 Schematic link representation in milepoint segments.

Users also may change default classifications of selected variables. Classification of a variable dictates how and what type of information is kept in the new data base. If a variable is classified as descriptive, each link contains offset information along with the value of the variable associated with each segment. For example, referring to the link in Figure 2, attached to this link in the new data base is information indicating that this variable has value *A* for 0.4 mi, value *B* for 0.3 mi, and value *C* for 0.6 mi. If, however, the value of a descriptive variable does not change between segments, redundant information is not stored. For example, if the variable in Figure 2 has value *A* instead of *B* in Segment 2, the new data base saves this information as follows: value *A* for 0.7 mi, value *C* for 0.6 mi. Inclusion of a large number of descriptive variables significantly increases data base size. To simplify manipulation of information, separate data files are created for each descriptive variable that contain pointers to network links.

Variables classified as measured have default aggregation/disaggregation rules associated with them. For instance, length, number of structures, and number of RR crossings for each segment are summed. If AADT is aggregated, a weighted averaging method is provided. As this system is enhanced, users will be allowed to enter conversion equations as well as define new variables as mathematical and logical combinations of road inventory variables.

Data Conversion

Actual conversion of a milepoint data base into an intersection/link structure occurs in an interactive manner. Ideally, if all road segments fit perfectly into a link, conversion would be rather simple. Complications arise from the two input sources, namely, the road inventory files and the intersection/link digital data base. In road inventory files, segments do not necessarily terminate at all intersections. Further, users may not have selected all roads in the network as part of their digital data base. Consequently, users must be queried on how to handle special cases that occur during link building.

Before conversion can take place, road inventory files must be downloaded from the mainframe to a PC. Due to the size of these files, it is recommended that data are sorted first by county and stored in separate files. Users may then download any county of interest when needed.

The digital map of the study area is displayed on the computer screen throughout the process. Two methods are provided for identifying links for conversion. Either the program will convert links sequentially in the file or users can select individual links for conversion. Before converting data structures, the digital network file is sorted by route number to facilitate a sequential conversion approach. The second technique, individual link selection, provides users the flexibility of displaying a regional or statewide network though actually building a data base for a subarea. A zooming function is provided in the model for more precise display of the area of concern.

TABLE 2 ROAD INVENTORY FILE FORMAT

Column(s)	Variable	Classification
46 - 50	Length	Measured
51 - 52	Surface Width	Measured/Descriptive
53 - 54	Shoulder Width	Measured/Descriptive
55	Surface Type	Descriptive
56	Base Type	Descriptive
57 - 58	Kind of Highway	
	# Lanes	Measured/Descriptive
	Type of facility & access control	Descriptive
59 - 60	Rural & urban public at grade crossings	Measured
61 - 66	AADT	Measured/Descriptive
67	Type of Section Identification	Descriptive
68 - 72	Milepoint	Measured
73	Route signing	Descriptive
74 - 79	System	
	Governmental level of control	Descriptive
	Location	Descriptive
	Federal aid system	Descriptive
	Federal, state & local domain	Descriptive
	Special system	Descriptive
	Public road	Descriptive
80 - 83	Operation	
	Reversible lanes	Descriptive
	Trucks/commercial vehicles	Descriptive
	HOV lanes	Descriptive
	Toll	Descriptive
84	Functional class	Descriptive
85	Special code	Descriptive

Once a link has been selected for conversion, the immediate network surrounding the link is displayed, including node numbers. This link is placed in a box and highlighted on the regional map. Information on route number of the link as well as route numbers of intersecting links is provided (see Figure 3). Link length, in miles, is calculated from digital coordinates and scaling information. Error in determining distance from digital coordinates is introduced by the digitizing process and compounded by line generalization techniques as described by McMaster (*6*). Thus, it is necessary for the conversion procedure to rely on additional information, when available, and estimation routines to match milepoint segments to links. This interactive system allows the user to have the final say in piecing together the network data base. A county code associated with each link is used to determine the appropriate file to search for road attribute data. Within a county file, all records associated with the highway route of interest are identified.

Primary information in road inventory files used in the search algorithm is beginning and end termini labels. If a sequential data conversion technique is used, all links in a route identify a path from reference point zero through the county to a second zero reference point. Links are processed along this path by matching record end termini labels to cross-

TABLE 3 ROAD INVENTORY HPMS FORMAT

Column(s)	Variable	Classification
97 - 98	Surface width	Measured/Descriptive
99 - 101	Approach width	Measured/Descriptive
102	Shoulder type	Descriptive
103 - 106	Shoulder width	Measured/Descriptive
107	Median type	Descriptive
108 - 109	Median width	Measured/Descriptive
110	Widening feasibility	Descriptive
111	Horizontal alignment adequacy	Descriptive
112	Vertical alignment adequacy	Descriptive
113 - 115	Percent passing sight distance	Measured/Descriptive
116 - 117	Speed limit	Measured/Descriptive
118 - 119	Average highway speed	Measured/Descriptive
120	Signal type	Descriptive
121 - 122	Percent green time	Measured
123 - 124	Parking	Descriptive
125	Terrain type	Descriptive
126	Type of development	Descriptive
127	Urban location	Descriptive
128 - 129	Grade separated interchanges	Measured
	At grade intersections with	
130 - 131	signals	Measured
132 - 133	stop signs	Measured
134 - 135	other or no control	Measured
136 - 137	Commercial access points	Measured
138 - 139	Structures	Measured
140 - 141	At grade railroad crossings	Measured
142 - 143	Type of Improvement	Descriptive
144 - 155	Sample number identification	Descriptive
156	Sample section subdivision	Descriptive
157 - 161	State HPMS sample number	Descriptive
162 - 163	AADT volume group identifier	Descriptive
164 - 168	Expansion factor	Measured
169	Pavement section	Descriptive
170 - 171	Structural number or slab thickness	Measured/Descriptive
172 - 174	Pavement condition	Measured/Descriptive
175 - 176	Skid resistance	Measured/Descriptive
177 - 179	Existing right-of-way width	Measured/Descriptive
180 - 181	Percent trucks peak period	Measured

TABLE 3 *(continued on next page)*

TABLE 3 (*continued*)

Column(s)	Variable	Classification
182 - 183	Percent trucks off-peak period	Measured
184 - 185	K-factor	Measured
186 - 188	Direction factor	Measured
189 - 193	Urban peak capacity	Measured/Descriptive
194 - 198	Urban off-peak capacity	Measured/Descriptive
199 - 204	Future AADT	Measured/Descriptive
205	Drainage adequacy	Measured/Descriptive

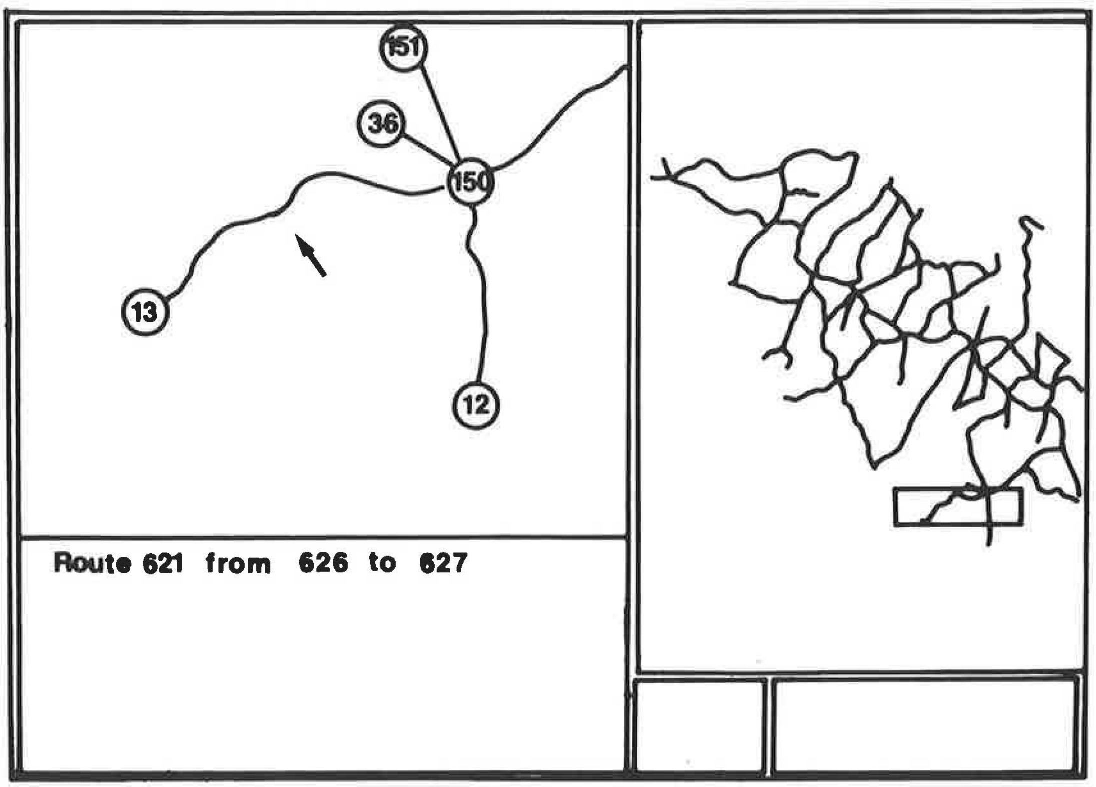

FIGURE 3 Screen representation of data conversion program.

route labels at intersections. If an intersection occurs between the endpoints of a road segment, distance information is used to disaggregate data in this segment and assign converted data to the two links. When multiple road segments form a link, selected variables are aggregated using rules defined by users. As records in road inventory files are being assigned to network links, they are displayed on the terminal to facilitate user intervention.

SUMMARY AND CONCLUSIONS

The model described is still in a design and development stage. On completion of programming, tests will be run on several networks. Emphasis will be placed on using available digital files, such as TIGER files, to reduce the effort and cost associated with digitizing network maps. Investigations will concentrate on sensitivity of network analysis to aggregation and disaggregation of supply variables, ability of the model to improve, in terms of accuracy, speed, and flexibility, the manual process of building a network using incompatible data, and user-friendliness of the procedure. As tests are run, improvements will be made to the model as required in order to develop a system that facilitates sharing of transportation data bases.

Issues of data accuracy and the impact of aggregation and disaggregation of network supply attributes for subregion analysis and data structure conversion are topics for continued

research. The model presented here is intended to facilitate the data conversion process. However, further investigation is required into appropriate models for network data aggregation.

REFERENCES

1. T. Nyerges. Locational Referencing and Highway Segmentation in a Geographic Information System. *ITE Journal*, Vol. 60, No. 3, 1990, pp. 27–31.
2. T. Henderson. Position Paper: A Comprehensive Proposal for the Acquisition, Use, and Maintenance of Geographically Related Information in the New Mexico State Highway and Transportation Department. In *Proc., GIS for Transportation Symposium*, AASHTO, Washington, D.C., 1989, pp. 219–268.
3. H. J. Simkowitz. Geographic Information Systems: An Important Technology for Transportation Planning and Operations. In *Proc., GIS for Transportation Symposium*, AASHTO, Washington, D.C., 1989, pp. 161–192.
4. F. L. Mannering and W. P. Kilareski. The Common Structure of Geo-Based Data for Roadway Information Systems. *ITE Journal*, Vol. 56, No. 7, 1986, pp. 43–49.
5. K. Kuykendall. *Representing a Highway Location Referencing System with a GIS in a Relational Environment.* Environmental Systems Research Institute, Redlands, Calif., 1989.
6. R. B. McMaster. The Integration of Simplification and Smoothing Algorithms in Line Generalization. *Cartographica*, Vol. 26, 1989, pp. 101–121.

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Use of Geographic Information Systems in Managing Hazardous Materials Shipments

MARK ABKOWITZ, PAUL DER-MING CHENG, AND MARK LEPOFSKY

The safe transport of hazardous materials is emerging as a significant concern impacting local, regional, and national transportation policy. For this reason, there is a pressing need to develop methods for evaluating alternative shipment routes, and for developing emergency preparedness and evacuation plans in the event that a hazardous cargo spill occurs. Because the analysis of hazardous materials shipping and handling necessarily involves a close interaction between the transport system and its surrounding environment, the advent of the geographic information system (GIS) provides important opportunities for providing improved decision support in managing safe transport. GIS applications are defined for hazardous materials transport problems, and the benefits that can be achieved through adaptation of GIS to this subject area are demonstrated. In this context, the following information is presented: (a) the decision environment for managing hazardous materials shipments, (b) GIS data availability to support analysis needs, (c) application of a first-generation GIS model to identify preferred hazardous materials shipment routes, (d) comprehensive approaches using GIS for emergency preparedness and evacuation planning, and (e) problems encountered in using GIS technology for hazardous materials transport applications. A GIS approach offers potential for addressing these subject areas. Models already operational today demonstrate the immediate value of using a GIS, and the future design of more comprehensive methodology should provide even greater benefits.

Each year, modes of transportation in the United States, excluding pipelines, together carry some 1.5 billion tons of hazardous materials—chemical and petroleum products, including acids, fuels, explosives, fertilizers, and a variety of industrial wastes (*1*). Of this, approximately 65 percent is carried by truck and rail from manufacturers to a vast array of users.

Faced with such widespread transportation and distribution of hazardous materials, and the associated potential for costly and health-threatening spills, government agencies at federal, state, and local levels, as well as industry, have been forced to address the regulation and routing of hazardous materials, in addition to emergency preparedness and response. These responsibilities have necessitated the development of comprehensive approaches to risk management that consider the physical and operational aspects of the transport system in concert with characteristics of the surrounding land use, such as population distribution and the location of environmentally sensitive areas. The advent of the geographic information system (GIS), therefore, provides an important opportunity for improved decision support for the safe management of hazardous materials shipments.

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The objective is to examine the role of the GIS in analyzing hazardous materials transport problems, and to demonstrate the benefits that can be derived by adaptation of GIS to this subject area. This discussion is presented according to the following sequence: (a) the nature of the hazardous materials transport environment, (b) data needs to perform analysis requirements and the ability of GIS to support these needs, (c) illustration of a first-generation GIS-based model to select safe routes for movement of hazardous cargo, (d) discussion of future enhancements involving GIS to reach a more comprehensive approach to management of hazardous materials shipments, and (e) problems encountered in using GIS technology for hazardous materials transportation applications.

PROBLEM FOCUS

Transportation considerations involving hazardous materials can be conveniently divided into two basic categories, namely decisions involving site selection and those focusing exclusively on the transport operation. In site selection, the location of shipment origins and generated volumes are usually known, and the question focuses on location of the destination site and the capacity of the terminal facility. A typical example of this problem concerns the decision about where to locate a hazardous waste disposal facility. For the site selection problem, transport mode and route selection are also decision variables, although they are hierarchical decisions, anchored to each specific site location and receiving capacity alternative. Consequently, transportation impacts feed into a broader process that leads to a siting recommendation.

The transport operation problem, which is a far more common application, assumes that the location of the shipment origin and destination are known, as are shipment volumes and receiving capacities. In this instance, choice of transport mode and preferred route are the sole decision variables, and analysis of transportation impacts leads directly to policy formulation. A classic problem in this area is the routing of an extremely hazardous material by truck, rail, or barge between the shipment origin and destination, where each candidate route will expose different communities to the potential of a release. The complexity in technical representation of the transport costs and risks involved and the political attention devoted to the routing question present imposing challenges on decision support model development.

Closely related to the question of routing is the area of emergency preparedness and response. As a release can potentially occur during loading or unloading at a handling

facility or while the shipment is in transit, the ability to effectively deploy emergency response personnel and schedule appropriate evacuation procedures (if necessary) is paramount. A considerable amount of preplanning may be needed so that appropriate actions can be taken in the event a release does occur; there is also the need for dynamic response while the incident is taking place. Knowledge of the location and capability of emergency response units, potential population requiring evacuation, and accessibility and capacity of the roadway system are all critical elements to an effective emergency preparedness and response plan. As it relates to the handling of shipments at facility sites, this problem has taken on added significance with the passage of the Superfund Amendments and Reauthorization Act (SARA). This legislation effectively requires local jurisdictions to develop emergency plans for dealing with specific hazardous materials (*2*).

Factors affecting decisions involving the management of hazardous materials shipments can be generally separated into economic and safety considerations. The chief economic consideration typically involves carrier/shipper operating costs to use the transportation system. Direct economic impacts are also associated with the costs of maintaining the infrastructure, developing and implementing regulatory policy, inspection/enforcement, and emergency response (including cleanup) programs.

Safety effects focus on the risks associated with the likelihood of an accident/incident that causes a container failure and subsequent materials release. In such instances, there is the potential for causing serious harm to the population and the environment. Consequence severity can be impacted by a number of factors, among which are rate of release, shipment size, toxic effects of the material, local demographics, and the response times and capabilities of emergency management personnel. Understanding the likelihood of different consequences is a fundamental part of risk assessment.

The analytical framework for addressing hazardous materials transport decision problems can be quite complex to represent mathematically. It can require identification and quantification of the state or condition of many transportation-related elements, including the following:

- Transportation infrastructure and use of the relevant transportation network.
- Transportation regulation and inspection programs affecting the transport facility.
- Characteristics of the population and environment adjacent to each network segment (link).
- Location and capability of emergency response units.
- Shipment and vehicle operating characteristics.

GIS provides an ideal environment for managing hazardous materials shipments because it involves the overlay of many transport network attributes as well as other GIS data layers (e.g., demographic, topographic, and weather) on individual network segments in order to properly characterize accident/incident likelihood and consequence to the population and environment. This application also involves the integration of the GIS with sophisticated mathematical models and search procedures to identify preferred management options (*3*).

INFORMATION REQUIREMENTS

The information required to support hazardous materials transportation analysis can be generally classified into the following three categories: (a) transportation network, (b) social/demographic factors, and (c) other geographical considerations.

Transportation Network

Transportation network considerations consist of physical dimensions (geometrics) of the transportation system and its associated use. Each network link (segment) and node (intersection) must be defined by its locational coordinates, so that these coordinates can be integrated with other geographical information to create a common referencing system.

Typical network attributes that are desirable to append to the transport network for hazardous materials transportation analysis include (a) distance, (b) average daily traffic, (c) number of lanes (tracks), (d) physical condition, (e) accident rate, (f) bridge and tunnel clearances, (g) curvature/grades, and (h) temporary restrictions. The geometric characteristics are important in defining each segment in terms of permissible traffic; for example, certain shipments may be restricted from passage on roads without sufficient clearance. Geometric characteristics are also used to classify transport segments into categories for subsequent analysis (e.g., accident likelihood may vary by curvature and grade).

Attributes more closely related to transport segment utilization correspond to the movement of traffic across the segment and the quality of service provided. Accident likelihood/severity and travel time are two principal outputs generated from the process of examining utilization in concert with design standards as determined through segment geometrics.

Most transport network information can be obtained through state agencies. The difficulty is in integrating this information and assigning it to the proper location of the physical network (*4*). As an example, difficulties can arise where traffic counts are taken at places that do not conveniently overlay with the locational framework in which accident statistics are compiled. Considerable progress is being made in this regard through the use of dynamic segmentation, a concept that allows for creation of interpolated segments and identification of points within a segment (*5*). Thus, an appropriate location reference system can be established.

Social/Demographic Factors

The interactions between the transportation system, the adjacent land use, and environment are defined herein as social/demographic factors. Included among these are (a) population within varying distances of the transport segment, (b) response time from the nearest first (and ultimate) responder and associated response capability, and (c) the distance to schools, hospitals, water supplies, and other ecologically sensitive areas.

Knowledge of the population distribution adjacent to the transport facility determines the impacted population that might

be exposed to a potentially hazardous materials spill. The distance from the transport segment, as one would expect, has implications on the level of exposure that depend on the characteristics of the release event.

The response time from the nearest response unit and the ultimate response capability are indicators of how quickly a spill can be reacted to and controlled should one occur at a given point in the transportation system. An important distinction must be made between first response (on-scene arrival) and ultimate response (capability to control the release). Although both are important, first response is directed more at responding to the immediate consequences of the incident, whereas ultimate response focuses on containing the source of the problem.

Proximity of schools, hospitals, water supplies, and other ecologically sensitive areas identifies the presence of sensitive locations and their (impact) distance from the transport facility. This may prove particularly important in the determination of routing criteria as well as in the development of emergency preparedness and evacuation planning.

Social/demographic factors can be generated from GIS data describing the surrounding land use, overlaying this information on the transportation physical coordinates, and deriving appropriate measures for each transport segment using computational geometry and other mathematical derivations. These attributes, in essence, would be computer derived and subsequently added as fields in the record structure of the transportation network data base.

Other Geographical Considerations

Other geographical considerations refer to information on weather, topography, and geology, all available through a GIS, that can potentially be overlayed on the transportation and social/demographic data to permit a more precise assessment of health impacts from a transport spill. Important weather considerations include wind direction, wind speed, and temperature for the purpose of determining release dispersion. Topography adjacent to the transport facility plays an important factor in dispersion, whereas geological characterization of the surrounding area has important implications on ground and surface water contaminant flow.

As in the case of social/demographic considerations, it is expected that these measures can be derived from GIS data and appended as segment level attributes in the transportation network.

ROUTING APPLICATIONS

In moving towards an idealized GIS approach to hazardous materials transportation analysis, the authors have been engaged in the development of first-generation hazardous materials routing models that rely heavily on GIS technology. The GIS applications environment used in this research possesses the following features: (a) can be performed using a stand-alone microcomputer, (b) provides enhanced graphics output, (c) permits flexibility in evaluating alternative routes, (d) is designed to accommodate future data collection and model enhancements, and (e) provides an opportunity to integrate generic approaches with selective customization.

The transportation network used in this system is a GIS road network maintained by Oak Ridge National Laboratory, based on a U.S. Geological Survey 1:2,000,000 scale map. Several network attributes have been assembled from various public domain sources, and have also enhanced the data base through the addition of new attributes and substitution of certain attribute values where more detailed information (e.g., state accident files and traffic counts) have been obtained. The network can support both national and localized routing studies, and can accommodate other scales and formats, such as the U.S. Geological Survey 1:100,000 scale maps and the Bureau of the Census TIGER files.

The principal social/demographic factor that is operational in the referenced hazardous materials transportation routing model is population. This is a GIS data base of enumeration district centroids with attribute information, available through the Bureau of the Census. A comprehensive procedure has been applied to these data to create an enumeration district boundary file and to spread the population in each district nonuniformly across this area according to a gradient method (*6–9*).

The enumeration district boundary file for each district is established by drawing lines that bisect each adjacent enumeration district centroid. Through recursive use of this process, enumeration district borders are shaped such that every district occupies a unique area surrounding its centroid, and collectively the districts occupy the entire county area.

The gradient method that is subsequently applied is based on the premise that the population in a district is likely to be distributed proportionate to the population densities of neighboring districts. Consequently, of two equal-sized areas located within the same district, the area located closer to a neighbor with a greater population density will be assigned a greater proportion of the district population than the area located closer to a neighbor with a lower population concentration. This is done to preserve the continuity of urban and rural land use which is independent of the nature in which enumeration districts are defined by the Bureau of the Census.

Once the gradient method has been applied, the entire county is divided into cells, each of which encompasses an area of 30 sec of longitude by 30 sec of latitude. This corresponds to approximately an area of one-quarter square mile. The centroid of each of these cells effectively becomes the GIS population data base for exposure analysis.

The overlay of the GIS population data base onto the GIS transportation network is subsequently performed, and computational methods are applied to derive relevant population exposure measures for hazardous materials transportation analysis. This measure is defined as the population bandwidth (see Figure 1). The bandwidth corresponds to an impact band on each side of a transport segment, and is drawn as a continuous line along the segment to represent that an incident can occur at any point along a shipment path. Using either chemical dispersion models or expert judgment, the maximum exposure distance for a particular shipment and material can be determined, and subsequently used to define the appropriate bandwidth. The affected population is then derived for the selected bandwidth using the previously described method.

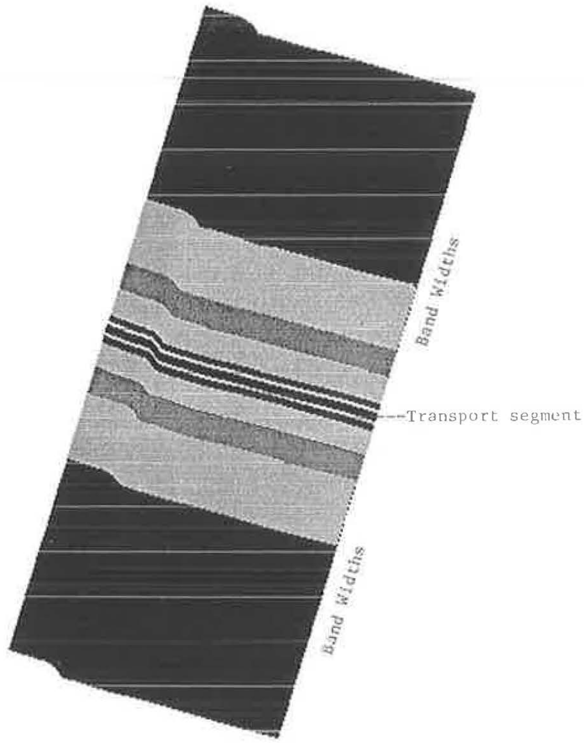


FIGURE 1 Spill exposure using transport band widths.

The search and solution process uses a network algorithm referred to as the "double-sweep method" (*10*). This algorithm provides an efficient search procedure and finds a global optimum, such that large-scale network (e.g., U.S. principal road system) applications can be solved in a matter of minutes. Network restrictions, such as prohibiting movement on certain transport segments, can also be easily accommodated in the solution environment.

The issue of routing is, perhaps, the most controversial regulatory question that federal, state, and local officials have had to contend with, as it relates to passage of hazardous materials through each jurisdiction, and considerable political pressure is being applied at several levels to impose routing restrictions on carriers. If imposed, restrictions typically force a carrier to seek a more costly routing but lower-risk alternative, creating an important tradeoff between economic and safety impacts in moving hazardous goods (*11*). The following application illustrates the use of the referenced GIS hazardous materials transportation routing model in revealing this conflict.

Figure 2 shows the results of an application of the GIS routing model to a shipment from Moses Lake, Washington, to Newport, Tennessee, in which the selected criterion was to minimize shipment distance. The same analysis is shown in Figure 3, except in this case the entire weight is placed on minimizing population exposure within a 3-mi band along the preferred route (POP 3), essentially a proxy measure for minimizing risk. Through comparison of these two alternatives that represent economic and safety criteria, respectively, some in observations can be made. Most notable are the different spatial routes involved in the optimal solutions.

In a policy context, not only would the pursuit of safety suggest a different preferred route, but it would also result in the impacts' being distributed to a different set of communities and states, causing a potential for political upheaval. The more circuitous route might also be a source of objection from industry. This, in essence, reveals the controversial circumstances in which routing regulation must be evaluated (*12*).

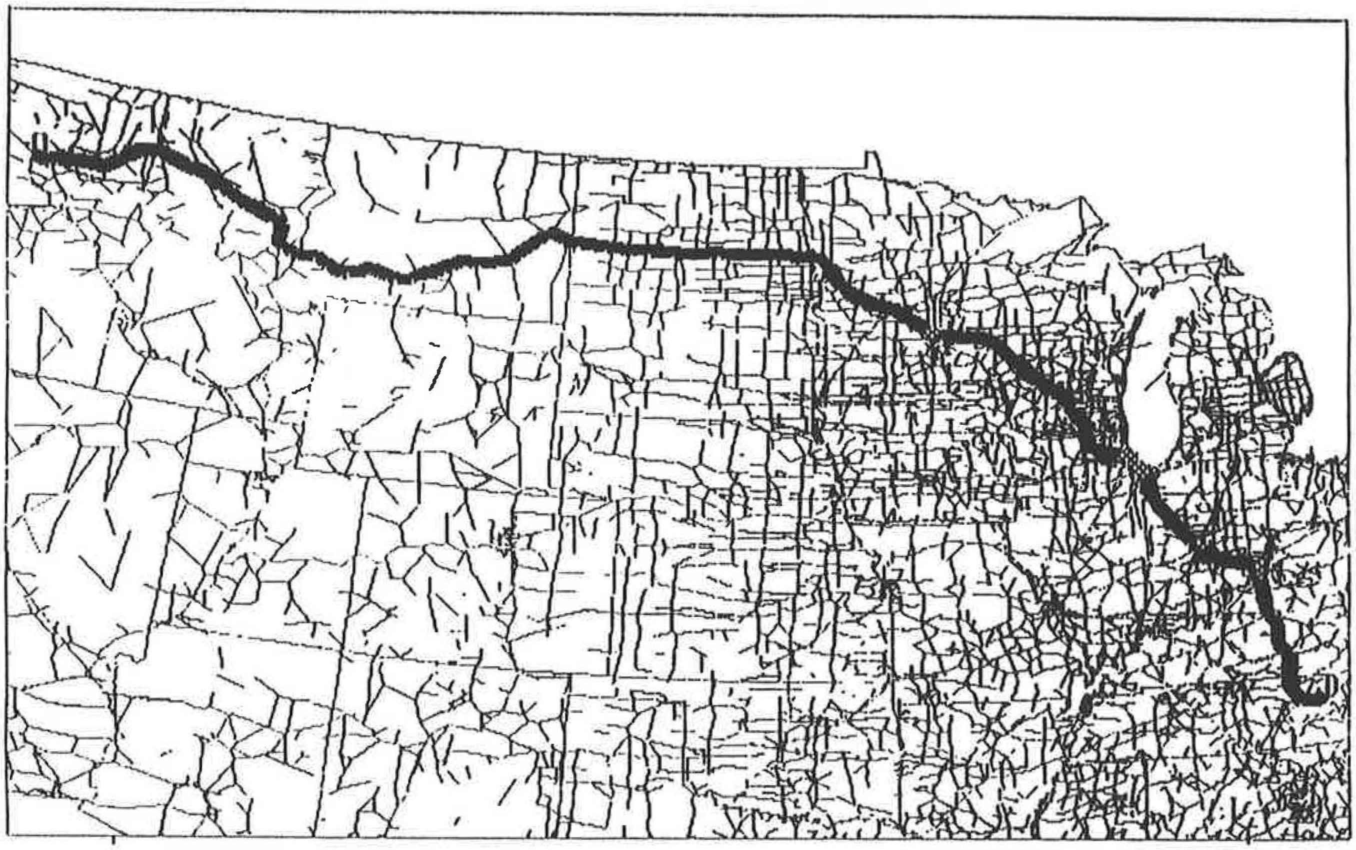
Compromise or negotiated solutions could be achieved through comparison of routing solutions prompted by the definition of different routing criteria. For example, in examining Figures 2 and 3, it appears that population exposure can be reduced by approximately 70 percent for an approximately 10 percent increase in trip distance, when moving from a totally economically based criterion preference to one in which exposure to population is the sole criterion. In both figures, several other impact measures are tabulated, so that the policy analyst can evaluate alternative routes on a multidimensional basis.

The legend used in these output tables is as follows:

- DISTANCE—total route distance (miles);
- POP_i—total route population living within i miles of the route;
- RELIABILITY—indicator of the level of operational safety on the route (formulated as a function of the inverse of the shipment accident likelihood);
- TIME—total route travel time (hours) under assumptions of uncongested, partially congested, and fully congested traffic, respectively; and
- COST—total shipment cost ($).

Other capabilities inherent in this first-generation GIS transportation routing model include the abilities to (a) zoom in or out from a geographical area, (b) label transport maps according to a choice among several descriptors (e.g., route number, segment number, segment distance), (c) select population exposure measures from bandwidths of 0.25, 0.50, 1, 3, 5, 10, and 25 mi, (d) make routing selections using criteria of minimizing travel time or accident likelihood in addition to minimizing distance or population exposure (or simultaneous consideration of multiple criteria), (e) require a shipment to pass through or avoid network segments or intersections where routing restrictions apply, (f) identify segments with outlier attribute values for a specified attribute (e.g., excessively high accident potential), and (g) define different transport network densities (e.g., Interstates only and all Interstate, state, and U.S. highways). These features permit the representation of a multitude of location-specific, hazardous materials transportation problems that agencies often confront.

Second-generation development is also underway to enhance the capability of GIS-based hazardous materials transport analysis techniques. These include (a) adding rail, marine, and intermodal transport to the routing and risk analysis system, (b) including emergency response locations in the mapping system and adding minimum emergency response time as a routing criterion, (c) including more comprehensive information on the transport network and surrounding area, such as weather data, topographic information, and location of environmentally sensitive areas, (d) inclusion of time-dependent attributes, such as assigning traffic congestion effects and interchanging employment and residential population exposure depending on time-of-day, and (e) developing chemical-



WEIGHT	(1.00)	(.00)	(.00)	(.00)	(.00)	(.00)
PATH	DISTANCE	POP .25	POP .50	POP 1	POP 3	POP 5
1	2534.97	488666	1021193	2213361	9059513	17200706

(.00)	(.00)	(.00)	(.00)	(.00)	(.00)	
POP 10	POP 25	RELIABILITY	TIME 1	TIME 2	TIME 3	COST
39027874	89786971	.9946374	2686.63	2887.38	3314.46	6975.00

FIGURE 2 Shortest distance path between Moses Lake, Washington, and Newport, Tennessee.

specific exposure measures using inputs such as wind direction and speed, temperature, physical behavior of the chemical under consideration, topography, and other relevant factors in understanding the size, shape, and movement of plume dispersion. These techniques will permit a more direct assessment of expected injuries and deaths on the basis of the toxic effects of a release.

EMERGENCY PREPAREDNESS AND EVACUATION PLANNING

As mentioned previously, another developing consideration closely related to hazardous materials routing is emergency preparedness and evacuation planning. These applications are complex because one must simultaneously monitor spill consequence, status of emergency response personnel, and availability and capacity of potential evacuation routes. Figure 4 shows these problems as defined in a GIS context for a release of hazardous cargo on the Washington Beltway. Four critical events are occurring concurrently that must be tracked and integrated for analysis purposes: (a) a spill has been reported and one or more emergency response units (with the Red Cross symbol) have been deployed and are en route to the scene, (b) a plume may be forming and spewing toxic fumes across land areas, (c) the possibility of evacuation exists and the identification of evacuation routes must be made, and (d) time is passing. Each of these issues is examined individually in the following discussion.

When a spill is reported, contact must be established with the first and ultimate responders, and these units are subsequently deployed to the scene. The identification of the appropriate response units can be identified using a GIS overlay of response unit location (with a capability attribute) onto the transportation system and location of the release site. Response times to the scene from each unit can be derived and the units with the minimum response time would be dispatched.

Plume formation depends on a number of factors related to the release, material involved, and site characteristics. As an output from an appropriate dispersion model, the plume size, shape, and direction can be overlayed onto the GIS data bases that represent the population distribution and location of environmentally sensitive areas. The number of people exposed at any given time can be determined, as well as the identification of affected schools, water supplies, etc. Most plumes contain inner portions in which the concentration, and

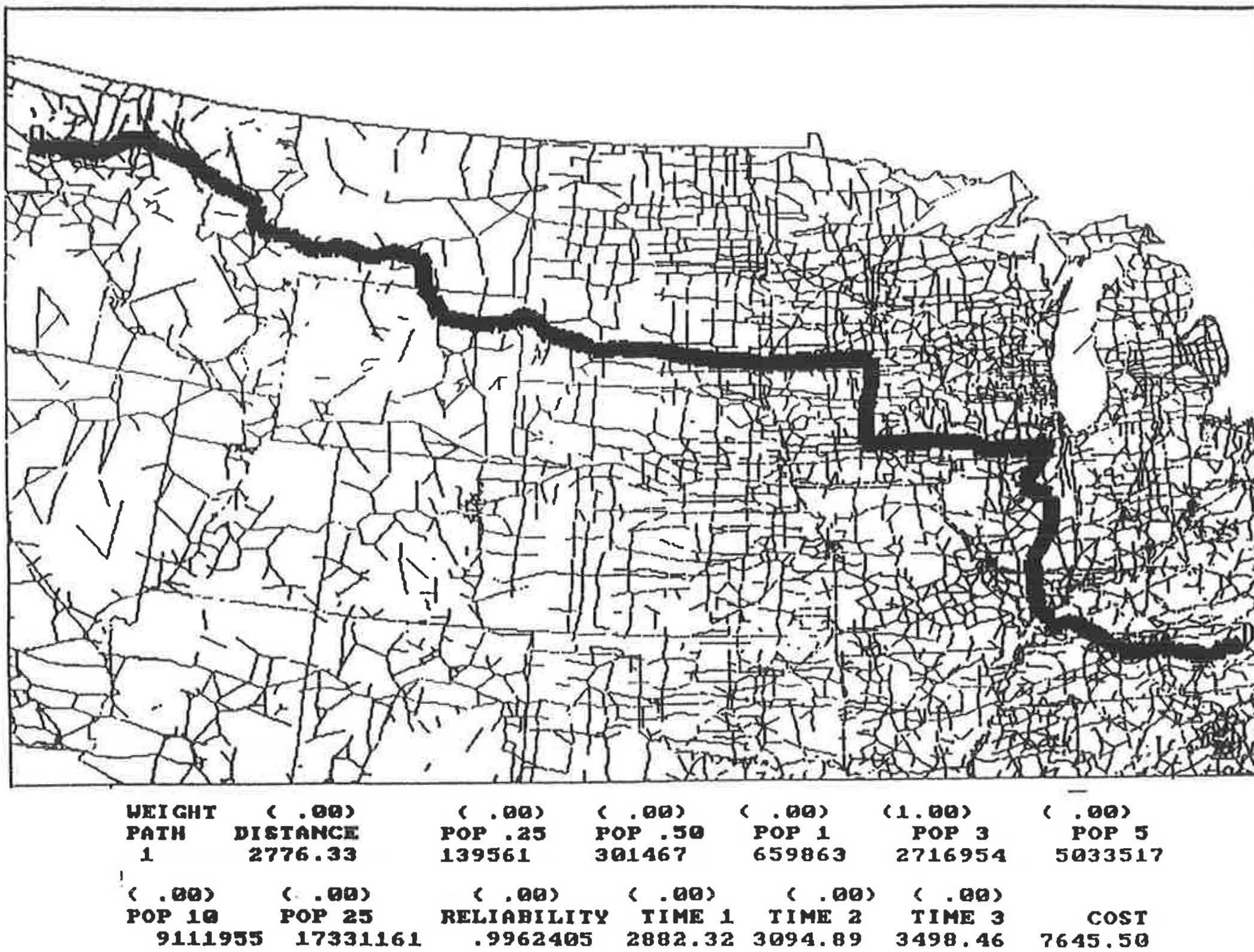


FIGURE 3 Minimum population exposure path (3-mi band width) between Moses Lake, Washington, and Newport, Tennessee.

consequently the dose to humans and wildlife, may be appreciably greater than on the outer edges of the plume. When these doses exceed the human threshold, the possibility of more serious health effects exists. Therefore, the ability to separate chemical exposure from more acute exposure that threatens human health is important and can be accommodated using the GIS. In Figure 4, separate computations are made for the population that has been exposed to a dose greater than the human threshold.

Because of the severity of the release and toxicity of the material, an evacuation may be necessary. The number of people who must be evacuated can be determined by overlaying the plume movement on the population as previously described. However, the ability of the network to accommodate evacuees depends on the capacity of the road system. Consequently, models allocating evacuees to specific evacuation routes must be developed. Moreover, the movement of the plume may be such that some potential evacuation routes may only be temporarily open until the time when the plume passes over the route in question, a condition that must be taken into consideration as well.

The passage of time makes this entire problem dynamic in nature, requiring agencies to take actions based on current, cumulative, and projected impacts across the entire duration of the release event. Significant occurrences during the event that could have a profound impact on the decision process include (a) the time at which emergency response personnel arrive at the scene, (b) the likelihood and time at which release containment can be achieved, and (c) abrupt changes in weather conditions.

The GIS approach to emergency preparedness and evacuation planning is evolving in two contexts, planning and real time. In the planning context, historical weather conditions can be used to form joint probability distributions of wind direction, speed, and temperature for the purpose of deriving probable weather scenarios for a particular transport segment. GIS release scenarios can then be subsequently simulated so that specific action plans are developed for each weather scenario in advance of when a spill might occur. These action plans could be maintained on file for reference should an incident occur, and given knowledge of the prevailing weather conditions at the time.

Real-time GIS analysis activities may be appropriate to monitor a shipment's location or to intervene in the decision process if and when a significant occurrence takes place. The technology for generating real-time information takes on two principal forms as it relates to this problem. Sensors that record up-to-the-minute observations of weather conditions can be strategically placed (with geographical location coordinates known) so that prevailing characteristics are immediately

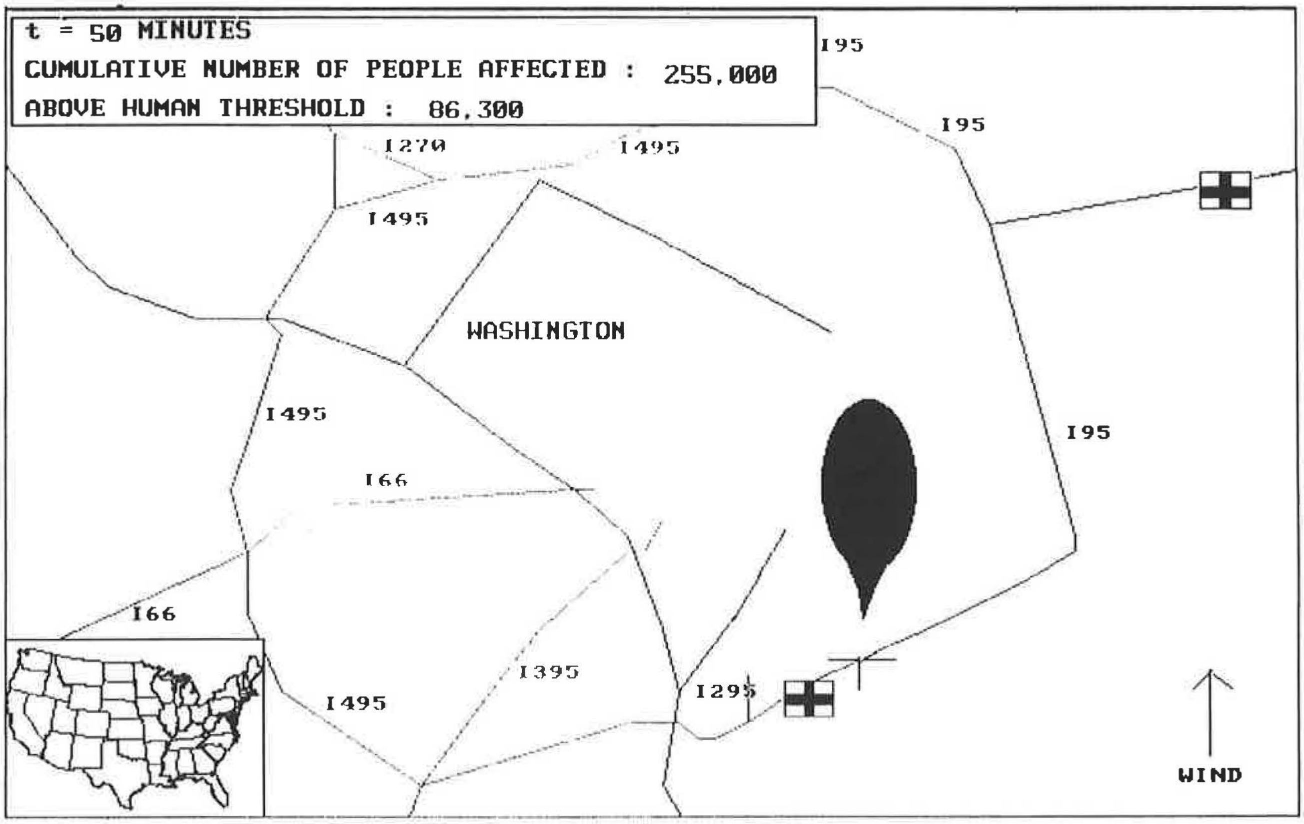


FIGURE 4 Consequences of and response to a release from a hazardous materials highway shipment.

recognized and can be used as model inputs in managing emergencies. Some chemical manufacturing plants, for example, are already using this technology. Real-time shipment monitoring based on GIS locational coordinates is also taking place through the use of satellite tracking and ground-based navigational systems. With increasing concern over managing transport safely and efficiently, one can expect the use of real-time GIS data collection to become more prevalent in the next decade.

Another area fertile for development is the overlap of topography on the transportation system. Plumes behave quite differently when terrain acts as a barrier to dispersion. GIS digital elevation files are available from the U.S. Geological Survey (USGS) to use in this context. However, in terms of using this information for application purposes, the problem becomes more complex because of the three-dimensional nature of plume formation. Methods for introducing topographic considerations into the emergency preparedness and evacuation planning context are beginning to be explored. Figure 5 shows current efforts to take digital elevation files and to portray the three-dimensional nature of the information. The files can be viewed from several different angles by rotating the axis of the images, as noted in the upper left-hand corner of the figure.

GIS TECHNOLOGY QUESTIONS

As the field of transportation is inherently geographic, GIS offers concepts and a technology with considerable potential for achieving dramatic gains in efficiency and productivity for a multitude of transportation applications. By its nature, managing the safe transport of hazardous materials requires integration of the full realm of issues involving the design and implementation of a GIS framework. As noted earlier, this is the case because comprehensive transportation risk assessment requires the collection and management of detailed attribute information on highway network geometrics and utilization, as well as spatial information on the surrounding land use, including population, topography, geology, and the location of special facilities. However, a multitude of methodological questions that focus on the underpinnings of GIS technology accompany such a comprehensive GIS applications environment. The principal concerns are presented in the following discussion.

Data Organization and Structure

The data bases used in the GIS application and methods by which multiple data bases are integrated can be constrained by the manner in which individual attributes are defined and measured. For example, the data collected to describe one highway network attribute may be measured at mileposts and assigned continuously along the highway, whereas another attribute may be measured according to fixed control sections. The resulting computer representation for each attribute is likely to be different, yet this information must be accurately merged where a GIS application requires access to both data elements (*4*). As mentioned previously, the use of dynamic

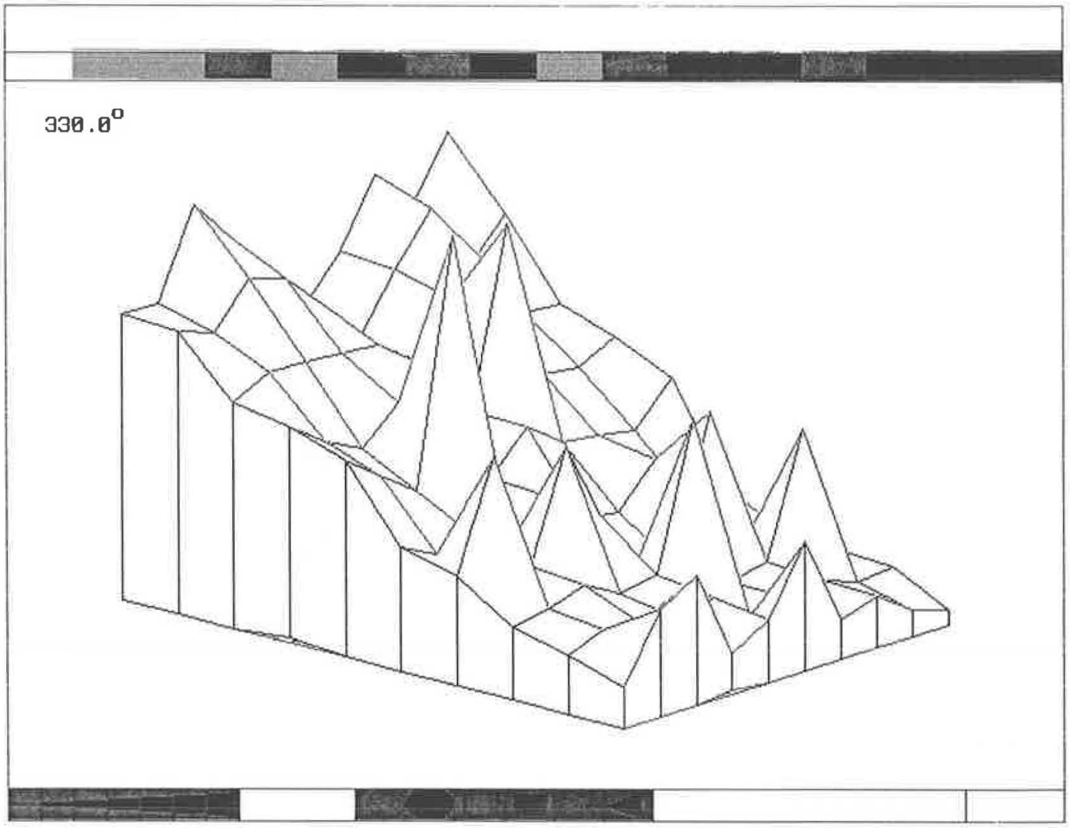


FIGURE 5 Digital elevation file for plume formation.

segmentation to create interpolated segments and identification of points along a string is a key to resolving these problems.

Map Scale

The scale of the map used for data capture affects the level of detail that one is able to extract from the map. A comparison of the USGS 1:24,000 scale map versus the 1:62,500 scale map shows, for example, additional levels of information because of the larger scale. Multiple thematic overlays required for hazardous materials transportation analyses could involve the use of maps with different scales' being transformed into the same base scale. However, this process does not translate to creating a GIS that has the same level of information throughout all the GIS overlays.

Location Reference System

Different databases may not possess the same location reference system. Common transportation reference methods include milepoints, reference points, feature based, and logmile systems (*13*). Latitude-longitude, state plane, and universal transverse Mercator are traditional reference systems for environmental studies. When GIS data bases to be overlayed use different location reference systems, the transformation between coordinate systems must be accomplished at an acceptable level of accuracy.

Data Conversion and Maintenance

Many agencies possess specialized digital data bases that are in spatial formats or that could be organized in such a manner. For example, Bureau of the Census files; digital elevation models from the USGS; and digital data from local, county, and state agencies offer the wise user a variety of sources of information that can be integrated into a GIS environment. Standard exchange formats must be used to expedite the transfer and useability of the data captured and archived at various locations (*14*).

From the standpoint of maintaining information so that it stays current, rather than attempting to include all data elements in one mammoth data collection effort, a better approach would be to establish a good cross-referencing system, with the responsibility for updates remaining with the agency that has jurisdiction for collecting this information. For example, updated accident rates could be derived interactively by tapping directly into accident counts, road inventory data, and volumes maintained by different agencies, but available through a common referencing system.

Data Accuracy/Quality

Inherent and operational errors contribute to a reduction in the accuracy of data contained within a GIS (*15*). Inherent error is present in the source documents and it is fair to say that every map contains inherent error based on the nature of the map projection, construction techniques, specifications,

and symbolization of the data. Operational error is introduced during the process of data entry and occurs throughout data manipulation and spatial modeling. Multiplicative error effects can arise when operational errors are introduced where inherent errors previously exist.

The major concern of these GIS issues as they relate to hazardous materials transportation analyses is the extent to which they impact the accuracy of problem presentation and, consequently, the policy actions that emanate from use of a GIS decision support tool. As more scientific effort is placed on the development of national standards to enhance the quality of information as well as standardization in the definitions and references used, spatial data transfer specifications, and cartographic features (*14*), these problems will be better understood and hopefully resolved. In the meantime, however, one should maintain perspective by recognizing that inherent and operational errors exist today in traditional approaches to transportation analyses. Hence, the advent of a GIS actually provides an opportunity to achieve a greater level of resolution and accuracy than available heretofore.

CONCLUSION

This discussion has attempted to focus on the merits of applying GIS concepts and technology to applications involving the transport of hazardous materials. Three principal areas of policy concern, those of routing, emergency preparedness, and evacuation planning, were singled out for consideration. Characteristic of hazardous materials transportation analyses is the measurement of interactive effects between the transport system and its surrounding land use. Consequently, GIS concepts present a promising approach for problem representation, algorithmic solution development, and impact prediction.

On the basis of the successful implementation of first-generation routing models and progress in designing GIS-based methods in support of emergency preparedness and evacuation planning, it appears that GIS will significantly extend the frontier of hazardous materials transport research and practice. Developments to date have already introduced important advances to the applications environment, and this field of development will continually evolve as improvements are made to GIS data collection techniques and accessibility.

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REFERENCES

1. Office of Technology Assessment, U.S. Congress. *Transportation of Hazardous Materials.* OTA-SET-304, U.S. Government Printing Office, Washington, D.C., 1986.
2. M. D. Abkowitz, G. List, and A. E. Radwan. Critical Issues in the Safe Transport of Hazardous Materials. *Journal of Transportation Engineering*, Vol. 115, No. 6, 1989, pp. 608–629.
3. H. J. Simkowitz. GIS: Technology for Transportation. *Civil Engineering*, June 1989, pp. 72–75.
4. T. L. Nyerges and K. J. Dueker. *Geographic Information Systems in Transportation.* FHWA, U.S. Department of Transportation, 1988.
5. K. J. Dueker. Geographic Information Systems and Computer-Aided Mapping. *Journal of American Planning Association*, Vol. 53, No. 3, Summer 1987.
6. D. H. McClain. Two Dimensional Interpolation from Random Data. *The Computer Journal*, Vol. 19, No. 2, 1974, pp. 178–181.
7. D. H. McClain. Drawing Contours from Arbitrary Data Points. *The Computer Journal*, Vol. 17, No. 4, 1971, pp. 318–324.
8. R. C. Durfee and P. R. Coleman. *Population Distribution Analyses for Nuclear Power Plant Siting.* Report Nos. NUREG/CR-3056, ORNL/CSD/TM-197. Prepared for U.S. Nuclear Regulatory Commission by Oak Ridge National Laboratory, Oak Ridge, Tenn., 1983.
9. P. J. Green and R. Sibson. Computing Dirichlet Tesselations in the Plane. *The Computer Journal*, Vol. 21, No. 2, pp. 168–173.
10. D. R. Shier. Iterative Methods for Determining the K Shortest Paths in a Network. *Network*, Vol. 6, 1976, pp. 205–229.
11. M. D. Abkowitz and P. D. M. Cheng. A Risk/Cost Framework for Routing Truck Movements of Hazardous Materials. *Accident Analysis and Prevention*, Vol. 20, No. 1, 1988, pp. 39–51.
12. M. D. Abkowitz and P. D. M. Cheng. A Bi-Criterion Approach to Selecting Preferred Truck Routes for Hazardous Materials Shipments. Working Paper, Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, Tenn., 1989.
13. D. Fletcher. Modelling GIS Transportation Networks. In *Proc., URISA 1988*, Los Angeles, Calif., Vol. 2, 1987, pp. 84–92.
14. Digital Cartographic Data Standards Task Force. Draft Proposed Digital Cartographic Data Standards. *The American Cartographer*, Vol. 15, No. 1, 1988, pp. 9–140.
15. S. J. Walsh, D. R. Lightfoot, and D. R. Butler. Recognition and Assessment of Error in Geographic Information Systems. *Photogrammetric Engineering and Remote Sensing*, Vol. 53, No. 10, 1987, pp. 1423–1430.

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Hydrologic Geographic Information System

EDWARD J. VANBLARGAN, ROBERT M. RAGAN, AND JOHN C. SCHAAKE

A geographic information system (GIS) was developed as a practical tool to streamline some of the operational problems faced by many agencies dealing with hydrologic analysis. Conventional manual analysis requires significant time and expertise. The expert system developed will automatically generate the drainage area and streamflow hydrograph for a watershed. The system is made feasible by using digital data that are available commercially for the entire United States. The data bases developed contain gridded elevation values and stream location coordinates. The software developed integrates the digital data with some unique terrain analysis techniques and fundamental hydrologic methods. The only user input required is the outlet location of the watershed. Internally, the program creates a gridded network of flow paths across the basin. By analysis of this gridded network, the drainage area and hydrologic information are defined. The system was tested on a variety of basins and compared with some standard manual methods. The geographic information system was able to reproduce the manual methods with tremendous savings of time and cost. Overall, the system is a practical tool for any agency that must consider hydrologic analysis of many areas.

Hydrologic analysis is a subject of interest to various scientific disciplines. Two basic steps done prior to any final hydrologic analysis are defining the basin area and estimating hydrologic model parameters. The conventional approach for deriving drainage area and model parameters involves significant time and expertise. In a recent survey, two frequently mentioned constraints to use of hydrologic models were inadequate time and lack of appropriate data (*1*). Because of the time and fiscal constraints faced by many agencies, an approach is needed to reduce the level of "manual effort" and rely on expert system concepts to optimize the contribution from "mature hydrologic expertise." Geographic information system (GIS) technology has been explored as a potentially fast expert system approach to obtaining various hydrologic information (*2,3*). The emergence of readily available, digitized data has made GIS especially feasible. Also, terrain analysis techniques have evolved to automatically "grow" drainage networks using gridded elevation data (*4,5*). Although previous studies produced encouraging results for GIS application, many areas still need investigation. Hydrology-oriented GISs are often constrained by a lack of terrain analysis capability and by requiring the user to digitize the input data. Conversely, most terrain analysis techniques do not fully couple with a hydrologic model. Also, research has suggested that constraining the elevation data analysis with digitized stream data could improve results (*6*).

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OBJECTIVE

The goal of this research was to develop a practical GIS for automatic delineation of a watershed area and estimation of hydrologic parameters. The specific objectives were to

1. Use commercial digital data, available nationwide, to minimize user input;
2. Develop an enhanced terrain analysis method using elevation and stream data;
3. Use a physically based modeling strategy that could be used on any type of basin; and
4. Evaluate results from the GIS against those obtained by conventional manual methods.

GIS DEVELOPMENT

Two essential cartographic data bases were acquired, covering the entire United States, that contained elevation and stream location data. The digital elevation (DEM) data were amassed by the Defense Mapping Agency (DMA) using 1:250,000 topographic maps. The DMA file contains a regular matrix of elevation values with a grid spacing of 3 arc-sec. However, for this study the data were reduced to a spacing of 30 sec of latitude and longitude. Thus the grid resolution is 0.5 nautical mi in the latitude direction. The spacing distance in the longitude direction is adjusted by the cosine of the latitude.

The stream data were obtained from the EPA River Reach file, which was developed from maps with a scale of 1:500,000. The EPA file contains vectors defining stream channel locations in latitude and longitude coordinates. Using the original file, another stream file containing the topologic connectivity of the stream network was created.

The GIS was constrained to use data that were available and affordable for the entire nation. Since this study was initiated, finer resolution DEM and stream data have become available from the U.S. Geological Survey (USGS). Although finer data were not used in this study, the GIS was developed with the capability to accommodate data of any resolution. Although concepts and obstacles from previous works were addressed to build the GIS, the software for the system was written specifically for it. Figure 1 shows a schematic of the GIS. The Tioga River near Mansfield, Pennsylvania, was used as an example to illustrate important steps in the methodology. The only user input required is the outlet location in latitude and longitude. Nearby stream data, from the EPA file, are used to properly register the outlet and define a computationally efficient analysis window (see Figure 2). The stream vectors are then rasterized and assigned to grid cells.

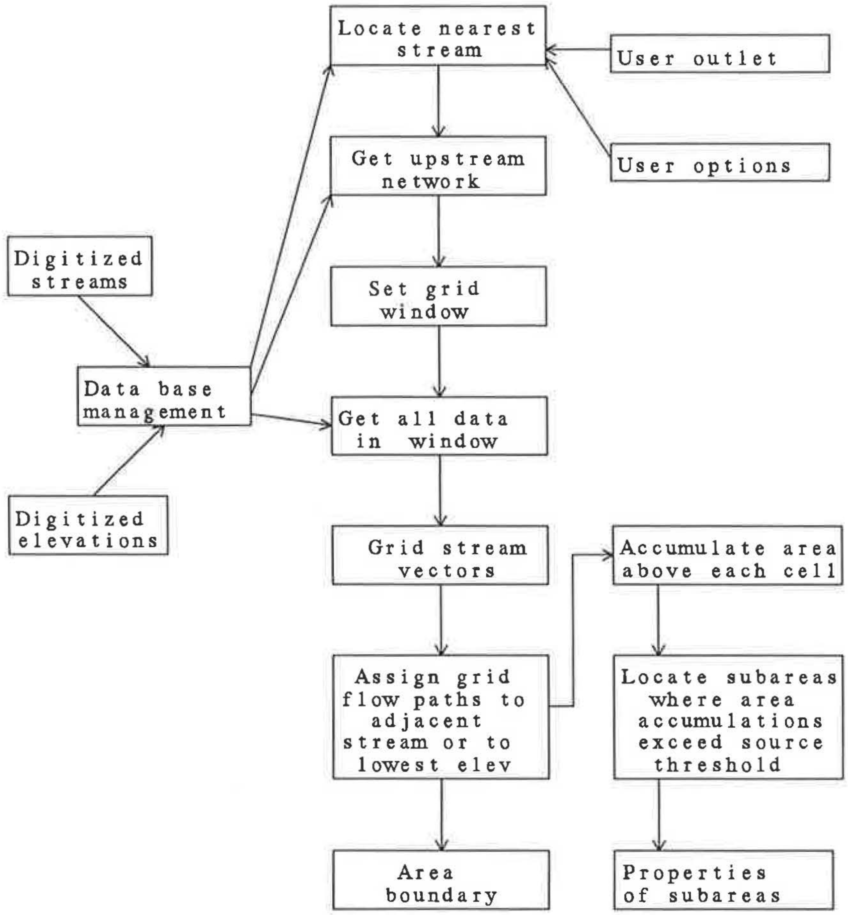

FIGURE 1 Flowchart of the GIS program.

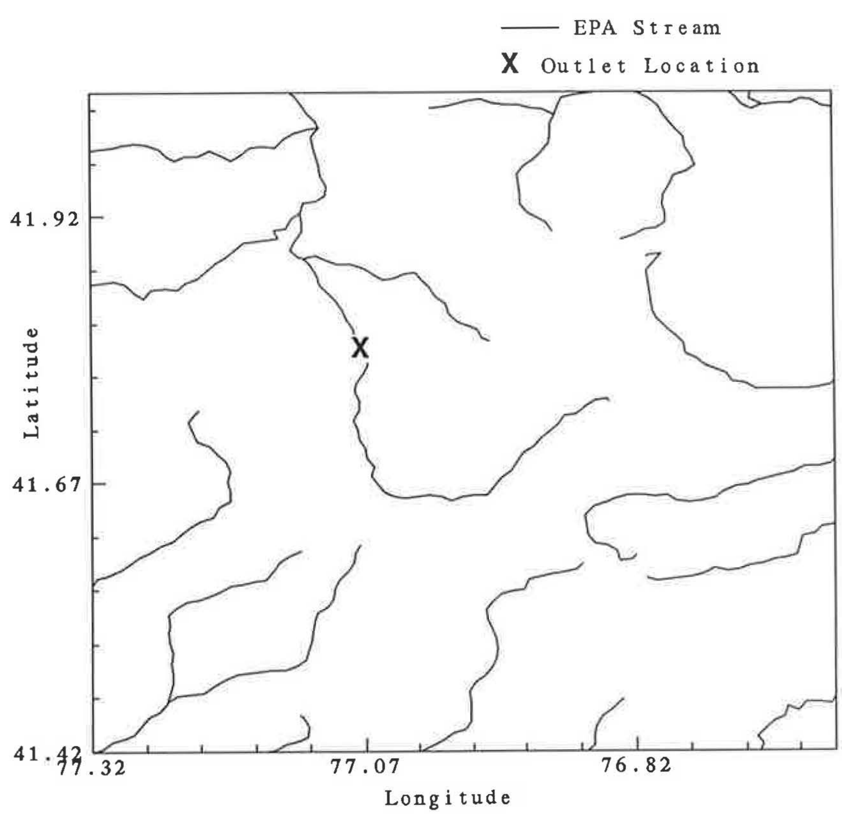

FIGURE 2 Map showing stream data and outlet location for example basin.

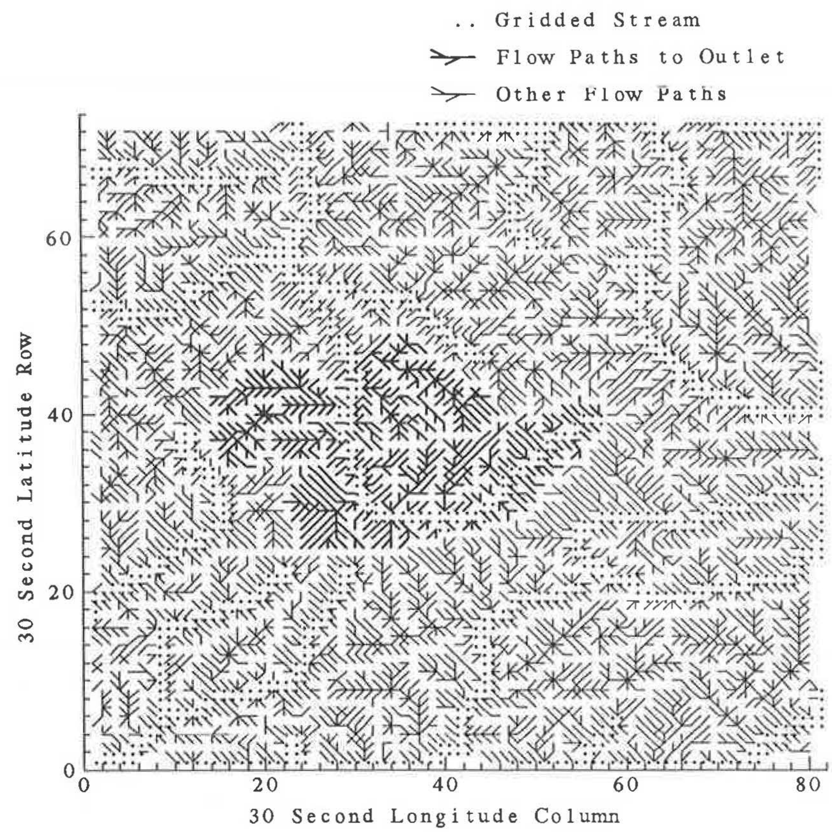

FIGURE 3 Gridded streams and flow path directions from terrain analysis for example basin.

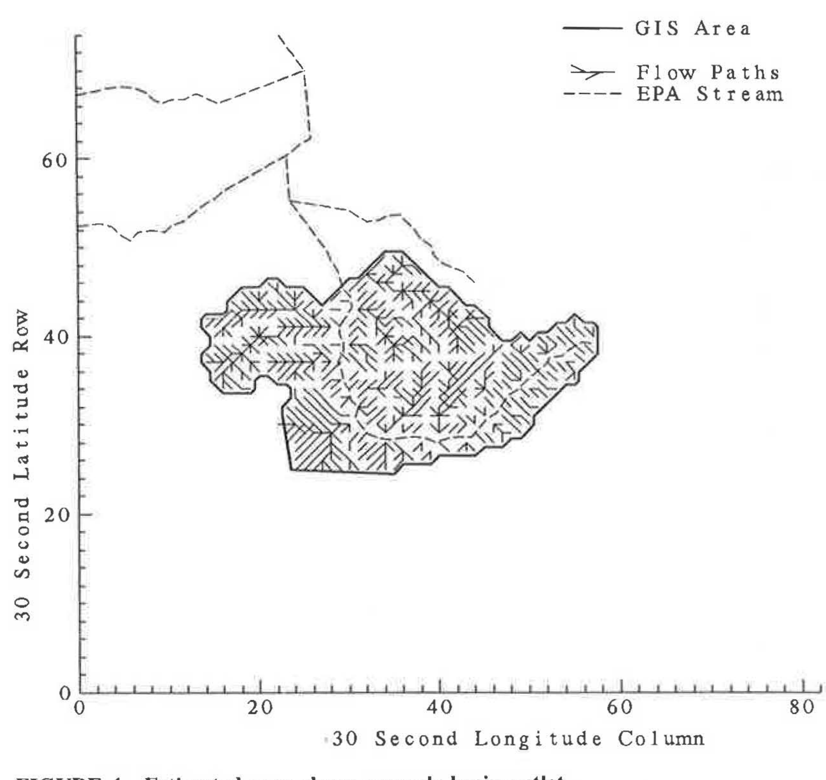

FIGURE 4 Estimated area above example basin outlet.

The flow direction of every grid point is assigned on the basis of steepest descent of the elevation data for the eight adjacent neighbors (see Figure 3). However, the elevation analysis is enhanced by letting cells drain to any adjacent stream cells instead of its lowest neighbor. The logic also contains numerous decision rules for resolving sinks, which are points lower than all surrounding neighbors. The topologic tree of grid cells flowing to the outlet is traced from, and the watershed boundary can be defined from, this flow network (see Figure 4).

The area draining to each grid cell is accumulated along with the length and slope of the cell's flow path. The subarea drainage network is defined by accumulating the area flowing to any point and locating subarea outlets at points exceeding a minimum source area (see Figure 5). In addition to the watershed boundary coordinates, the output consists of a file with hydrologic information for each subarea (see Table 1).

The final process is to derive the widely used unit hydrograph model from the subarea file (see Figure 6). The physically based strategy outlined by Siebach (*7*) was adopted for this purpose. The strategy uses channel cross sections estimated by the geomorphic relationships of Dunne and Leopold (*8*), along with several standard hydrologic and hydraulic equations. Subareas are sorted according to travel time, which is based on flow velocity computed with Manning's equation. Then travel times and drainage areas are summed to generate a time-area curve. The time-area curve is coupled with linear storage routing to generate a unit hydrograph. The unit hydrograph model can then generate a complete streamflow hydrograph for any given storm.

RESULTS

A prototype area was selected to test the capabilities of the GIS. Thirty-three test basins, from 50 to 1,500 mi^2, were selected throughout the mid-Atlantic area (i.e., from New York to Virginia). The GIS was used to automatically delineate the drainage area and generate peak flows for two storm events in each basin. For comparison, flows were also generated using conventionally derived unit hydrographs used by the National Weather Service (NWS).

When compared to published USGS drainage areas, the average absolute error in GIS-derived area was 5 percent with a standard deviation of 6 percent (see Figure 7). Practically speaking, the drainage area errors were quite low and acceptable. The low errors are somewhat surprising considering the coarse resolution of the DEM data. One reason for the GIS success was the use of stream data in the terrain analysis. By degrading the stream data, it was found that errors increased up to 30 percent when no streams were used (see Figure 8).

The area errors tend to decrease in nonlinear fashion and become less variable as the basin size increases, especially on basins greater than 150 mi^2. Similar to the findings of previous studies, it was found that errors generally increased with grid size (*9*). Thus, it appears that application of the GIS to basins smaller than the test basins should use finer-resolution DEM data.

For the hydrograph simulation, errors in the peak flow were obtained by comparing estimated flows with gauged observations. Peak flow errors were computed for the conventional NWS methods as well as for the GIS. The average peak errors for the GIS were 28 percent and 3 hr for the peak flow and time to peak (see Table 2). The errors using the NWS techniques were 28 percent and 4 hr. More important, there were no significant differences between the GIS and conventional methods. Deviations from actual observations for either method were probably because of limitations in estimating rainfall over large basins.

The total effort to analyze all of the test basins using the GIS was approximately 30 min. On the other hand, the conventional manual approach to define the area and parameters required several years' effort. Also, the conventional unit hydrographs were calibrated with historic storm events making them, in theory, an optimal function.

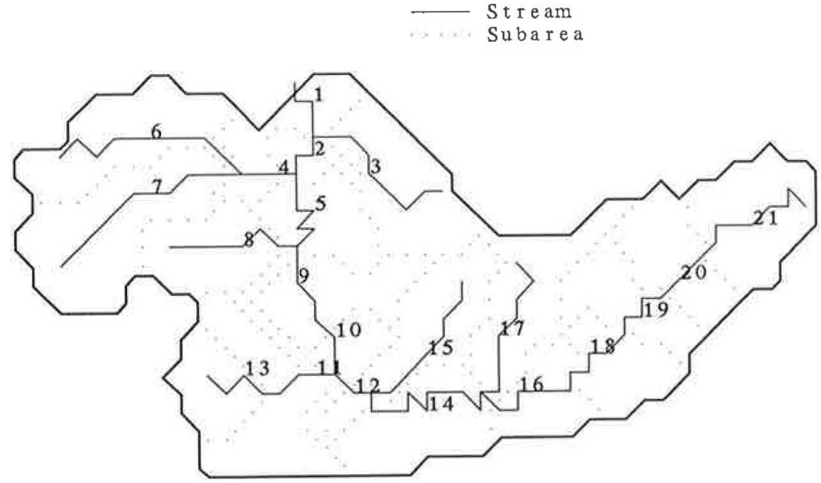

FIGURE 5 Definition of subareas and estimated stream channels for example basin using subarea threshold of 5 mi^2.

TABLE 2 AVERAGE HYDROGRAPH ERRORS FOR ALL BASINS FOR THE GIS AND CONVENTIONAL NWS METHODS

	Peak Flow (% Error)		Time to Peak (hours)		Peak Stage (feet)	
	GIS	NWS	GIS	NWS	GIS	NWS
¦Average¦	28	28	3	4	1.0	1.0
Std Dev	23.9	23.9	3.0	3.3	2.1	2.0
Comparison of Paired Observations ¦ GIS-NWS ¦ :						
Average	0.05		-0.44		-0.09	
Std Dev	16.86		2.77		1.10	
t-statistic	0.02		-1.21		-0.61	

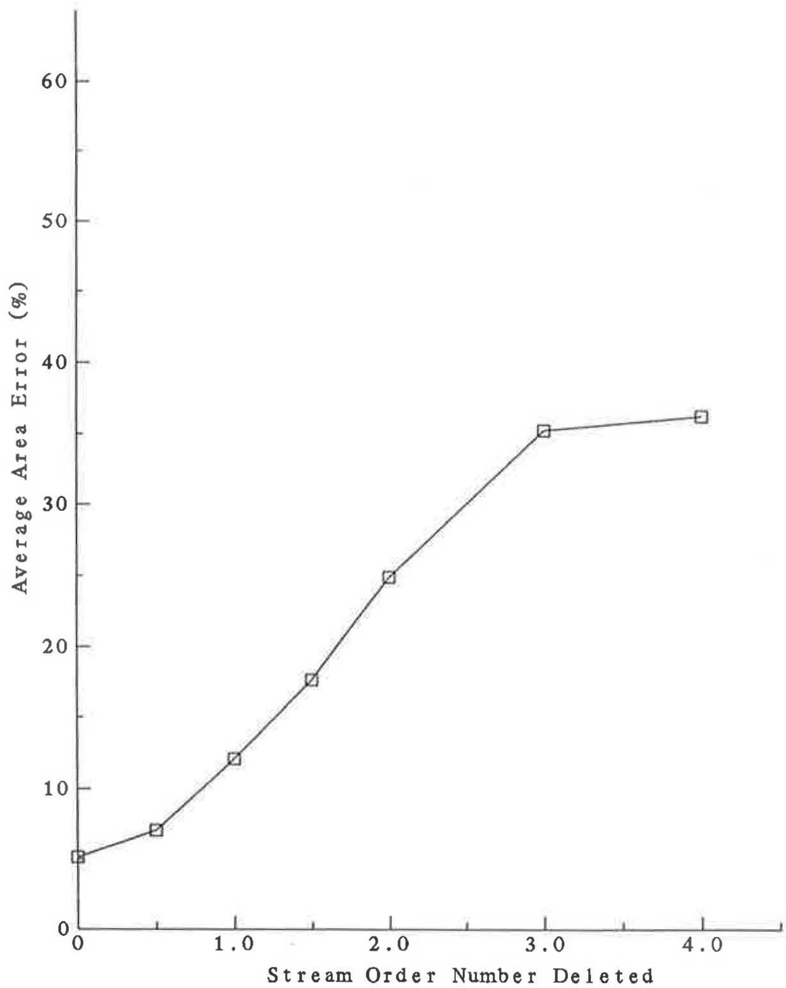

FIGURE 8 Change in average drainage area errors as digitized streams are deleted.

CONCLUSION

Overall, the study showed that a GIS could be used as a cost-effective alternative to conventional manual methods. The system developed is a convenient tool to define watershed boundaries and perform hydrologic analysis using sound physical principles and easily obtained digital data. In fact, peak flows generated by the GIS differ little from those produced with conventional, event-calibrated methods.

The GIS performed quite well at reproducing the drainage area. Also, the unique use of digitized stream data significantly improved the watershed growing capability. The coarse digital data used in the study appear adequate for rather large areas. However, finer-resolution elevation data would probably give improvements on smaller basins.

In addition to comparing favorably to the conventional methods, the GIS has several added advantages. The physical model used by the GIS is specially useful for ungauged areas where historic data are not available for conventional calibration. The biggest advantage is that information obtained manually could require years to process, whereas the GIS generates information in a matter of minutes.

REFERENCES

1. T. A. Austin. Utilization of Models in Water Resources. *Water Resources Bulletin*, Vol. 22, No. 1, 1986, pp. 49–56.
2. J. M. Hill, V. P. Singh, and H. Aminian. A Computerized Data Base for Flood Prediction Modeling. *Water Resources Bulletin*, Vol. 23, No. 1, 1987, pp. 21–27.
3. A. T. Silfer, J. M. Hassett, and G. J. Kinn. Hydrologic Modeling of Small Watersheds: The TINFLOW Model. *Proc., Engineering Hydrology Symposium, ASCE, Williamsburg, Va.*, 1987, pp. 545–550.
4. L. E. Band. Topographic Partition of Watersheds with Digital Elevation Models. *Water Resources Research*, Vol. 22, No. 1, 1986, pp. 15–24.
5. S. K. Jenson and J. O. Domingue. Extracting Topographic Structure from Digital Elevation Data for Geographic Information Systems Analysis. *Photogrammetric Engineering and Remote Sensing*, Vol. 54, No. 11, 1988, pp. 1593–1600.
6. J. K. Sircar. *Computer Aided Watershed Segmentation for Spatially Distributed Hydrologic Modeling*. Ph.D. dissertation, Department of Civil Engineering, University of Maryland, College Park, 1987.
7. P. R. Siebach. *The Integration of Desk Top Image Processing and Geographic Information Systems for the Operation of HEC-1*. M.S. thesis, Department of Civil Engineering, University of Maryland, College Park, 1987.
8. T. Dunne and L. B. Leopold. *Water in Environmental Planning*. W. H. Freeman and Co., San Francisco, Calif., 1978.
9. J. D. Fellows and R. M. Ragan. The Role of Cell Size in Hydrology Oriented Geographic Information Systems. IAHS Publication 160, *Proc., Hydrologic Applications of Space Technology*, Cocoa Beach, Fla., 1986, pp. 453–460.

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Evaluation of GIS Workstation Performance Within a Distributed Network Environment

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As part of the initial development phase of GIS implementation at the North Carolina Department of Transportation, a GIS workstation evaluation was carried out from December 1, 1988, to April 30, 1989. The primary purpose of the evaluation was to test the performance of graphics workstations within a distributed network environment. The workstation evaluation tested hardware, network capabilities, and operating systems for a transportation GIS (GIS–T). During the project, workstation vendors were selected; criteria were developed for the testing of workstation performance; performance tests were executed; and recommendations for GIS workstation procurement were made. The methods used to evaluate graphics workstation performance for a statewide transportation GIS are outlined. Workstation products from three vendors, International Business Machines (IBM), Digital Equipment Corporation (DEC), and SUN Microsystems were evaluated. Results of the evaluation are presented in the context of workstation performance tests, network capabilities, operating systems, vendor support, and workstation prices. Recommendations for workstation procurement specific to the needs of the North Carolina Department of Transportation are made.

A geographic information system (GIS) workstation evaluation for the North Carolina Department of Transportation (NCDOT) was performed as part of an initial development phase of GIS implementation. The evaluation took place from December 1, 1988, to April 30, 1989. The objectives of the workstation evaluation were to model proposed physical and operational computer environments, evaluate graphic workstation performance, and formulate recommendations for hardware procurement for a GIS for transportation (GIS–T).

Technical information presented in this paper was gathered from a variety of sources, and because of the dynamic nature of the hardware and software markets, is subject to change without notice. This evaluation was performed under a strict set of guidelines specific to one agency's needs and requirements at a particular point in time, and the recommendations detailed in the evaluation are based on those constraints. These recommendations are not meant as a general endorsement of any products and should not be construed as such; rather, the overall goal of this paper is to present in an actual context the methodological framework used in performing a GIS workstation evaluation.

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The workstation evaluation tested hardware, network capabilities, and operating systems for a GIS–T. The GIS software used in this evaluation was Environmental Systems Research Institute's (ESRI's) ARC/INFO software. The primary tasks accomplished during the initial phase of GIS implementation at NCDOT consisted of the following: (a) selection of workstation vendors, (b) development of workstation performance test criteria, (c) execution of workstation performance tests, (d) evaluation of performance test results, and (e) recommendations for GIS workstation procurement.

The evaluation of workstation performance was based on a number of criteria, including the speed with which workstations responded to various functions, networkability, analysis of operating systems, vendor support, system problems, and the formal and informal documentation of system performance by members of the NCDOT GIS development team and GIS delegates.

GIS WORKSTATION VENDORS

GIS workstation vendors were selected on the basis of criteria established by NCDOT's GIS Implementation Committee between July and September 1988:

1. The vendor must have been ported to ESRI's ARC/INFO software at the beginning of the evaluation period;
2. The vendor must be recognized as a national leader in GIS technology and must have a strong financial portfolio;
3. The vendor must be able to support the pilot project and ensuing statewide implementation of a transportation GIS in North Carolina; and
4. The vendor must have suitable existing GIS workstation products available for testing.

After considerable review, three vendors were chosen to participate: International Business Machines Corporation (IBM), Digital Equipment Corporation (DEC), and Sun Microsystems. These vendors were chosen because they met the selection criteria outlined above.

The vendors were requested to develop proposals for low- and high-end GIS workstation solutions to meet NCDOT's GIS needs at various organizational levels (e.g., state, division, and field). Throughout most of the evaluation period, the GIS laboratory contained five workstations from the three selected vendors. All were networked together on an ethernet local area network (LAN) for most of the evaluation period.

Vendors were allowed to bring in additional equipment during the evaluation period as new workstations were announced. Later during the testing period, DEC brought the VS3100 into the GIS laboratory for evaluation. At the end of the evaluation period, SUN Microsystems made two new workstations available for testing. Following is a list of the workstations that were evaluated by the GIS Implementation Committee:

Vendor	*Workstation*
IBM	RT-PC MODEL 125
	RT-PC MODEL 135
DEC	VS3200
	VS3100
SUN Microsystems	4/110
	386i/250
	4/60
	4/330

GIS WORKSTATION TESTING CRITERIA

In August 1988, the GIS Implementation Committee developed a series of testing criteria to test the performance of graphics workstations in executing various tasks and to evaluate the operating systems and networkability of each workstation. The price of each workstation was also considered.

In order to evaluate the performance of the graphics workstations, a set of benchmark tests was carried out. A series of Arc Macro Language (AML) programs was written to determine the performance of commonly used ARC/INFO commands on various workstations.

Following is a brief description of the ARC/INFO commands that were used in the AML performance benchmarking. These commands were chosen as representative of many tasks: editing, topological construction, graphic generation, data conversion, overlay analysis, and attribute file management. These tasks generally would be carried out on a daily or weekly basis within a GIS–T at NCDOT. They place a variety of demands on a workstation and have been broken down into three functional classes:

Input/Output Intensive Processes

- *ADDITEM* adds a new item to an existing INFO attribute file
- *APPEND* combines features from two or more coverages into a single coverage.
- *COPY* duplicates a coverage. All information associated with the coverage is duplicated.
- *DESCRIBE* summarizes information about an ARC/INFO coverage.
- *DISSOLVE* merges adjacent polygons that have the same value for a specified item.
- *DLGARC* converts a digital line graph (DLG) file either in standard or optional format into a set of ARC/INFO coverages.
- *EXPORT* converts an ARC/INFO coverage into an ARC/INFO interchange file.
- *GENERATE* uses flat ASCII files containing *X* and *Y* coordinates to produce an ARC/INFO coverage.
- *IMPORT* creates a coverage, INFO file, or flat file from an ARC/INFO export file.
- *KILL* deletes a coverage or specified INFO file.
- *LABELERRORS* checks a coverage for errors in polygon labeling.
- *NODEERRORS* checks a coverage for errors at the intersections of arcs.
- *PLOT* creates an ESRI plot file to be sent to a plotter for plotting.
- *UNGENERATE* converts an ARC/INFO coverage into a flat ASCII file containing *X* and *Y* coordinates.

CPU and Input/Output Intensive Processes

- *BUILD* builds topology between arcs and generates attribute files for polygons, lines, or points.
- *CLEAN* checks an ARC/INFO coverage for duplicate lines, breaks up arcs (lines) whenever they cross, snaps together arcs within specified tolerance, deletes arcs under a certain length, and builds topology between arcs.
- *IDENTITY* computes the geometric intersection of two coverages. All features that overlap are preserved.
- *INTERSECT* computes the geometric intersection of two coverages. Only those features in the area common to both coverages will be preserved.

Graphics Output Intensive Processes

- *ARCPLOT* displays a coverage to a graphics terminal screen using ARCPLOT commands.
- *DRAW* displays a coverage to a graphics terminal screen.

In addition to the application benchmarks just described, a number of industry standard performance benchmarks, which pertain specifically to hardware, were examined. Among these are MIPS (millions of instructions per second), Linpack, Dhrystone, and vector draw speeds. The Linpack benchmark involves the use of linear equations that test the performance of floating point computations. The Dhrystone benchmark measures integer performance. At the present time, there are no industry-set standards for vector draw speeds.

GIS WORKSTATION PERFORMANCE TESTS

The results of all AML performance tests were recorded for each workstation. Elapsed times for the performance tests varied significantly among the workstations. Table 1 presents the elapsed time for all processes.

Of the initial five workstations tested, the SUN 4/110 was consistently the fastest in all test categories. It was followed by three workstations that yielded results that were quite similar to each other. In terms of overall averages, the IBM RT 135, VS3200, and SUN 386i were fairly comparable, although the IBM RT 135 was slightly faster than the other two. The IBM RT 125 was much slower than all other models. Figure 1 shows the total time taken for each workstation to perform the AML performance tests and also shows the breakdown by functional classes.

TABLE 1 ARC/INFO WORKSTATION PERFORMANCE TESTING, ALL PROCESSES (ELAPSED TIME IN MIN:SEC)

Test	VAX 3100	VAX 3200	IBM 125	IBM 135	SUN 386i	SUN 4/110	SUN 4/60	SUN 4/330
DLGARC	02:44	03:21	03:54	01:43	04:44	01:32	00:55*	00:33
UNGENERATE	49:33	67:48	04:15	02:02	02:22	01:50	01:17*	00:50
GENERATE	13:29	13:53	142:06	72:22	63:46	36:35	22:54*	17:16
EXPORT	20:28	43:49	23:08	14:57	25:33	10:53	07:51*	06:21
IMPORT	09:36	10:30	27:34	12:29	18:13	08:27	07:33*	04:43
ADDITEM	02:09	03:14	02:36	01:04	03:23	01:26	01:28*	00:43
BUILD	04:19	06:17	04:28	02:03	06:31	03:09	02:44*	01:49
CLEAN	17:01	20:43	54:19	22:25	22:36	12:33	08:40*	04:27
DESCRIBE	00:09	00:12	00:24	00:11	00:30	00:12	00:17*	00:03
DRAW	04:48	04:57	11:55	05:55	08:13	02:51	02:14*	01:26
IDENTITY	35:42	43:25	109:32	57:12	46:26	24:12*	17:25*	08:39
INTERSECT	27:36	31:04	99:00	52:50	39:24	20:49*	13:33*	05:41
DISSOLVE	04:48	07:09	03:26	01:36	06:32	02:09*	01:34*	03:21
LABELERRORS	00:14	00:17	02:29	01:57	00:52	00:42*	00:22*	00:12
NODEERRORS	01:02	01:52	09:22	09:40	02:23	01:32*	01:00*	00:30
APPEND	01:01	01:28	01:14	00:28	05:36	01:02*	00:30*	00:21
COPY	00:42	00:50	00:47	00:28	02:34	01:59*	01:14*	00:09
KILL	00:05	00:07	00:12	00:05	00:50	00:10*	00:04*	00:02
ARCPLOT	00:56	00:52	01:48	00:54	01:41	00:44*	00:39*	00:23
PLOT	01:21	01:27	02:49	01:29	01:35	00:40*	00:46*	00:22
TOTAL TIME (Min:Sec)	197:43	263:15	505:18	261:50	263:44	133:27	93:00	57:51
AVERAGE TIME (Min:Sec)	09:53	13:10	25:16	13:06	13:11	06:40	04:39	02:56
MEDIAN TIME (Min:Sec)	03:32	04:09	04:05	02:00	05:10	01:55	01:22	00:47

Tests were run with no other processes running in the background or over the network.

* Data used for these tests were accessed through remote mounts; the data used for SUN 4/110's was resident on the SUN 386i, and the data used for SUN 4/60's was resident on the SUN 4/330.

In terms of average time taken to perform the 20 tests, the SUN 4/110 was twice as fast as the IBM RT 135, VS3200, and SUN 386i. It was almost four times faster than the IBM RT 125. After the benchmark tests had been completed on the initial five workstations, the same performance tests were carried out on the VS3100 (a late arrival to the performance test process). This workstation was slower than the SUN 4/110, but faster than the IBM RT 135, VS3200, and SUN 386i in all functional categories of testing.

Toward the end of the evaluation period, the new SUN 4/60 and SUN 4/330 workstations were made available for testing. These two workstations were much faster than all of the other six machines tested. Using the 4/110 (the fastest of the other six) as a base indicator, the SUN 4/60 yielded results that were, on the average, nearly 1.5 times faster. The SUN 4/330 was over two times faster than the SUN 4/110. This difference was even more dramatic in the CPU and input/output intensive processes for which the SUN 4/330 was three times faster than the SUN 4/110.

Performance specifications for each workstation, such as MIPS, Linpack, and Dhrystone, are presented in Table 2.

WORKSTATION NETWORK CAPABILITIES

In evaluating the computer environment for the GIS–T, networking capabilities of the workstations were weighted

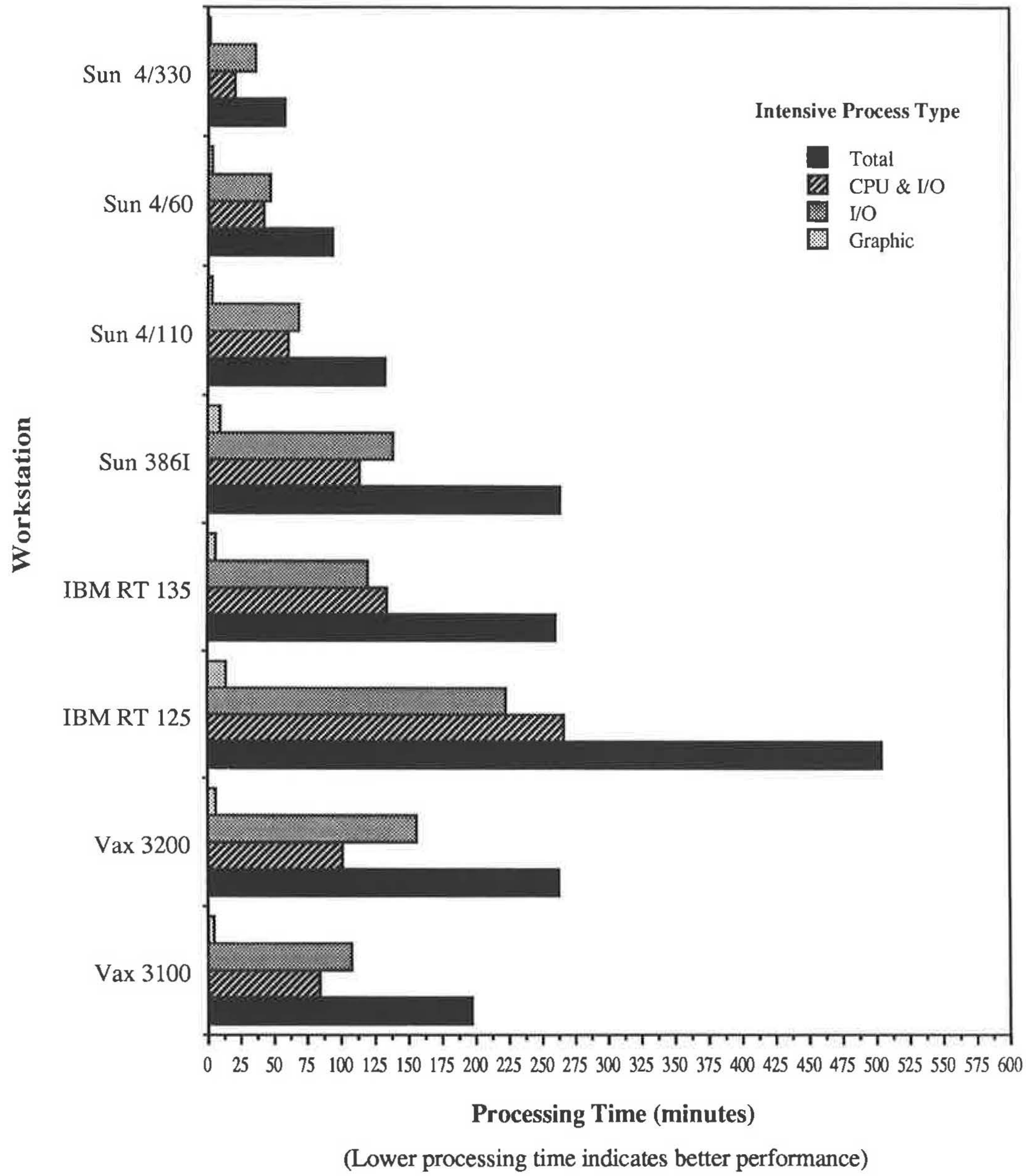

FIGURE 1 ARC/INFO workstation performance tests (overall summary statistics).

heavily. The following networking capabilities were considered.

Host Connectivity and Terminal Emulation

A critical aspect of the GIS at NCDOT involves the ability to access attribute information that describes characteristics of the road network. Because the majority of this information is stored on the IBM 3090/600 mainframe at the Transportation Data Services Center (TDSC), it is essential that workstations have access to the mainframe. The simplest method for connection to IBM mainframes is by emulating, or functioning as, a 3270 device. Because of the large demand for 3270 communications, many vendors offer 3270 emulation packages and support Systems Network Architecture (SNA). With a combination of communications hardware and software, workstations can function as 3274 controllers or 3278/79 terminals. The abilities of each workstation to emulate various terminal types through software, to support SNA, and to interact with IBM mainframes were of critical importance in the evaluation of hardware for a GIS-T.

File Transfer

File transfer between different types of hardware platforms (i.e., personal computers, workstations, minicomputers, and mainframes) is facilitated by the use of Transmission Control

TABLE 2 WORKSTATION PERFORMANCE SPECIFICATIONS

Workstation	MIPS	Linpack (sp)	Linpack (dp)	Dhrystone (dhry/sec)	2D Vectors/sec
SUN 4/60	12	2.5mf	1.4mf	22,045	406,000
SUN 330 GX	16	3.6mf	2.7mf	27,777	454,000
SUN 4/110	7	1.6mf	1.2mf	13,759	21,000
SUN 386I	5	*	*	8,333	*
VAX 3100	3		0.4mf	4,545	*
(DEC 3100)	14	3.7	1.6mf	25,026	*
VAX 3200	3	*	0.4mf	4,545	*
IBM RT 125	4.5	*	0.4mf	8,200	*
IBM RT 135	6	*	0.4mf	10,416	*

* Not published

Protocol/Internet Protocol (TCP/IP), which was supported by all workstation vendors in the GIS lab.

Distributed Services

More advanced proprietary and nonproprietary network software, like DECnet, Aegis, Network File System (NFS), HPnet, and others, provide sophisticated networking services. These services include block file transfers, remote workstation operation, system kernel services, file interchange capabilities, multiple node access, multiple file sourcing, single sourcing of network-wide software, and remote device access and services.

Among the more important services needed within a GIS environment are remote file and device access. These enable users to use disk space and files on remote workstations. Access to remote files is obtained by mounting remote devices. Remote file access, or mounting, provides an invisible, or transparent, connection between the workspace on the user's machine and the file system being mounted. It has the appearance of being local. The only networking software available to accomplish this task that was supported by all the vendors within the GIS laboratory was NFS, which was developed by SUN Microsystems.

Application Program-to-Program Interface

Before a GIS–T can be fully implemented at NCDOT, a seamless linkage must be created between the cartographic data base, i.e., the road network, and the relational attribute data base, which describes characteristics of this network. The cartographic data base is resident on the workstations in ARC/INFO format and the attribute data base exists on IBM DB2 systems. ESRI has stated that this linkage can be accomplished through IBM's Logical Unit (LU) 6.2. LU 6.2 was developed to allow communication between application programs that operate in a distributed processing environment. Support of LU 6.2 is an essential requirement of a GIS–T workstation.

DOS Server/DOS Applications

MS–DOS, developed by Microsoft, is the standard operating system in use on most IBM and IBM-compatible personal computers. The widespread use of MS–DOS at NCDOT and the organization's substantial investment in software applications that run on MS-DOS mandate that the workstations under evaluation support DOS activities.

Network Flexibility: Ethernet and Token-Rings

As networks of increasing complexity are placed in use at NCDOT, network flexibility will be a key concern in the growth of the GIS–T. GIS workstations will be incorporated into both local and wide area networks and will have linkages to personal computers, minicomputers, mainframes, and other workstations resident within various locations across the state. Important networks to be considered are Ethernet and Token-

Ring. NCDOT has an SNA-statewide Ethernet in Raleigh and is considering the use of Token-Rings in field offices. The ability of workstations to operate within these environments and the level at which they can operate, i.e., capabilities and functions, was of obvious concern in the evaluation.

In the context of these six important considerations, the networking capabilities of the evaluated workstations are discussed.

DEC

Demonstration of GIS network requirements was restricted to the VS3200, because the VS3100 was a late entry into the evaluation process.

1. The VS3200 was able to demonstrate a 3270 session to the mainframe by acting as a 3274 device and was capable of emulating a 3270 device and acting as a server, with 128 concurrent sessions.
2. File transfer between the DEC workstations and all other workstations in the GIS laboratory was executed through the use of TCP/IP's file transfer protocol.
3. Although not demonstrated, DEC stated that remote file access was possible within the VAX/VMS environment through DECnet's Distributed File Service (DFS).
4. DEC stated that their workstations have the capability to provide application program-to-program interface by supporting LU 6.2.
5. Through the use of VAX/VMS services for MS–DOS and DECnet, DOS applications can be run on VAX systems. In addition, VAX servers can be used to store DOS data files and applications. Resources, such as laser printers, can be shared.
6. DEC workstations can function on Ethernet networks but not Token-Rings.

IBM

1. Remote login to the mainframe from the IBM RTs was achieved through the emulation of 3278 terminals.
2. File transfer between the IBM workstations and all other workstations in the GIS laboratory was executed through the use of TCP/IP's file transfer protocol.
3. Initially IBM used their Distributed Services (DS) software to perform remote mounts between the IBM systems; however, considerable problems were encountered. In addition, because DS is not supported by other workstation vendors, it could not be used to mount file systems on non-IBM UNIX systems within the GIS laboratory. Because of these problems and constraints, IBM switched to NFS. Remote mounts through the use of NFS were successfully accomplished among IBM systems and between IBM systems and other UNIX systems within the GIS laboratory; however, at the present time IBM's implementation of NFS has limited file-locking capabilities. Remote logins to other workstations with UNIX operating systems were possible. Remote logins to the VAS/VMS systems were not supported by IBM.
4. IBM stated that their workstations have the capability to provide application program-to-program interface by supporting LU 6.2.
5. A wide range of DOS activities was supported on both IBM workstations.
6. During the evaluation period, IBM workstations were the only workstations in the GIS laboratory to operate within both Ethernet and Token-Ring networks.

SUN

1. Connection to the IBM mainframe was demonstrated by SUN. SUN machines accomplished the generation of 3270 sessions by emulating a 3274 device.
2. File transfers between the SUN workstations and all other workstations in the GIS laboratory were executed through the use of TCP/IP's file transfer protocol.
3. Remote file access was possible through the use of NFS. The SUN workstations in the GIS laboratory were able to mount all other UNIX workstations.
4. Communication between application programs in a SUN environment is supported by SUN's Peer-to-Peer software.
5. DOS files and programs were successfully stored on both SUN workstations. The SUN 386i had an Intel chip that allowed for a separate DOS partition.
6. SUN workstations can operate within an Ethernet network. SUN is currently developing communications software that will allow their equipment to be used within a Token-Ring environment.

OPERATING SYSTEMS

In the evaluation of operating systems, the following criteria were considered: ease of use, network capability (discussed in the previous section), window systems, system security, upwards and downwards compatibility, and history and standardization.

DEC

DEC's workstations (VS3100 and VS3200) used the VAX/VMS operating system. For several years, DEC has worked with MIT to develop the X Windows System. DEC's implementation of X Windows System is DECwindows. DECwindows is a sophisticated, multitasking system that integrates many desk-top publishing features and provides easy access to applications on several operating systems.

SUN

The operating systems on SUN workstations are based on the Berkeley version of UNIX, with the incorporation of most of AT&T's System V features. This operating system is an extremely popular multiprocessing system with many advantages. The UNIX operating system is a portable one that can

be implemented on dozens of different machines. Because of this, software vendors and users become computer independent, and programs and data are easily transported from one machine to another. The UNIX system supports a large number of software applications and programming languages and has a high degree of upwards and downwards compatibility.

SUN workstations have SunView window systems. SUN began developing window systems before X-windows were developed and, as a result, SunView is a mature window system that is much faster than X-windows. More than 2,500 applications are available for the SunView window system.

IBM

The IBM RT workstations used the System V version of the UNIX operating system. This operating system was developed by AT&T and has many of the same positive features as the SUN UNIX system. The IBM RTs used IBM AIX/RT-X Windows, Version 2.1. This window system is based on X-windows and was designed to support graphics applications. With this system, multiple application processes can operate within a given window, and multiple simultaneous windows can be used.

PILOT PROJECT VENDOR SUPPORT

On the whole, support from all three vendors was good during the pilot project, but it varied in certain aspects. Initially, DEC had problems committing their resources, and two months passed before they were able to link their hardware to the GIS LAN. After this occurred, their support improved. SUN support was good throughout the entire project. SUN was the quickest of all three vendors to get workstations running and to respond to and solve any problems that arose. As a result, the SUN workstations experienced the least amount of down time. IBM was the first vendor to commit its resources to the pilot project and it provided the most support. In addition to the workstations, IBM supplied the project with many other resources, including an IBM 6186 eight-pen plotter and an IBM PS/2 Model 80 computer.

In terms of the statewide implementation of a GIS–T, it is essential that good support from vendors continue. One of the most important aspects of this support is the amount of time it takes for a vendor to respond to problems, not only in the Raleigh office, but in field offices throughout the entire state.

WORKSTATION SYSTEM PROBLEMS

Each of the workstations varied in terms of the number of system problems that were encountered during use. On the whole, few system problems were encountered on the SUN workstations. The SUN equipment was functional for almost the entire duration of the GIS workstation evaluation (see Figure 2). This was due, in part, to the excellent support from SUN personnel. On the other hand, many problems were encountered with the IBM workstations. Both the IBM 135 and IBM 125 were inoperable for much of the evaluation period. Many of the problems with these two workstations were eventually resolved by software improvements by ESRI and an increase in the expertise of IBM personnel.

As noted in the previous section, there was a significant lapse between the time the VS3200 was first installed and the time it was connected to the LAN. Afterwards, few problems were encountered with this workstation. Three workstations were available for only a short period of time and could not be evaluated thoroughly. These were the VS3100, SUN 4/60, and SUN 4/330. However, the long-term quality of performance of these systems can be inferred from the performance of other VAX and SUN workstations that were evaluated more thoroughly.

GIS Development Team Observations

The GIS development team included GIS analysts and consultants, and representatives from the Transportation Data Services Center. Response of the GIS development team to the SUN 4/110 was positive. The SUN 4/110 was fast and reliable and few problems were encountered with UNIX, the SUN windows, or the text editor. Downloading of files from the mainframe to the SUN 4/110 was efficient and effortless. With respect to the ARC/INFO software, the 4/110 had a number of positive features. One of these involved the boxing in of the map extent in ARCEDIT, a feature that neither the IBMs or DECs exhibited. Without this feature, it was difficult to delineate a map extent accurately. Only one bug was encountered with the SUN 4/110 and this concerned the execution of INFO programs. When INFO programs were run on the system, there was no indication of a program's end (i.e., by returning to INFO). Response to the SUN 386i was also favorable. This workstation possessed most of the positive features noted for the SUN 4/110 with the exception of its slower processing time. The INFO program bug did not occur on the SUN 386i.

The VS3200 elicited positive response from the development team. As previously noted, VAX/VMS is a sophisticated operating system that is easy to use. The window systems and resolution of the monitor were good, but the workstation was slower than the SUN 4/110. File transfer between the mainframe and VS3200 was cumbersome and posed problems because of the limitations on record length with remote job entry (RJE).

The IBM workstations had some problems. The positive features of these workstations were the monitors, with their pure colors, and the UNIX (AIX) operating system. However, many problems were encountered while using ARC/INFO software. Occasionally, certain graphic functions caused the screen to lock up, and the cursor in ARCEDIT was too large to accurately select features. In addition, the IBM 125 was slow compared to all other workstations in the GIS laboratory.

GIS DELEGATE TRAINEE OBSERVATIONS

At the onset of the project, representatives from various departments within NCDOT were appointed as delegates to

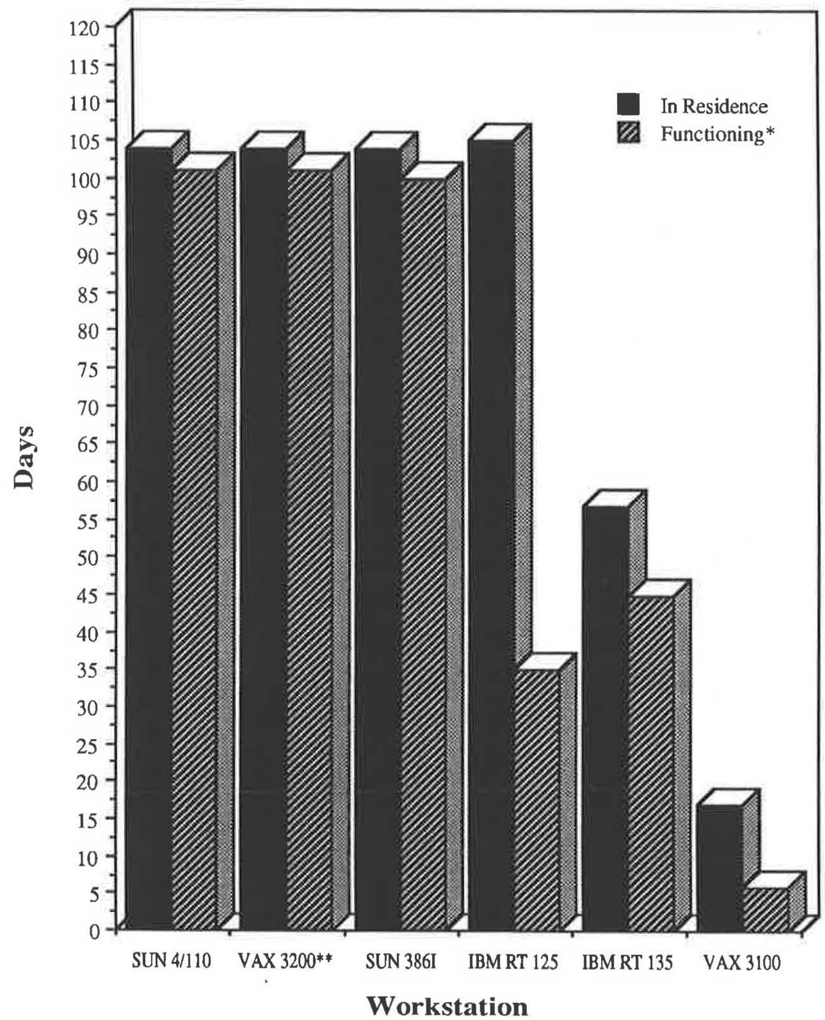

FIGURE 2 Workstation functional performance.

work with the GIS development team to define users' needs and assist with application development. A number of important observations about hardware and operating systems were made by GIS delegates after an ARC/INFO training session that took place in December 1988.

Nearly all comments about the SUN 4/110 were positive. Again, the 4/110 was noted for its speed, reliability, and user-friendly editor. The delegates found the window system easy to use and were favorably impressed by the resolution of the monitor. Attitudes toward the SUN 386i were similar, with the exception that it was significantly slower.

Response to the VS3200 was also favorable. Some trainees felt that the VAX/VMS operating system commands were easier to learn than UNIX commands. The windows, although less sophisticated than SUN windows, provided no problems.

With the exception of comments about the large screen and high quality of the monitor, response to the IBM RTs was less favorable than that of other workstations. Many bugs were encountered with the IBM workstations, including screen lockups, trouble with keyboard cursor control keys, and the inability of the monitor to refresh obscured screens. Many negative comments were made about the two-button mouse, and the windows were harder to use than SUN or DEC windows.

A number of workstation features were viewed by the GIS delegates as being highly desirable. These included speed, reliability, a three-button mouse, keyboards with numeric keypads, mouse-driven system editors, a mouse-driven menu operating system, and the ability to easily recall and edit previously typed commands (history command).

PRICE

There was a considerable amount of variation, not only in the cost of workstations themselves, but in the amount of software or extras that were included in the purchase of the workstation. Figure 3 shows the relative cost of workstations

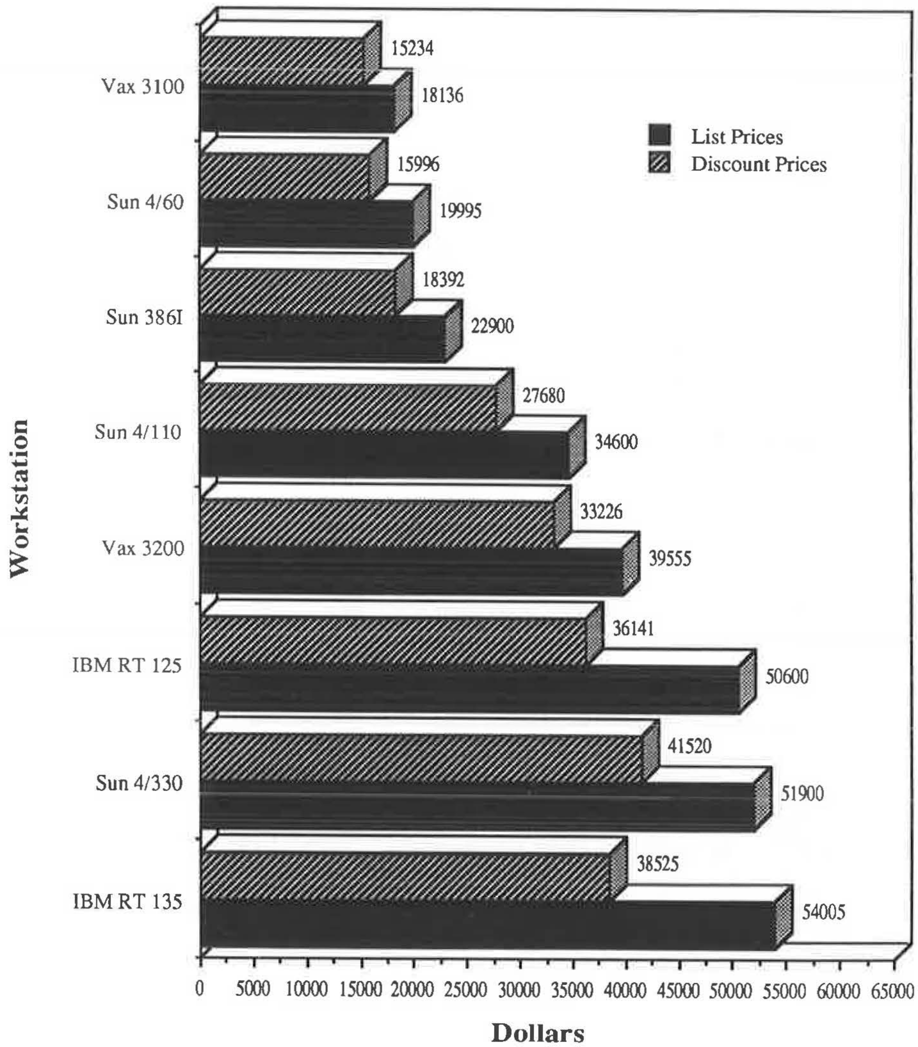

FIGURE 3 GIS workstation prices.

comparably configured (according to April 1989 prices). The cost performance of each workstation is shown in Figure 4. Cost performance was evaluated by devising an index that took into account the price of each workstation and the average time, in seconds, that it took each workstation to perform the 20 AML tests previously discussed.

CONCLUSIONS

Workstation technology is evolving rapidly in the computer industry, a fact substantiated by the continued introduction of new lines of highly advanced workstations. Workstations with increased speeds and prices near those of personal computers are now available for GIS technology. Graphics capabilities and processing performance, however, are superior to personal computer technology.

The UNIX operating system, although marketed in several versions and in varying stages of development, offers many advantages over other operating systems and is rapidly becoming the operating system of choice among workstation vendors. Multitasking and enhanced window performance, increased CPU performance through Reduced Instruction Set Computer (RISC) architecture, ease of porting new applications, and compatibility from vendor to vendor are some of the significant enhancements offered by UNIX. The UNIX operating system also has many advantages in terms of network flexibility. UNIX, in conjunction with NFS, provides interoperability across a heterogeneous computer network, allowing users to store and access files that reside within a multivendor environment. Although not actually a standard, many vendors are implementing NFS on their systems. NFS was developed by SUN Microsystems and has been tested on many networks, including Ethernet, Token-Ring, Apple Talk, and others. UNIX has incorporated commonly used communications protocols, such as TCP/IP, into its command language to provide for a variety of network services, such as remote login and remote file transfer. Because of its many advantages, the UNIX operating system should be an important consideration in GIS applications.

After reviewing the results of the 5-month workstation evaluation, NCDOT's GIS development team recommended SUN

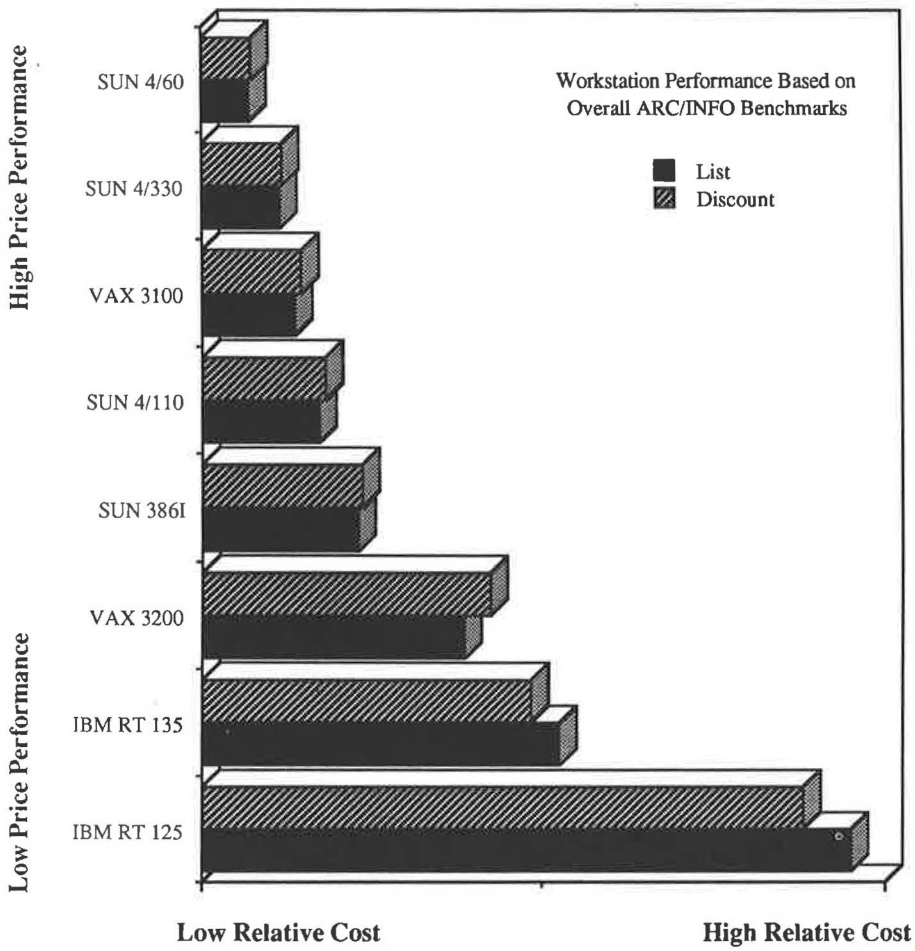

FIGURE 4 GIS workstation price performance (based on vendor's list and discount prices).

Microsystems as the workstation of choice for the initial implementation of GIS at NCDOT. SUN was able to demonstrate clearly superior levels of price, performance, reliability, network flexibility, ease of use, system integrity, and support. The newly released SUN 4/60 workstation was the lowest priced workstation in the test and performed at double the speed of the nearest competition. The SUN equipment worked nearly every day since its installation. When repairs or modifications were necessary, they were made quickly and effectively. In all network functions tested, SUN workstations performed as though they were designed for the end user rather than a computer programmer.

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Emergent Roles for Optical Media in Transport Engineering

MARCUS WIGAN

Computer-based systems for the delivery of engineering information are beginning to become cost-effective for a growing number of road and civil engineering applications. Optical media, mastering, and authoring requirements are explored, and the serious problems inherent in the evaluation of the use made of such systems are considered. Examples of the appropriate use of analog (Laservision) and digital (CD ROM) forms of optical storage in various transport applications are given. The ability to handle high-quality images and text, to access standards-approved computer programs for specific applications within the context of a certified Standard, and the rapid changes in accessibility to digital terrain and cadastral data are about to have a major impact on road engineering and training. Examples of hypertext and expert systems for this purpose are now being tested as part of a project evaluating an enhanced version (the third edition) of *Australian Rainfall and Runoff*, and these methods are being evaluated for their ability both to deliver information more cheaply and for their potential to improve engineering practice. CD ROM optical disk delivery forms a key part of this process. The locational requirements of pavement, traffic, road, and transport information systems all point to greater use of GIS methods. As a direct result of several Australian reviews of transportation survey data needs and uses, the use both of GIS methods for data integration and of optical media for collated and economic distribution and archival access have emerged in Australia as widely recognized requirements of all future such surveys.

The requirements for mass storage devices both with imaging and data capacity have been growing for some time. The combined ability to access visual information randomly, associated with selected items of information drawn from a mass of data, is attractive to many different road application engineers. A parallel thrust has been the world-wide growth of the 300-mm Laservision disk format in the markets for computer-based training and museum collection recording and display. Road and transport applications include

- Photologging,
- Mapping,
- Terrain data,
- Water resources data,
- Transportation and spatial movement data,
- Navigation,
- Training, and
- Vehicle operator environment simulation (with landscape montage creation).

Each of these applications makes special demands that can be serviced well by making various data and processing services available on optical media of various types. A number of these applications, and the associated issues of image processing and geographical and graphics data bases, are covered in a national workshop for operational road organizations held at the Australian Road Research Board (ARRB) in 1987 (*1*).

The document delivery and educational aspects being tested in the water and flood estimation field as a joint Monash and ARRB project are documented elsewhere (*2–4*). This project will be considered as the first of the application domains to be discussed.

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DISTRIBUTION AND EDUCATIONAL SUPPORT USING OPTICAL MEDIA

Professional engineers now face an overwhelming amount of information that must be integrated in the options for, and solutions to, any particular problem (*2*). This trend is leading to a substantial need for more effective means of keeping practicing engineers up-to-date and in touch with recent developments (and in a better position to discharge their legal liabilities in this direction—an issue that can no longer be ignored).

The methods, format, and effectiveness of both novel and different forms of release of substantial bodies of information (e.g., structural or operational codes of practice or standards) in engineering are therefore issues demanding serious and practical attention. This problem is relevant to all engineers. There is a continuous need to update professional knowledge throughout an engineer's working life.

Unfortunately, much of the currently useful information is presently held in forms that are not easily accessed. For example, even though engineering codes contain a vast amount of knowledge in a particular area, they are paper based, and generally poorly indexed and badly cross-referenced. There are often maps, nomograms, and reams of specialized design charts to be obtained as well. These aids are usually also expensive to publish. Consequently, the information is difficult to access, and the user must be experienced if his design is to satisfy the high standards set by the quality of the information.

The issues that need to be addressed and potential contributions include the following:

	Computer/optical Media Contribution	
Issue	*Computer*	*Optical media*
Quantity of information	High	High
Organization of information	High	Neutral
Accessibility of information	Mixed	Mixed

Issue	Computer/optical Media Contribution	
	Computer	Optical media
Interpretation of the information	High	Neutral
Economic distribution of the materials	Medium	High
Quality of design assisted by the materials	High	Neutral
Means of effective updating	High	Medium
Ability to integrate the materials with other tools	High	High
Suitability for self-study	High	High

The educational effectiveness is to be tested (*3–5*).

A suitable test example is the third edition of *Australian Rainfall and Runoff* (AR&R) (*6*), a document of considerable relevance to local government engineers and those working for state road authorities for the design of such constructions as bridges, culverts, and floodways. The first volume of the third edition has 350 pages of text, and the second volume adds 110 pages of A2 size maps. Because this represents a 350 percent increase in size over the second edition, the costs of production, printing, reproduction, and distribution already show compact disk read-only memory (CD ROM) as a potentially cost-effective alternative even before the additional opportunities offered by a computer environment plus mass (optical) storage have been exploited to add value and improve accessibility.

Monash and ARRB have been building hypertext (i.e., reauthored nonlinear text) versions of various chapters of the *AR&R* (*6*) using the Guide hypertext authoring product by OWL International (*7*), which is based on the work in the U.K. (*2*). The users of the current AR&R have also been surveyed for their experience both with this document and other sources of hydrology data and with computers in general (*3*).

In order to make effective use of engineering information, text, diagrams, programs, and advice in a machine-readable format, it is simply not enough to do what has already been done: namely, to transfer unaltered and unstructured text, numbers, programs, and graphics to a CD ROM—however useful as an archival base for wide distribution, access, and security of the data base and its documentation (*8*). US West Inc. already produces mass hydrology data on CD ROM, and the printed text version of AR&R is supported by a range of hydrology programs available from third parties.

The special features of optical media are

- The capability of cutting the cost of reproduction of this massive package of material as a single convenient unit, and
- Enhanced accessibility to the material thereby collated, as access is now mediated by a computer system, with all of the nonlinear, graphics, and other capabilities that the computer can potentially provide.

In order to gain these benefits, it is necessary to create and build some additional structure into these basic materials.

The authoring of the chapters in hypertext has required much additional structure to be added to the basic text. It is clear that the requirement to provide multiple paths through the information, to identify the overall structure and linkages in the material, and to provide sensible graphics to the material all add up to much the same task as reauthoring the basic material into a form more suitable for a paper, a lecture course, or a full teaching workshop. In each case, the interactive features must be built in, and the teaching and communication aspects require greater attention than is usual in most manuals or textbooks, which rely on such added interpretation when being used as set books.

PHOTOLOGGING OF ROADS AND ADJACENT FACILITIES

The value of visual forms of recording road surface and environment and condition have long been known (*9*). However, the costs of large quantities of records on 35-mm film are high. The monitoring of roads and their surface condition and adjacent facilities has been approached by many bodies using 35-mm slides and film, but usually with mixed success as a result of the difficulties in accessing the materials once captured. Video tapes appear to offer a good method of cheaply and economically capturing large quantities of such material, and several road authorities have tried it, but with mixed success (*1,10–13*).

The most significant problems found with the videotaped photologs of roads were

- No one wanted to use them because of the difficulty in finding target information, and
- The resolution of the images was too poor for most practical purposes.

The underlying problems were that the access to the individual frames on the video tapes was a slow and cumbersome process that took a lot of time and effort on the part of the users, and the typically 200-line resolution of the domestic VHS video tapes used just was not good enough to justify the effort.

The state of Connecticut, which is quite small (by U.S. or Australian standards), has had an active photologging unit for some time. This unit has addressed both of these problems (*13*). It has been using 35-mm film to log the visual surface of the roads, and transfer this to 300-mm Laservision disks for storage and access. Note that Laservision is a trademarked specific standard for 12-in. analog optical disks. They also provide some numerical data overlaid on the top of the video screen to key the information otherwise available at a given location straight onto the video record. A Connecticut photolog video disk loaned to the author was manufactured in 1985, long before the refinements now available could be used. It is therefore the lowest quality that would be obtained by anyone using this type of approach to road inventory systems, and the control and searching facilities now available or also in use in Connecticut. Details of some of the locations and their frame index numbers are available from the author.

There are two types of video disk: continuous longplay video (CLV), which can only be randomly accessed at time or chapter intervals, and computer active video (CAV), which is recorded slightly differently, with 54,000 still images on each side of the disk, as the recording method permits a single image to be displayed with complete stability indefinitely. Recently the addition of digital frame stores, digital sound tracks, and other refinements have blurred the differences between these two styles of disk, as digital frame stores can

be used to capture any frame into a frame buffer for stable display. These newer players are still expensive and in short supply, and the CAV format will continue to be used by the cheaper players.

The equipment that can most readily be used in Australia is the Pioneer LV4200 NTSC 50/60 cycle and LV 4100 PAL industrial computer-controlled Laservision player with analog sound tracks only. Both are readily available in Australia, and about 100 examples of the NTSC equipment are in daily use at the Sydney Powerhouse Museum. NTSC has gained a lead in the Australian domestic and display markets, whereas professional training uses both PAL and NTSC players and material. It is worth noting that the Sony command set can also be used with its dual standard Laservision player, which reads both NTSC and PAL disks and outputs PAL signals to the display.

The Pioneer LV4200 and the Sony LDP1500 are the two players most widely supported by Apple Computer HyperCard stacks. Optical Data Inc. has created both programs for the IBM PC (under the MS–DOS operating system) and HyperCard controller stacks and data bases (on the Apple Macintosh) for large collections of NASA space and air travel images and motion clips, with a considerable amount of ancillary material added on the computer data bases attached to the MS–DOS or HyperCard host programs. The Voyager Co. of Los Angeles has a series of HyperCard tools for the Pioneer and the Sony, and also authors a whole range of CAV disks. The advent of HyperCard and its clones for Unix and MS–DOS, together with Apple Computer's and IBM's steady moves toward multimedia and educational applications have begun to provide a new foundation for Laservision disks, as well as for CD ROMs (which Apple now manufactures). The graphical orientation of the Apple range of computers provides the obvious link between optical media and its product marketing interests. It remains to be seen if the market will respond.

Meanwhile, the costs quoted in Australia for premastering a videotape, mastering a pressing, and producing the first ten 300-mm Laservision disks in PAL or NTSC format are already less than $10,000 (Australian dollars) for continuous videotape transfers—but up to $50,000 for the premastering of 54,000 different still images on a CAV disk designed as an image database, typified by the NSW Printing Office art collection disks. (All prices shown here are indicative, and refer to early 1989; major movements, generally downward, have already occurred, and can be expected to continue.) This high cost is incurred by the synchronization of the eight-field PAL video images with the recording process. The manpower required for such a large quantity of information individually addressed will always be substantial. The costs of CD ROM mastering, premastering, and disk production are roughly comparable, but are already drifting noticeably lower.

Laservision mastering costs are still noticeably greater than for CD ROM mastering, but CD ROM is not as yet a good basis for large numbers of still or moving full-color images. Uncompressed 24- or 32-bit full-color images could require more than 2 MB of disk space, only about 500 still images on a CD ROM. The Sarnoff Laboratories/Intel DVI format for compressed still and full-motion imaging on CD ROMs, which will still take some time to reach the field in an economic form, may be an improvement. Laservision 300-mm disks in CAV format handle up to 108,000 still images per disk, or 2 GB of digital data. Data compression and expansion schemes based solely on software, yet running fast enough for real time use in many cases, are now also beginning to appear in increasing numbers.

A range of different encoding and decoding systems are readily available to add several hundred megabytes or more of digital or audio data to this massive inventory of images.

The advent of S–VHS (400-line resolution) domestic video recorders and low-cost 500,000-pixel CCD cameras has now—in 1989—brought road system (and bridge structure) photologging to an economic position. Sime and Hudson (*11*) emphasized that this level was about the lowest acceptable level of resolution to achieve really useful logging results. They used 35 mm with careful transfer to the disk in the first few rounds of their work, and found that the 400-line resolution or better of a Laservision disk itself was acceptable—and that the random access nature of CAV laser disks made the photolog records a product in demand. The serial slow access of video tape was apparently the major blockage to wider takeup of the earlier cassette-based logging system in the state.

The association with data bases under MS–DOS, Apple, or Unix provides the other component required to make optical media really useful and effective in the field. The association of a high-quality visual image with an accident location or intersection contains far more information than can normally be captured in a data base efficiently by any other means. Random access to high-quality still images recorded in analog form on a Laservision disk still provides the best results at the most economic cost.

The addition of a Laservision-based directory of photographic-quality images and maps of the streets of Melbourne to the recently completed ARRB detailed accident data base for Melbourne (*14*) would be a typical—and well worthwhile—example of the added utility that it is now economically possible to provide.

If this Melbourne visual data base were to be installed (say under Oracle or Titan) on an MS–DOS machine, then queries to the data base could easily be arranged to invoke a particular still frame (or motion sequence) stored on a Laservision disk. There are several methods for simultaneously storing the digital data required—perhaps even for the data base itself—on the same Laservision disk, thereby making the Laservision disk an extremely high-quality random access archive system, which could still be easily replicated and put into high-activity use in many locations at an economic cost. The compact, complete, and accessible random access record thereby produced would normally require only a microcomputer and a video monitor for self-documented (and possibly even self-running) large-scale data bases. The role and economics of such enhanced and robust forms of mass data delivery now justify close examination, as the trend to networked distributed data base systems gathers pace.

The addition of data to a Laservision disk can be achieved by a range of methods: some affect the use of the disk as a mass still image frame store, others do not. For example, EnVision cards in a PC AT (*15*) would permit the entire current data base to be encoded onto a single disk inside a subset of the still-frame image tracks, or the LV ROM system

adopted by Phillips and the BBC (for the 1 GB of ancillary information recorded on the three-disk Laservision set comprising the Domesday Book) could be used.

Phillips uses the audio tracks, whereas EnVision and their kin provide for a fluid mastering mix of data, audio, and image in any combination by using the full video bandwidth of the Laservision disk. In either case, a specialized encoder and decoder are required, but in the case of the Domesday Book the disks can still be read as a series of still-frame and moving images. A further form of encoding is to utilize the video bandwidth reserved for the blanking interval on a videotape recording. This technique was used, for example, by the Melbourne Royal Children's Hospital for videotape records for which the coincident recording of the simultaneous data logging digital and analog information was required to be available with (and therefore on) a visual record.

There are wider implications in the use of high-quality Laservision analog color image records: the geographic information system (GIS) has grown up in the land information and surveying field as means of handling multiple overlays of information over a fixed two-dimensional cadastral geographic map or three-dimensional full-terrain specification. These systems still have some major deficiencies, but have more and more to offer land and transport engineering and planning organizations. Standard genlocked output from microcomputers (typically, the Videologic MIC–2000 and MIC-3000 interface cards for IBM PC, and Torch for Apple Macintosh II, both of which permit full-quality video to be displayed in synchronization with computer-generated text and graphics) can be used to overlay live video graphics from a data base retrieval over a high-resolution Laservision-stored image of a map (thereby saving a massive amount of storage, computation time, and cost).

This mode of operation is used by military aircraft laser disks of various types, where the coincidence of a head-up display or terrain feature map underlay from the disk is synchronized with the computer-generated selective information overlay. Using the mixed-media style of low-cost data base, it is straightforward to include still-frame pictures of specific targets, features, or other visual imagery to be associated with particular situations or locations.

Until GISs—such as ARCInfo and TIGRIS—improve significantly (*16*), this approach is likely to add more practical value to accident and transport data bases at low cost with a short lead time than a move to GIS integration (worthy though that would be), and also to drastically simplify the means of access to such large bodies of data, and provide it in a more usable and assimilable form.

The software requirements for effective mixed-media graphical and digital data bases are not yet clear. The benefits of using a graphical paradigm for responding to queries made of a pavement information data base have been demonstrated (*17*), but it is clear that a significant convergence between GIS, road information data bases, and visual records is now imminent and should be used in any new transportation survey: recommendations to this effect have already been made this year (1989) by consulting teams (both including the author) for the two largest Australian states. Relational data bases have their problems, and the new generations of hypertext structures and object-oriented data base systems [arising from the current wave of artificial intelligence input into data bases and information retrieval (*5*)] will be considerably more suitable. To apply some effort to understanding and investing in the software aspects of this new type of information resource is timely and will play a large part in building the demand for (and reducing the cost of using) large-scale optical media and their associated services.

OPTICAL STORAGE REQUIREMENTS FOR TRANSPORTATION DATA SETS

The value of optical storage systems lies both in their capacity and in the economy in providing a genuinely archival storage medium. Transportation surveys have been carried out since the early 1960s, and have long been known for their demands of large numbers of magnetic tapes and substantial computer processing times.

This perspective has been radically altered by the development of fast microcomputers with gigabyte storage capacity. However, the fragility of these data sets has continued to be a problem. It is all too common for tapes to be released unintentionally, for parity errors to emerge on older tapes, and—even more common—the basic documentation required to identify and describe the contents of the tapes becomes disassociated with the tapes themselves, thereby rendering the information virtually useless (*8*).

Transport is not the only field to suffer from this type of problem, and the SSRC Social Science Data Archive at Essex University in the U.K. has encountered all these problems and more. The user demand for their information product is now such that they have created a number of 12-in. Laservision disks that are permanently on line. Such systems provide the easy opportunity for high-integrity backup, random access, and the integration of the textual, graphical, and numerical information for each survey in a form that provides a sound and easily replicable archival or access unit. The ability to add computer programs, video, and other forms of motion and still-frame imaging to these records also exists.

In this field, Wigan (*7*) has previously recommended the use of optical media to cover the first group of goals, and it is clear that the economics of this process are indeed excellent with the market and technical developments of a scant 2 years. It should not be assumed that CD ROM would be the only medium (*18*). Worm and erasable optical disks also offer the ability to do direct mastering of large numerical data bases, specially now that hard disks of 600-MB and larger are readily available for microcomputers. The questions about interchangeability and error correction standards agreements still dog Worm and erasable optical disks, and until these are cleared up (as has been done for CD ROM with High Sierra and ISO 9660, the distribution potential of such in-house mastering will remain problematical.

The current existence of CD ROM drives for Apple and IBM PCs, both capable of reading the High Sierra and ISO 9660 formatted files and file systems, establishes CD ROM as the medium of choice for the present. Erasable optical disks meeting CD ROM form factors and High Sierra data formatting conventions may yet appear, but do not materially alter the present market position of CD ROM. ARRB is

continuing to work on finding and testing methods of realizing these potential benefits for transportation and text data bases. The first such CD ROM scheduled to be mastered in the first quarter of 1990 (*19*) includes one of the *AR&R* hypertext prototypes integrated with hypertext versions of the technical papers describing the project (*2–4*).

The marketability of this type of data is becoming strongly established. The BBC Domesday Book is now being marketed in two tiers: one for the schools for which it was originally aimed—and the other, at a substantial premium, for the commercial interests that are finding this type of integrated graphics, visuals, and numerical data base a tool of major marketing significance. The Museum of Victoria has already moved to a Laservision disk basis for the visual records in this collection, and uses the Titan large-scale data base system to index and cover the collections: the links between Titan and the laser disks have now also been forged. Titan is a data base developed by Melbourne University and RMIT specifically for large databases. It is now marketed by Knowledge Engineering.

VEHICLE NAVIGATION

An ability to contain a large amount of detailed graphical information in a robust random access format is attractive in all sorts of transport applications. Military aircraft are now able to use the AMOD-II Lockheed laser disk system to deliver terrain and navigation data in an optical disk system "intended specifically for use in high performance aircraft. . . ." Specialized laser disk systems for maritime navigation have also been produced, with the entire world's charts recorded in vector format, and with ancillary information to permit ship alignment assistance under computer control.

Road vehicle navigation systems also aim to use CD ROM techniques, and the ETAK car navigation system company in Silicon Valley plans to use CD ROM to deliver their future services, built on their current geographic data base efforts. Car navigation systems and CD ROM mapping storage are widely expected to become economic for at least part of the motor vehicle market by Phillips and others (*20*). Such navigation systems are also equally helpful for other modes, including pedestrians in suitable circumstances (*21*).

Vehicle navigation applications currently lean towards the 130-mm CD ROM/CD Audio approach as the domestic market has driven the prices down for this type of technology. However, competition between satellite location (communication) and dead reckoning with local updates (on-board computation and mass storage) systems has yet to be joined in earnest. On the road, the AutoGuide system due to be tested in the U.K. would fit best with the on-board optical disk approach in supporting communications and beacon assistance, whereas the French systems lean more towards active location by frequent communications. On the sea, the Disk Navigation Company of Sweden (*22*) combines all these methods, and uses CD ROM to provide navigation and maneuvering assistance through direct interactive control of the vessel, while linking in to satellite, Loran, Omega, and ship-born location and logging devices.

In either case, the economics of mass data transfer mean that an on-board optical disk with large amounts of digital or analog maps or location-specific visual, text, or digital information, will provide a massive boost for the production and distribution of the necessary master optical disks. As the reproduction costs are so low (a few dollars), the existence of a mass market will permit this product to become economically available for the wide range of identified specialized uses in transport engineering.

Large-scale data base systems are required for locational and navigational systems as these, like the other types of transport and land-related data systems, are all turning to cadastral, terrain, imaging, or laser disk support to handle the increasingly nonhomogeneous nature of the items and entities to be indexed.

The convergence of GIS, transportation survey, road, and land information and textual data base requirements means that greater attention should now be paid by those in these fields to such systems as CSIRO's SIRO-DBMS extensions of Oracle, GADD (*23*), and Titan as well as the newer developments in GIS systems such as Intergraph's TIGRIS that are emerging now that ARCInfo is becoming mature in the marketplace. It is difficult to see the next round of transportation surveys' being undertaken without the use of GIS methods for either the survey phase or at least the data base structuring.

SUMMARY

Optical disk applications in transport are already in use, and others are becoming economical quite quickly. All depend on the ability to create compact, robust, and cheap storage units that can contain graphical, video, aural, and digital information in large quantities and with random access.

The most significant new applications to emerge will probably be the simple addition of visual records associated with spatial aspects of road information systems, followed by motor vehicle navigation systems.

The educational and text data base impacts of optical disk technology are likely to appear first in the publishing, educational, and technology transfer areas of engineering, and may have a greater effect than all of the other applications and data bases combined if they can help to maintain, update, and improve the performance of experienced engineers in their job.

ARRB is about to publish a trial information resource CD ROM (*19*) to test several of the application areas. This CD ROM contains a wide range of transportation databases, information retrieval and hypertext resources in addition to a stereo audio track which can be played by a conventional domestic CD audio player.

The rapid convergence of management and operational data requirements in road and transport-related organizations already demands the gigabyte storage scale of optical disks, and the ability to replicate such large data bases and add audio, visual, and analog information will be progressively taken up. Increasing pressure can be expected on GIS software vendors to produce true object-oriented data base systems capable of integrating GIS, graphics, and relational data base models, and set up to handle huge quantities of data in an integrated manner.

Optical storage media provide a viable method of creating, managing, storing, distributing, and accessing such multi-agency data bases. The more difficult questions of the types and

nature of the data base software (as distinct from the basic index creation and user interface query software) to make best use of this newly found potential mastery of the basic data are being addressed by Titan and other innovative efforts.

GLOSSARY

Acronym	*Definition*
CAV	Computer Active Video form of Laservision recording that is recorded as 54,000 still images on each side of the disk. This permits a single image to be displayed indefinitely with complete stability.
CCD	Charge-Coupled Device: a robust form of camera design that permits high-speed capture of images with wide lighting tolerances.
CDI	Continuous Data Interactive: a method of compressed image recording and expansion that permits up to 70 min of live video to be recorded on a single CD ROM. Patented by the ex-RCA Sarnoff Research Laboratories (now Intel).
CD ROM	A standard for 1,300-mm digital optical disks, the same size as domestic CD audio optical disks, and read on modified players for that type of disk, thereby reducing the cost of the players and broadening the market from the start.
CLV	Continuous Longplay Video: a form of Laservision recording that can only be randomly accessed at time or chapter intervals.
Expert systems	Advisory or diagnostic computer programs that are designed to mimic or replicate a degree of human judgment, advice, or regulation.
Genlock	A term used to specify the ability of two video signals to be synchronized and displayed as one.
High Sierra	A standard format for digital CD ROM recording agreed at a series of conferences led by Microsoft and others in the mid-1980s. The basis for the ISO 9660 standard, which is High Sierra with some marginal (but irritating) alterations.
HyperCard	An innovative program provided with Apple Macintosh computers that makes nonlinear text and graphics handling easier for non-programmers. It has had a wide impact, and is now a common basis for multimedia control programs, including Laservision disks and CD ROMs.
HyperText	Nonlinear text, with many branches and means of navigation through it.
Laservision™	A standard for 300-mm optical analog disks initiated by Phillips, DiscoVision, and Pioneer for consumer and professional usage in the late 1970s.
LV ROM	A form of data encoding on Laservision disks designed by Phillips for use with the BBC Domesday Book project and its successors.
NTSC	The form of video encoding used for video broadcasting and recording in the U.S., Japan, and some other countries. Widely used in Australia for domestic and museum Laservision records.
PAL	A modified form of NTSC, offering more resolution and better color stability. Essentially a modified West German standard, adopted in most of Europe and in Australia for public broadcasting and domestic use in various forms (PAL–I, PAL–D, etc.). The versions of PAL used in Europe and Australia are significantly different in a number of respects.
S-VHS	An enhanced version of the JVC Company domestic VHS standard, which permits up to 400+ lines of horizontal resolution on special material tapes in domestic VHS format. Downwardly compatible with current VHS players. Requires either a special monitor or an RGB adaptor box for playback at the full 400+ line quality level.
WORM	Write Once Read Many optical disks. These are of archival quality and may only be written once. Standards for these removable disks have not yet stabilized.

REFERENCES

1. R. J. Troutbeck and M. R. Wigan (eds). *Workshop on Visual Data Acquisition and Application*. Research Report ARR 151. Australian Road Research Board, Vermont, Victoria, Australia, 1988.
2. R. Hadgraft and M. R. Wigan. Assessment and Improvement of the Codification and Delivery of Engineering Experience. In *Proc., Watercomp '89*. National Conference Publication No. 89/8. Institution of Engineers, Australia, Canberra, ACT. 1989, pp. 160–164.
3. R. Hadgraft and M. R. Wigan. Towards Effective Field Support and Retraining for Engineers Who Use *Australian Rainfall and Runoff*. In *IEAust. Hydrology and Water Resources Symposium*. Christchurch, New Zealand, National Conference Publication 89/19. Institution of Engineers, Australia, Canberra, ACT. 1989, pp. 468–472.
4. R. Hadgraft and M. R. Wigan. A Possible Prototype for a New *Australian Rainfall and Runoff*. In *IEAust. Hydrology and Water Resources Symposium*. Christchurch, New Zealand, National Conference Publication 89/19, Institution of Engineers, Australia, Canberra, ACT. 1989, pp. 481–482.
5. M. R. Wigan. Information Provision and Access: A Users View. *Library Software Review*, Vol. 8, No. 3, 1989, pp. 130–137.
6. *Australian Rainfall and Runoff* (3rd ed.). IEAust, Sydney, 1987.
7. M. R. Wigan. *Australian Personal Travel Characteristics*. Special Report SR 38. Australian Road Research Board, Vermont, Victoria, Australia, 1987.
8. M. R. Wigan. The Secondary Use of Transport Survey Data. In E. Ampt, A. J. Richardson, and W. Brog, *New Survey Techniques in Transport*, VNU Science Press, Netherlands, 1985. pp. 131–148.
9. T. Datta, K. H. Tscuchiyama, and K. S. Opiela. *Cost-Effective Inventory Procedures for Highway Data: Users Manual*. Report FHWA-IP-85-14, FHWA, U.S. Department of Transportation, 1985.

10. M. Perfater and G. Harris. *An Investigation of the Uses of Videotape in Transportation Operation*. Report FHWA/VA-86/20. FHWA, U.S. Department of Transportation, 1987.
11. J. M. Sime and J. H. Hudson. *Photolog Laser Video Disk for Highway Monitoring, Evaluation and Data Storage*. Department of Transport, Wethersfield, Conn., 1986.
12. J. H. Hudson and J. M. Sime. *Procedure Manual for Photolog Laser Disc Production*. Department of Transport, Wethersfield, Conn., 1986.
13. Laser video discs, computer discs for road evaluations. *Better Roads*, March 1985.
14. D. C. Andreasen. *Disaggregation of Accident Data by Road Hierarchy*. Internal Report AIR 1123-1, Australian Road Research Board, Vermont, Victoria, Australia, 1983.
15. M. Fritz. Still-Frame Audio: 300 to 1 Compression Ratio Maximises Disc Space. *CBT Directions*, March 1989, p. 10.
16. J. Dangermond. A Classification of Software Components Commonly Used in Geographic Information Systems. In D. Peuquet and J. O'Callaghan. *United States/Australia Workshop on Design and Implementation of Computer-Based Geographic Information Systems*. IGU Commission on Geographical Information Systems, Amherst, N.Y., 1983.
17. M. R. Wigan. *The Use of Prototyping and Graphics Methods for Road Information Systems*. Technical Manual ATM 25, Australian Road Research Board, Vermont, Victoria, Australia, 1988.
18. T. Hendley. *CD-Rom and Optical Publishing Systems*. CIMTECH Report 26, Hatfield Polytechnic, Hatfield, U.K., 1987.
19. M. R. Wigan. ARRB Information Resource CD-Rom. Publication CD-Rom-1/ISO 9660, Australian Road Research Board, Vermont, Victoria, Australia, and 22-p. booklet as supplied with this CD-Rom separately available, in press.
20. J. K. Beardmore. Laservision Technology as Applied to Route Guidance Systems. In *Vehicle Route Guidance, Navigation and Control*, IEE Colloquium, London, U.K., 1987, pp. 11/1–11/6.
21. Oracle Communications. In *Integrated Transportation Information System*. Report TP 8293E, Montreal, Canada, 1987.
22. V. Karager. La Carte Electronique. *Navigation*, No. 141, 1988, pp. 63–69.
23. C. N. G. Dampney and B. D. Johnson. Database Management Systems for the Geosciences. *Exploration Geophysics*, Vol. 19, No. 1/2, 1988.

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