Application Challenges for Geographic Information Science: Implications for Research, Education and Policy for Transportation Planning and Management

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Abstract: *Decisions made by transportation planners and managers impact our daily lives, and these professionals increasingly rely on information technology to assist in their work. This application area provides numerous challenges for geographic information science. This paper begins by describing the dimensions of these challenges, and uses several scenarios to illustrate where we are now and where we may be going. The views of the future from the scenarios lead to a discussion of a series of research challenges and questions. These questions are framed within the 10 research challenges defined by the University Consortium for Geographic Information Science. The paper concludes with a discussion of the educational needs of the transportation community.*

The Dimensions of the Application Challenge: Transportation Planning and Management

Choices about transportation alternatives permeate our daily lives. We are accustomed to making quite sophisticated decisions about the times we travel, the transportation mode we choose, the routes we select, and the multipurpose trips that we link together as we plan our day. Because the impact of traffic congestion (as well as events such as automobile accidents and spills of mysterious white powder on the roadway) is so evident and striking to us as individuals, transportation in our regions is often high on our personal agenda of policy issues. Other decisions that we make, such as choices of resident and employment location, are consciously influenced by regional transportation patterns, as well as by our current economic status and stage in life. Transportation is also a focus of major media attention, with daily news coverage of accidents and traffic reports on the radio station. Stranded cars are popular photo opportunities for journalists covering the impacts of ice storms, hurricanes, and floods. A look at any local newspaper will reveal a focus on land use and transportation issues. It is these issues that impact our rents and property values as well as our quality of life. The media covers the issue, whether it be the "highway revolts" that involved large numbers of citizens in the 1960s or a small group of residents lobbying for reduced speeds on a local street. It is no wonder that transportation issues are consistently high on the agendas of our local, state, and federal politicians.

In comparison to other public issues, the public seems relatively well informed on the relationships between population growth, land use patterns, congestion, and sprawl. Recently, the mayor of Atlanta called for regional land use control mechanisms to deal with increasing traffic congestion. The mayor pointed out that new employers would not want to relocate to Atlanta if there is transportation gridlock. It is likely that many Atlanta residents had noticed this condition and recognized its potential outcome long before the mayor proposed something as radical (in the U.S., at any rate) as regional land use planning and coordination. Although modeling the relationships between land use and transportation is complex, an intuitive understanding of their interrelationships seems clear to informed citizens. Calls for communities to be more "livable," "sustainable," or "transit-friendly" are well publicized by the press and supported by politicians in election speeches.

The professionals that work in the field of transportation planning and management have diverse responsibilities. Each state has a transportation department that is responsible for planning, designing, constructing, and maintaining the transportation infrastructure. Many of the professionals in the Department of Transportation (DOT) are civil engineers, trained in the areas of design and construction. They work hard to make sure bridges are safe and to ensure that automobiles (and their passengers) are not damaged by hitting potholes in the roadway. Because transportation projects are sometimes locally controversial, they have also often found themselves embroiled in land use conflicts.

Also involved in the transportation planning process are the professionals in the various metropolitan planning organizations (MPOs). These professionals are typically educated as urban and regional planners or civil engineers. Charged with the task of travel forecasting under the Intermodal Surface Transportation Efficiency Act (ISTEA) and the newer Transportation Equity Act, these professionals evaluate major highway capital improvements using models developed 25 years ago. Under ISTEA, the planners were instructed to evaluate a broader range of transportation alternatives and to integrate land use more directly into the forecasts. It is not surprising that the earlier models were not well suited to the task. The Travel Model Improvement Program was initiated to improve these models, with the following objectives:

- increasing policy sensitivity and the ability of planners to respond to emerging issues of growth management, environmental concerns, and changes in the activity patterns of households;
- redesigning the forecasting process to reflect the more complex behavior of today's traveler and to take advantage of changes in data collection technology;
- making the model results more useful for decision makers; and
- improving land use and development forecasting procedures to provide better information for travel demand forecasting and to assure that a feedback loop occurs between transportation and land use within the models (Shunk et al. 1995).

A third group of transportation professionals is concerned with the planning, design, maintenance, and operation of transit systems. These professionals also are generally trained as urban planners or civil engineers and engage in activities of project prioritization and selection, demographic analysis for route design, public information, construction and maintenance of facilities, and system operations. In recent years, the transit professionals have responded to such challenges as providing access to those covered under the Americans with Disabilities Act, designing more flexible transit alternatives for low-density development patterns and evaluating the accessibility of transit for citizens in Welfare to Work programs.

The Challenge of Transportation to the Quality of Life in our Communities

The interstate highway programs reflect the profound impact of the public's investment in transportation. Federal expenditures have given the citizens of the U.S. unrivaled mobility. The negative impact of this mobility is increased air pollution and the obvious loss of open space due to sprawl. The fabric of neighborhoods and towns, and their social communities, has been torn by highways, and many transit-dependent communities remain underserved. Time lost in traffic congestion impacts our national productivity as well as our personal quality of life. Efforts to reduce congestion through less costly programs of Transportation Demand Management (also known to some transportation planners as Tinkering and Dickering on the Margin) have had only marginal success.

Two significant federal actions in the 1990s illustrate the importance of transportation to the national needs and deserve mention here. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) changed many of the processes and procedures traditionally used in transportation planning (Perkins 1998). The focus on new construction was lessened and a stronger emphasis was placed on the management of current and future transportation resources and the encouragement of increased transportation options. The MPOs were given the responsibility for evaluating and modeling relationships between land use and transportation decisions within their transportation plans. Management systems were mandated to provide data and improve analysis in the development of state and metro-area transportation plans. This action has resulted in a renaissance of long-disused land use models and the development of new models. Greater public involvement in transportation decision making was also specified in ISTEA.

Transportation agencies were required to show "meaningful" reductions in air quality emissions and highway congestion levels. Among other themes, management systems based on information technologies were required, and many agencies adopted geographic information system (GIS) technology to comply with the mandates. Sutton et al. (1994) described the conceptual design of a system-based GIS-T technology for congestion management system that fulfills one of the mandates. Other transportation management systems extensively using GIS technology include those for pavement management (Thomas 1998).

The Transportation Equity Act (TEA-21) continues many of the programs begun under ISTEA (http://www.fhwa.dot.gov/tea21). Management systems are intended to improve the process of deciding on project-funding priorities, and GIS technology has been incorporated in some of these processes (Ibaugh 1997). The requirements focus on the collection, management, analysis, and dissemination of spatially related data to assist in the evaluation of transportation alternatives. Under TEA-21, increases in funding for road construction, as well as non-roadway projects, and for Intelligent Transportation System (ITS)-based projects are mandated. ITSs use communication and computer technologies to approach a number of transportation challenges. Research and development funding (especially for ITS-related work) is also increased under TEA-21.

One section in TEA-21 is of particular note to the remote sensing community within geographic information science (GIScience). Section 5113 requires the U.S. Secretary of Transportation to develop and implement a national policy "to validate commercial remote sensing products and spatial information technologies for application to national transportation infrastructure and development and construction," in cooperation with the National Aeronautics and Space Administration, university research consortia, and others. Some of the most promising emerging uses of space imagery for transportation include:

- transportation database augmentation of existing GIS databases maintained by state and county governments and MPOs;
- infrastructure inventory management for the selection of right-of-way corridors, intermodal facility siting, change monitoring, and pavement maintenance;
- enhancement of transportation planning, including improved land use information;
- environmental assessment and monitoring of compliance with environmental regulations and changes in vegetation health from road runoff;

- hazards assessment and management, including search and rescue, accident detection and response, damage assessment due to natural disasters, emergency response planning, and mitigation; and
- traffic management, including monitoring of traffic congestion and flow patterns (Brecher 1999).

How can geospatial data technology and GIScience contribute to improving our transportation system? To enliven the discussion and raise issues for debate, we next present scenarios for where we are now and where we may be going.

Where We Are — Scenario 1:

A GIS group within a state DOT is struggling with a legacy GIS. The system comes from a CADD tradition and its use has focused on supporting engineering design. A statewide layer of major roads has been digitized using Digital Orthophoto Quarter Quadrangles (DOQQs). Much of the discussion regarding the design has focused on decisions about the linear referencing system.

The DOT road layer has increased positional accuracy over some other public data sources for street centerline files. Some attribute data are attached to the vector layer, including the number of lanes and traffic volume information; however, street names and address ranges are absent. Several contracts to outside GIS consultants to use conflation techniques for adding names and address ranges have ended in failure. So far, resources have focused on data development, and few applications have been developed. Management views the system as an expensive investment with little perceived benefit.

Although another state agency that focuses on protection of the environment has information (including land use and wetland layers) that the transportation engineers would find useful, data sharing between the agencies has historically been difficult because of translation difficulties between the vendor platforms. This problem is in the early stages of improvement. The DOT is willing to share its road layer with others, but there have been few takers.

Where We Are — Scenario 2:

Just 50 miles away, the state Transit Authority is also investing in GIS. After five false starts with pilot projects, GIS implementation is now expected to be successful. The Transit Authority evaluated the DOT's road layer, but concluded that it would not work for many transit applications that require street and address data. They also inquired about the statewide 911 program, but discovered that this program is using proprietary street data that cannot be shared.

Consequently, the Transit Authority recently approved a large expenditure to purchase street files from a private vendor. Although the vendor promised highly accurate attribute data, the GIS staff is discovering that the quality varies widely in different regions of the state. Although the GIS staff planned to create Federal Geographic Data Committee-compliant metadata, they are having difficult assessing the accuracy and collecting other important metadata fields from the data vendor. The Authority has plans for many GIS applications, including interactive mapping on the World Wide Web (Web), but none has actually been developed over the past 5 years of experimentation with GIS.

Where We Are — Scenario 3:

An MPO in the same state has the mandate to incorporate the interaction between land use and transportation into their transportation model. The MPO has used a standard transportation model for many years, but the structure of the network data required for the model input is based on a matrix data structure (travel times from the centroids of traffic analysis zones). The planners use a stage-wise modeling approach where demand is generated by the characteristics of the population in fixed traffic zones; demand is allocated to destination zones using gravity relationships and, given origin-destination pairs, the route choice is then predicted.

Results from these earlier models are reflecting less and less well the complexity of the travel patterns in the region. The planners have heard that other agencies or consultants have developed software tools to allow the use of GIS for data input to and data display from this model, but they have not had time to investigate further. Some of the earlier land use/transportation models are also being redesigned to be loosely coupled with GIS; however, the staff has not had time to evaluate them.

Where We Are — Scenario 4:

A small non-profit organization funded by the state DOT and Transit Authority handles ride-share information and provides ride-matching information to the public. A young staff member with some experience in GIS and computers has big plans. At a recent national GIS conference, she noted many innovative uses of interactive mapping technology on the Web. She would like to develop an Internet application that provides information on how many potential ride-share matches there may be between a person's home and their work destination, information regarding the bus stops and routes closest to their home, and up-to-date information on road construction in the region. Unfortunately, the Transit Authority cannot share their new street files with her because of vendor contract restrictions on their use for Internet applications. With only a small budget available, she has decided that the first step is to take a continuing education course in Visual Basic and see what she can do on her own.

Where We're Going (Maybe)…

Several years later, the state DOT is much smaller, providing some regulatory and intergovernmental services.[1] Many of their responsibilities have been outsourced and privatized. Some policy-making and planning functions are still being done internally, and the agency is now held more accountable by the public to meet its stated goals with respect to environmental quality. The entire GIS staff has left the organization and all GIS work is now outsourced to a private company.

Private organizations have become the geospatial data and service providers.

The good news for the former DOT GIS staff, now in a successful private firm, is that many of their technical problems are solved. Increased interoperability between systems means most translation problems are in the past. However, the staff does note that serious interoperability issues remain. Universal network connectivity is now a reality and a distributed, component-based global network is in place. The focus is now on clients and services, and not on applications, products, and platforms.

A "second-generation GIS-T renaissance" is occurring inside of the DOT now that better data and services are available to them. The management and performance monitoring systems envisioned under ISTEA and TEA-21 are largely in place. Some issues related to data update remain problematic.

GIS-T conferences were once dominated by public sector planning and transportation professionals. The new range of consumer products has made everyone a GIS-T consumer, even though they are not aware of it. Most consumers are whizzes at using their map-based "yellow pages," trip planners, and mobile 911 emergency units. Nearly everyone has PDAs and mobile IP addresses with "voice, e-mail, Web browsing, computing, and mobile positioning services. The combination of cellular technology, mobile positioning systems (GPS [global positioning system] or cellular based) and thin client computing is creating entirely new markets for transportation information services (Fletcher 1999)."

The Transit Authority must now have the most current and accurate network data, since their entire electric bus fleet is spatially aware and all scheduling and logistics are automated. Most of their data is now from high-resolution remote sensing imagery and is inexpensive relative to the cost of their original street files, although costs and pricing policies are still a concern. In fact, the information environment is so rich now that managing the glut is becoming problematic. New "commuter computer" systems with on-demand pickups are proving successful in even the most sprawling suburbs.

The planning staff at the MPO is now using an entirely different set of models. The older stage-wise processes are gone. Microsimulation models are now the order of the day. Activity-based approaches predominate. In these models, space, time, and daily activities are integrated within a GIS context.

The young staff member from the non-profit organization has done well and is now President of a large firm that develops Web-based transportation applications for transit authorities. Web-based transportation applications have grown rapidly.

Linkages between Transportation and the UCGIS Research Challenges

The future scenarios described above provide many research challenges and raise a variety of questions. Fletcher (1999) posed an interesting question: "How [do we] operate in a world with millions of spatially enabled, Internet attached travelers, shippers, carriers and vehicles – each collecting and processing real time positions locally. Each of these nodes will demand and expect connections to hundreds of geographic data reference sites, including those maintained by state and local transportation agencies."

The vendors in this mass market for the new spatially enabled consumer toys are different from the current GIS-T vendors. Who will they be? Who will remain focused on the data capture, maintenance, and warehousing of the transportation network data? How will procedures of data capture and maintenance change with the increased availability of high-resolution satellite imagery?

Many GIS-T services will be found within standard desktop applications using smarter tools and interfaces. The interfaces will be increasingly sophisticated, incorporating three-dimensional visualization, eye tracking, and speech recognition. What about the users of the new GIS-T services? Will they be content to just browse geographic data? If they have only a limited understanding of more complex spatial analyses, will they use the new tools incorrectly? Will we have enough educated geographic information scientists to develop these applications correctly and responsibly?

All of the UCGIS research challenges are reflected in the needs of the transportation community. The scenarios described in the preceding sections strongly point to the importance of "Spatial Data Acquisition and Integration." Multiple agencies are involved in various aspects of transportation planning, and management and data sharing have proved difficult. The data sharing arena includes producers, users, and integrators who collect data from the field, legacy databases, and from other data producers. For transportation planning applications, accuracy and currency are major concerns. The integration of data from multiple sources, at a variety of scales, is the order of the day.

Of particular note to the data integration challenge is the recently formulated DOT Remote Sensing Applications to Transportation Project. This 5-year research project is intended to help develop the technology base for remote sensing applications to transportation. Research is expected to focus on the following:

- automating the transfer of remote sensing information in a form suitable to perform transportation analysis;
- developing methodologies for choosing appropriate remote sensing technologies and systems for transportation;
- developing automatic image analysis processes for application to transportation; and
- developing new approaches for remote sensing applications to measure regional pollution levels.

Research is already underway in this important area. For example, the feasibility of using a combination of satellite imagery with coordinated traffic ground counts has been studied at Ohio State University (Merry et al. 1996).

Particular demonstration projects will focus on a survey of user interest, and monitoring tools for pipeline safety, and may include remote sensing applications for the management of:

- regional traffic;
- freight terminals and ports;
- rural infrastructure;
- regional databases for transportation planning;
- National Environmental Policy Act streamlining and environmental assessment; and
- disaster response.

"Distributed Computing" is core to the successful use of geospatial information technology in transportation planning. This is clear from considering the implications of Fletcher's future scenario above. How will we operate in a world with millions of spatially enabled, Internet-attached travelers, shippers, carriers and vehicles – each collecting and processing real time positions locally?

Because information about transportation is of vital interest in our daily lives, we are already seeing many innovative uses of the Internet in providing geospatial information for transportation. Some of these applications are using state-of-the-art Internet GIS (Peng 1998). Real-time transit route and schedule information, road construction, and traffic information are several of the more interesting current applications on the Web (for a Web application that tracks buses around a university campus, see http://blis.units.ohio-state.edu, and for an application that tracks buses on several Seattle routes, see http://www.its.washington.edu/mybus). Future research will focus on the customization of trip planning for both automobile and transit users based on real-time traffic information and the traveler's own trip origin and destinations. Research is needed to develop algorithms for dynamic trip planning. The focus on customization for individual travelers provides an opportunity for dynamic traffic management by dynamically assigning or advising travelers of the best route to take. Research is also needed in dynamic traffic assignment to rebalance the traffic based on the changing congestion levels of road segments and travelers' destinations.

Transportation applications require data objects, an area in which GIS has typically not dealt with well. Examples include non-planar topology (e.g., overpasses) and route structures (e.g., bus routes). Note that bus routes take on characteristics that are independent of the road segments that comprise them (e.g., service frequency and headways, and bus stops between street intersections).

These requirements mean that transportation applications are particularly in need of research in the area of "Extensions to Geographic Representations." Two of these needs are briefly discussed here. The first is the lack of agreement among transportation organizations on defining transportation objects. This problem is well described in a recent paper by Dueker and Butler (1999). There are two major problems in defining transportation objects: different definitions of roads, and different criteria used to break roads into logical segments. In their paper, Dueker and Butler proposed a new GIS-T data model that defines relations among transportation data elements. A National Cooperative Research Program project 20-27(3) is in the process of attempting to bring consensus to GIS-T data models. The Dueker-Butler model represents one approach. It is based on a feature (object) database approach best suited for a federated system's environment with legacy data of varying spatial accuracy. An alternative approach is a location (geometry) approach as suggested by Sutton (1999). This alternative is designed to work in an environment where the location of transportation features would be redigitized using high-precision GPSs. This approach focuses on enabling linking of spatially accurate tracking or events to a spatially accurate map base.

Another crucial need in the area of extensions to geographic representations relates to the dynamic character of transportation applications. Spatial-temporal extensions are necessary. Transportation is a much more dynamic process than many traditional GIS subjects. Traffic congestion can materialize in as little as 5 minutes, and cannot easily be handled in time slices. Transportation involves movement over time. Many transportation analyses require visualization of these relationships. Finally, transportation infrastructure changes characteristics in important ways over time (e.g., reversible lanes, and peak versus off-peak services and charges).

How do we represent moving objects such as vehicles, package shipments, and storms in a GIS? Dueker (1999) asks how we incorporate a new Dynamic or Moving Object class into GIS-T. He outlines three approaches:

- a static object with frequently changing positions;
- a new object class with location as an attribute rather than part of the definition; and
- a moving object construct with starting location and attributes of direction, speed, and destination to define a moving object.

We note that in transportation applications there are frequently objects whose attributes change over time. These changes often occur during the course of a day (e.g., reversible lanes and transit ridership on a bus line as passengers board and disembark).

Advances in multimedia technologies, 3-D and 4-D data models and visualization, data warehousing/mining/management, autonomous agents, etc., will continue to have a significant impact on GIS technologies and alter our views of how transportation planning and management is best done. For example, rather than think in terms of photo-realistic modeling/visualization of every aspect of a transportation network problem, it may be more useful in some contexts to link abstract maps to the libraries of spatially -referenced video clips of traffic congestion, transit/road settings, etc.

Research issues in the "Cognition of Geographic Representation" are particularly rich to an application area that centers on physical movement around our built and natural environments. Knowledge of routes (procedures for getting from one place to another) is one of the most fundamental forms of spatial cognition, and research on wayfinding and navigation can contribute to routing algorithms. A provision for wayfinding information to drivers in real time raises issues of cognitive attention, sensory modality, and human-computer interaction that go well beyond traditional models of map use and dashboard design.

In the scenarios described above, we saw the complexity of the transportation-planning environment with its organizational structure across multiple federal, state, and local organizations. Currently, many transportation organizations produce and/or purchase street data for different purposes. Data sharing of this important transportation framework layer has proved difficult.

Various aspects of the "Interoperability of Geographic Information" challenge are relevant to this issue. Data sharing and interoperability are usually difficult, but are even more difficult than one might think in the case of transportation planning and analysis. The street network is a key "framework" data set for the important set of GIS applications that rely on address matching. However, there are a number of multiple representation issues and "one size does not fit all" applications. Transportation planning requires different road representation models for different applications. For example, pavement management and engineering/construction applications have traditional CAD and aerial representation needs, but routing and transportation logistics require network connectivity models with road types and route numbers that can overlap.

What is the appropriate model for the transportation network? The street centerline is useful for some applications. However, for other applications we need to consider the streets as having lanes and width. Should we include geometric width (lanes) as attributes or as geometric features? We might use a centerline for each direction. However, what if there is a median or exit ramp? Other issues involve 3-D problems. How do we handle overpasses, tunnels, and elevated roads? Should streets be the geometric feature (either centerlines or areal features) or the voids between the blocks?

Other representation issues involve segmentation of streets and routes. Should the segmentation of roads be from intersection to intersection? Or perhaps the segmentation should be from driveway to driveway? When we are representing bus routes, we discover that many bus stops are not at street intersections. Should the segmentation of bus routes be from bus stop to bus stop? Software vendors are making improvements to dynamic segmentation functionality. This functionality helps with the segmentation problem, but can also complicate our use of, say, ridership data that have simpler analytic meaning if segmentation is from bus stop to bus stop rather than a percent-of-distance along an otherwise segmented route.

Many applications in Intelligent Transportation Systems (ITSs) are emerging that provide research challenges and opportunities. These applications include advanced traveler information systems, automatic trip planning, in-vehicle navigation systems, vehicle tracking and routing systems, and incident management systems. These applications require interoperable, comprehensive, and high-quality data with locations and time as central dimensions. They also require temporal-spatial data models that can better handle real-time moving objects. Interoperable data models should be built to better represent dynamic objects, linear objects, and networks. More research is needed to improve algorithms to do dynamic routing to take advantage of real-time traffic information.

Interoperability issues raise important and deep questions in the area of transportation because of the multi-representational needs described above and also because of the changing nature of interoperability efforts as technology evolves. For transportation applications, there will be an increasing flood of data as distributed and mobile computing and ITSs will involve widespread real-time monitoring of the location and behavior of vehicles, people, facilities, etc. We should view this information as a rich, dispersed feed of raw, georeferenced data that must serve multiple purposes (not just transportation planning). This introduces interoperability and information management/integration issues that push the envelope on what today's technologies can handle.

As data and applications increase, it becomes all the more important to view the applications as layered components. We do not want to create single-purpose applications built on top of independently maintained road networks. For example, the Massachusetts Executive Office of Health and Human Services spends approximately $86 million per year on the transportation of clients with special needs. While this agency is outside the other transportation-related agencies and has special data needs (e.g., which buses are accessible and where are pickups possible), it is hoped that their scheduling and routing applications draw upon shared-road networks, geography, and demographics as well as routing algorithms, user interfaces, and the like.

Object-oriented modeling is likely to improve our application designs. However, the real needs for transportation planning go far beyond improved capacity to handle inheritance and multiple representation. In the future, useful object models are likely to be structured around conceptual features (e.g., of routes and passengers) rather than geometric features (their x, y, z shape and location). This will further complicate issues of interoperability.

Similarly, "Scale" issues arise frequently in GIS-T applications. Navigation, tracking, and event location using GPS require different scales than network analysis for regional transportation analysis. Do we represent streets as centerlines or as lanes? How do we deal with off-ramps? There is a need for research to assist in the development and standardization of intermediate layers of digested data that are built from fine-grain road and parcel layers. Increased access to enormous volumes of fine-grain data about parcels, land use, road and road-usage characteristics, etc., is not by itself sufficient to feed all our models and algorithms. Research is needed to digest the fine-grain data into intermediate layers that form a more useful set of building blocks for our models and algorithms. An example of current research work at the Massachusetts Institute of Technology focuses on adding local land use characteristics into models that predict mode choice and "trip chaining" behavior. The idea is to use factor analysis (and related techniques) to distill road density, cul-de-sac density, land use patterns, and other characteristics into a few summary measures (for the neighborhood around one's home and work place, and the corridor in between). These more aggregate measures can then be used as basic building blocks in models that predict travel behavior.

The transportation forecasting models provide a rich setting for research in the area of "Spatial Analysis in a GIS Environment." As described, above, this challenge is particularly relevant in our attempt to model more closely the complex travel patterns of households and to create the feedback loop between land use and transportation. The history of these models is long and rich, and sometimes controversial. As we move from traditional stagewise process models to disaggregate, behavior-based models, what GIScience research is needed to support the development? Will GIS be loosely coupled to or central in the design of new land use/transportation models? In the forecasting applications, spatial-temporal data structures are also core concerns.

Traditionally, GIS is used in transportation for project-level engineering and program-level planning. However, as the primary mission of state DOTs evolves from design and construction to one of maintenance and operation of existing infrastructure, the focus will be on system-level management and decision support systems. Furthermore, as transportation-planning models move from the traditional aggregated zonal level models to more disaggregated microsimulation models, GIS-based data that are more detailed is required. As this change occurs, operational information will be used more directly in the planning process, and the results from planning models will feedback into the operations models.

This emerging trend to unified transportation system management will require a flexible and interoperable network data model, and transportation data warehouses that are accessible and suitable to a variety of both operational and planning decision support systems. Research is needed to increase the interoperability between GIS data and operation and planning models. Particularly, research is needed on automatic data transformation and extraction between dynamic objects, linear objects and real data to serve the needs of both operational and planning systems.

The transportation layer is one of the current National Spatial Data Infrastructure (NSDI) framework layers. Transportation features are therefore a key element in "The Future of the Spatial Information Infrastructure." What research is needed to ensure that data sharing of this crucial framework layer can be accomplished? What are the major organizational obstacles to data sharing among transportation organizations? It seems that transportation agencies often do not "play well" with others. There are some historic reasons for this, including:

- adequate funding that lessens the necessity of data sharing;
- a "stove-pipe" mentality where projects are completed in-house from beginning to end, including data collection;
- network data structures that are application- and mission-specific (i.e., state DOTs are not concerned with local roads);
- technology and modeling traditions that make it difficult to share a common network across multiple applications; and
- link-node data structures that are not well suited for transactional updating.

The NSDI framework transportation standard tries to address some of these technical problems.

Changing technology is continuing to expand and complicate our notions of GISs and the GIScience needed to address relevant transportation applications. Expanded and higher-speed networks change the nature of what we mean by data sharing and model integration. For example, there is a shift in focus from squirreling away data sets within an agency to sharing data services. A specific instance is the MIT ortho server (see http://ortho.mit.edu) that slices and dices digital orthophotos on the fly to produce customized snippets of imagery that can be delivered (at appropriate resolution) via the Web to browsers and applications using Application Programming Interfaces (APIs) and formats that fit within interoperability standards. The use of orthophotos enables transportation networks to be readily overlaid on imagery, and the shift in focus transforms the interoperability issues from questions of archival data format to APIs and client-side data structures.

"Uncertainty" in geographic data and GIS-based analyses appeared as a core issue in the transportation planning scenarios. Dueker and Butler (1999) point out that there are two participants whose accuracy requirements drive the data sharing process. These two participants are: 1) emergency management, E911, and computer-aided (emergency) dispatch (CAD); and 2) vehicle navigation applications with the most demanding need for spatial accuracy of street files.

Dueker and Butler (1999) note that the latter application area "is sometimes referred to as 'map matching' of GPS-derived location of vehicles to the correct street or road in the road database. Identifying the correct ramp of a complex freeway interchange where a disabled vehicle is located is a particularly demanding task. Similarly, ITS tolling applications may require tracking vehicles by lane of multiple-lane facilities."

These two groups of participants have the most demanding need for currency, completeness, and accuracy. How can GIScience help them visualize the uncertainty in the spatial data for these critical activities?

"GIS and Society" issues permeate transportation planning. Issues of equity are central to the mission of transit planning organizations. How can we improve our transportation services for everyone? Both ISTEA and TEA-21 call for increased public participation in transportation policy. Can GIScience research in this area improve our ability to involve the public in meaningful ways in this process?

Linkages between Transportation and the UCGIS Education Challenges

All of the UCGIS education challenges are reflected in the educational needs of the transportation community. In the case of distance learning and other "Emerging Technologies for Delivering GIScience Education," the converse is also true! One of the attractions of distance learning as an emerging technology is the increased option it gives students to study in a place and at a time of their choice. Rather than make that additional trip to the university during rush hours, students may work at home at midnight. Students outside of easy commuting range may participate in virtual courses. Faculty members discover that using e-mail and listservers reduces their "student traffic" during office hours.

"Supporting Infrastructure" is always a concern in GIScience where laboratories must be funded, built, staffed, and maintained. To teach transportation applications today requires the acquisition of specialized GIS packages or "extensions," an added licensing expenditure in the absence of software donations. Exposure to some of the more specialized state-of-the-art modeling software in transportation that often incorporates a GIS component would benefit students in professional-oriented programs, but the specialized packages are often expensive and the vendors, accustomed to working with a narrow client group, are less familiar with university donations and site license programs.

"Access and Equity" are core issues in transportation policy as well as GIS education. Issues of equity are a focus in both ISTEA and TEA-21. The transportation application area (particularly transit applications) could provide strong examples within a GIS curriculum to illustrate the importance of ensuring that GIS technologies and data are available to disadvantaged groups and impaired individuals. Transit-dependent populations and those with physical disabilities benefit greatly from increased ease of access to transit information.

The education priority related to "Alternative Designs for Curriculum Content" focuses on changing a "one-size-fits-all" education model to tailoring GIScience education in diverse professions. Many transportation planners and engineers are educated in civil engineering departments. Although some civil engineering departments are active in GIS education, it appears that it is not yet common to have GIS required in this engineering field. Educational materials tailored to transportation applications are not as widely available as those related to environmental applications, for example.

"Professional GIS Education Programs" may help cover some of the gaps in GIS education for the engineering community. There is currently a gap between supply and demand for GIS-T professionals, which is likely to increase. Professional training for employees in state DOTs and for transit professionals has been supported by the federal DOT for a number of years. Again, the preparation of tailored educational materials is required. Perhaps transportation and transit application exercises and lecture material, developed for these professional courses, could be shared more widely within the academic community.

"Research-based Graduate Education for GIScience Students" should cover many of the topics described in the research section above. It is not clear where some of these topics (i.e., linear referencing systems and spatial-temporal data structures) appear in today's graduate curriculums. Effective knowledge of the underlying principles for GIS-T applications should be included within all GIScience graduate curriculums.

The "Learning with GIS" priority advocates incorporating two emphases into American education. In learning with GIS, planning and engineering students are exposed to GIS transparently, while studying specific transportation problems. In learning about GIS, students focus directly on the theory and methods of GIS. To make use of the new GIS-T technology will require users and developers to be better educated.

"Accreditation and Certification" is an interesting topic for this application area. Both engineering and urban planning are disciplines that have both certification and accreditation processes. The examinations for planning certification now incorporate some basic GIS questions. It would be interesting to see if the Engineer-in-Training and Professional Engineering (P.E.) exams currently cover any GIS topics. Conversely, the certification of GIS professionals might incorporate questions about the specific concepts underlying the transportation framework layer.

The current generation of transportation GIS practitioners is not well trained in the geographical sciences. Many only know GIS from a software vendor's training course, and are unable to use GIS for much more than data visualization. This lack of background makes it difficult for them to articulate their needs to vendors because they do not know the difference between limitations in the software versus theoretical constraints. This also makes them unable to fully exploit GIS because they know little about spatial analysis and cartographic principles. These deficiencies point out a need to introduce basic GIScience principles into traditional transportation curricular, and to provide short course training to the current generation of transportation professionals that is not vendor-centric.

Policy Implications of Transportation Applications

There are many places in the TEA-21 legislation for the innovative use of GIS technology. GIScience research supporting this innovative use is crucial to new applications and decision support systems. A focus on improved data collection and management, particularly of geospatial data, is evident in both the ISTEA and TEA-21 legislation. The policy implications of improvements in the ability of transportation planners and engineers to collect, manage, analyze, and visualize geospatial data include:

- improved analysis of transportation project prioritization and investment;
- enhancement of citizens' abilities to participate in the transportation decision-making process;
- reduced congestion and improved environmental quality; and

- improvement in the efficiency and equity of our transportation alternatives, and better balanced and more sustainable transportation systems.

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[1] Many of the ideas in these future scenarios are from Fletcher (1999).