PB98-109762

GIS APPLICATIONS FOR PUBLIC TRANSPORTATION MANAGEMENT

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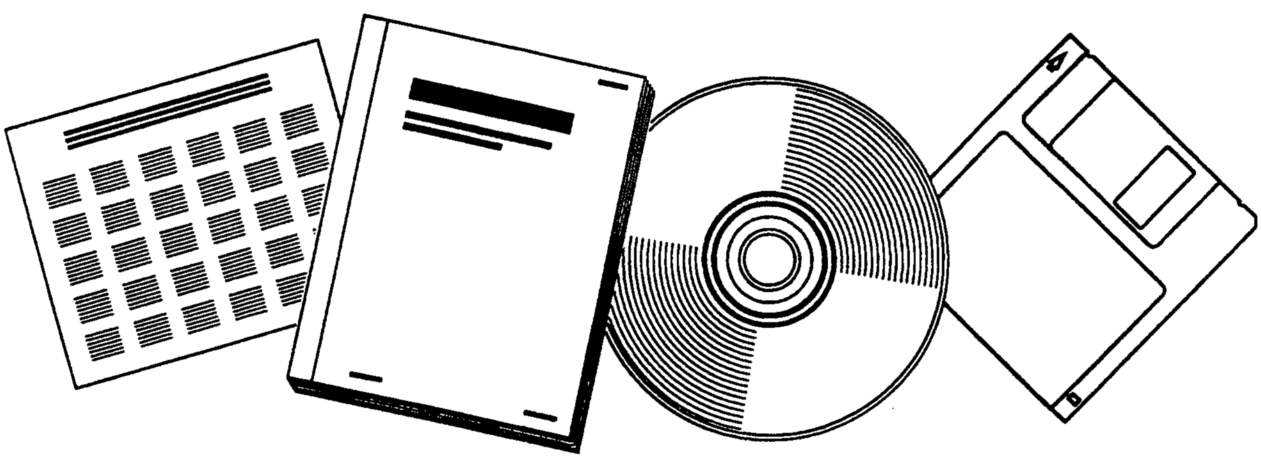

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GIS Applications for Public Transportation Management

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A consortium with · Florida State University · Florida A & M University · Florida International University

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16 Abstract

Geographic information systems (GIS) have proven to be powerful tools that are capable of storing, displaying, and analyzing spatially distributed information. GIS has been used in a wide array of transit applications including demand modeling, service planning, operations, service monitoring and evaluation, customer services, marketing, facility and real-estate management, etc. However, current GIS lacks the adequate capabilities of handling temporal information. As a result, analyses are mostly performed assuming a fixed time point. Longitudinal analyses that take time into consideration cannot be easily accomplished. For many applications, information constantly changes with respect to both space and time. A temporal GIS capable of handling temporal as well as spatial information will greatly expand the current GIS applications and allow new information to be obtained. In this report, results of a study on temporal GIS applications to various transit management tasks are summarized. The state-of-the-art of temporal GIS research and development is reviewed. Potential benefits of applying temporal GIS technologies to transit are investigated. A simple method to record the changes in spatial objects and their attributes with respect to time has been developed using PC ARC/Info relational databases and a means to query the spatiotemporal data. The use of this temporal GIS method is illustrated using an example related to transit planning and service evaluation.

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EXECUTIVE SUMMARY

INTRODUCTION

Despite the rapid development and wide application of GIS and GIS-T tools, it appears that the development of GIS capabilities in dealing with temporal information is still limited. Current GIS software mainly supports cross-sectional spatial analysis, that is, spatial information may be analyzed for a fixed time point or time period for which information is assumed to remain unchanged. The reality is, of course, different. Population, economic activities, transportation facilities, travelers' behaviors, to name a few, all change with time. These changes and their interactions with the transportation system need to be understood and considered in transportation decision-making. With the current GIS technology, it is difficult to answer questions such as where and when changes occur, what patterns may be observed about the changes, and what may be the underlying causes. These questions, however, may be easily addressed by a temporal GIS that both stores the temporal information and provides spatiotemporal analysis tools. The need for and the benefits offered by a temporal GIS are evident. For instance, a temporal GIS would allow the relationship between land use patterns and travel demands to be analyzed over a long period of time. The data regarding the conditions of transportation infrastructures such as guideways, roads, and bridges may be continually collected and stored, and deterioration may be monitored and modeled. Transit operating data may be more efficiently stored and retrieved for analysis at a later time. Transit system performance may be evaluated by considering the effects of decisions made regarding transit route layout, transit level of service, policies supporting transit, etc.

This research is intended to explore the potential benefits of temporal GIS for public transit management and to study the issues related to temporal GIS applications to transit. We have developed a simple method to record the changes in spatial objects with respect to time using ARC/Info relational databases as well as means to query the spatiotemporal data, which provided a basis for understanding the requirements for a temporal GIS and problems associated with the construction of the temporal databases.

RESEARCH OBJECTIVES AND METHODOLOGIES

Despite the wide-spread use of GIS as a tool in various transportation areas, there has been limited overall awareness among transit professionals of either temporal GIS technologies or their possible applications to public transit management. The goal of this research is to gain a better understanding of the potential benefits of the temporal GIS technology to public transportation management, which include planning, operation, and maintenance, and what is required to implement temporal GIS applications for transit. The objectives to be achieved include the following:

1. Understand the needs and tasks of public transit management and the potential benefits that may be brought by a temporal GIS;

ABSTRACT

Geographic information systems (GIS) have proven to be powerful tools capable of storing, displaying, and analyzing spatially distributed information. GIS has been used in a wide array of transit applications including demand modeling, service planning, operations, service monitoring and evaluation, customer services, marketing, facility and real-estate management, etc. However, current GIS lacks adequate capabilities of handling temporal information. As a result, analyses are mostly performed assuming a fixed time point. Longitudinal analyses that take time into consideration cannot be easily accomplished. For many applications, information constantly changes with respect to both space and time. A temporal GIS, capable of handling temporal as well as spatial information will greatly expand the current GIS applications and allow new information to be obtained. Summarized in this report are the results of a study on temporal GIS applications to various transit management tasks. The state-of-the-art of temporal GIS research and development is reviewed. Potential benefits of applying temporal GIS technologies to transit are investigated. A simple method to record the changes in spatial objects and their attributes with respect to time has been developed using PC ARC/Info relational databases and a means to query the spatiotemporal data. The use of this temporal GIS method is illustrated using an example related to transit planning and service evaluation.

KEYWORDS: geographic information systems, spatiotemporal analysis, public transit, transit planning, transit operations

Table S.1 List of Transit GIS Application Areas

APPLICATION AREAS	USERS
Transit ridership forecasting, service planning, market analysis	Baltimore MTA, Bay Area MTC, Bi-State, Chicago RTA, City of Phoenix, DART, DVRPC, GGBHTD, HGAC, Houston Metro, LIRR, MARC, NJTA, NOACA, NYCTA, NYMTA, Omaha-Council Bluffs MPO, Port Authority NY&NJ, Portland Metro, SANDAG, Seattle Metro, SEMCOG, SMART, Tampa Urban Area MPO, TTD, WashCOG
Map products design and publishing (for example: system maps, route schedules and maps, operator maps)	Bi-State, City of Phoenix, CTPS, DART, DVRPC, Houston Metro, MARC, Miami MPO, MTDB, NJT, NOACA, NYCTA, Omaha-Council Bluffs MPO, Port Authority NY & NJ, Portland Metro, RVTD, SANDAG, Seattle Metro, Tampa Urban Area MPO, WashCOG
Fixed facilities and real estate management (for example: bus stops, transit stations, park and ride lots)	Baltimore MTA, Chicago RTA, City of Phoenix, DART, DVRPC, GGBHTD, Houston Metro, LIRR, Miami MPO, NYCTA, NYMTA, RVTD, SANDAG, Seattle Metro, SMART
Telephone-based customer information services	City of Phoenix, DART, DVRPC, NOACA, NYCTA, Seattle Metro
Transit scheduling and run time	DART, DVRPC, NJT, RVTD, Seattle Metro
Ride matching (for car and van pools)	DART, MARC, Miami MPO, Seattle Metro
Automatic vehicle location	DART, NJT, Seattle Metro
Transit pass sales	DVRPC, MTDB, Seattle Metro
Paratransit schedule and dispatching	TTD
Improved transfer points and connections	NYCTA

Source: (Schweiger 1992)

2. Investigate the issues involved in the development of temporal GIS tools and software for transit applications;

3. Identify the problems associated with the development of temporal GIS databases and applications; and

4. Identify future direction of temporal GIS research and applications for public transit.

The research methodology used is a combination of literature reviews, software development, data collection, and data analysis. The following research tasks are completed:

1. Literature Review - to examine the current GIS applications in transit, determine the state-of-the-art of temporal GIS technologies, and to identify similar works on the subject of temporal GIS applications in transit.

2. Software Development - to enable the demonstration of temporal GIS applications, software tools were developed to store, manage, and manipulate temporal information.

3. Data Collection - to develop examples of temporal GIS applications.

4. Development of examples of temporal GIS applications.

CURRENT TRANSIT GIS APPLICATIONS

GIS applications have been implemented at many transit agencies over the past 10 years. A 1992 study by Schweiger provides an overview of these GIS applications in public transit nationwide. Schweiger conducted 74 interviews with 67 organizations across 30 states, including 46 transit agencies, and 21 Metropolitan Planning Organizations (MPOs). The results of that study showed that GIS was being used or being implemented at that time for a wide variety of applications. Among the 46 transit agencies, 21 have GIS, and of the 21 MPOs, 15 have GIS. In 1995, another survey was conducted by Harman (1995), 269 entities were contacted, and 202 survey forms were completed. Later, all transit agencies and MPOs in urban areas with a population of over 200,000 were interviewed. Nearly every transit agency (TA) with a fleet of 500 and above indicated that they were using GIS in some form or another. GIS is used in transit agencies mostly in areas related to transit planning, transit operations, such as scheduling and run cutting, marketing, fixed route and paratransit dispatching, customer services, and facility management. MPO GIS uses are mainly for forecasting ridership, service planning, and development of map products. **Table S.1** provides a summary of the transit GIS applications in industry.

TEMPORAL GIS

A fundamental difference between a conventional GIS map and that of temporal GIS is that the former describes a static state of the physical world while the latter a dynamic state, a series of which depict the history of the physical world being modeled. Current GIS technologies provide static data models and tools that support the capture, query, analysis, and display of geographic information for a fixed time point. Since existing GIS software does not support the storage and analysis of temporal information, historical data are difficult to maintain or use. At present, to include temporal information and make temporal analysis possible in existing GIS software packages, extensive customized software development is required.

According to Langran, the fundamental functions of a temporal GIS are inventory, analysis, updates, quality control, scheduling, and display (Langran 1992). Inventory is the storage of complete descriptions of the study area, which include changes in both the physical world and in computer storage. Analysis involves the investigation of, in addition to spatial phenomena, the changes in spatial patterns with time and the causes or effects of such changes. Updates are concerned with ensuring that the database provides the most current information. Quality control provides a means to minimize the chance of errors by checking the validity and consistency of new data based on the historical information about the real world phenomena that they describe. Scheduling is a mechanism that allows predefined actions to be triggered by events such as changes in data or the elapse of a certain time period. Display involves the generation and presentation of the temporal changes that may be qualitative as well as quantitative in nature.

There has been much literature on the theories of temporal and spatiotemporal databases. Many data models have been proposed. The major temporal GIS models are the snapshot model, update model, composite model, 3D/4D model, and integrated model. The snapshot model stores spatiotemporal information by a series of map layers depicting the same phenomenon over the entire space, one for each time slice (Langran 1993, Peuquet and Wentz 1994). The update model stores only one full version of a data set, with new information added as updates (stored separately) whenever changes occur (Langran 1992, Peuquet and Duan 1995). The space-time composite model is similar to the update model but stores both past and present data in the same layer and constantly maintains the topology (Langran and Chrisman 1988). This model allows historical information to be preserved by identifying spatial units that have unique attributes and existence in terms of time, but runs into the problem of spatial objects being decomposed progressively into smaller objects and their identifiers having to be changed retroactively. The 3D/4D model treats time as a fourth dimension and every spatial object would be defined by coordinates in the form of either (x, y, t) or (x, y, z, t) (Hazelton *et al.* 1990). This data model is much more complex and requires a GIS developed from scratch. No implementation has been reported using this data model. The integrated model combines some of the aforementioned models to take their individual advantages and overcome some of their disadvantages (Peuquet 1994, Kelmelis 1991, Osborne and Stoogenke 1989). There have also been attempts to model both spatial objects and processes of their changes (May 1994a, May 1994b, Raper and Livingstone 1995).

POTENTIALS OF TEMPORAL GIS FOR TRANSIT MANAGEMENT

Four areas are selected for the study as shown below:

Application Area	Description
Transit planning	maintain TAZ definition inventory transportation facilities demand model validatation, calibration data verification model development transit project coordination policy analysis
Service planning	evaluation of route ridership potentials understand ridership variations with time and trend identify factors impact ridership utilization of AVL data
Travel information	real-time schedule information pre-trip planning data collection
Transit service evaluation	route performance driver performance vehicle loading schedule adherence

A PROTOTYPE TEMPORAL GIS

To study the use of temporal GIS for transportation applications and to explore the possibility of extending the capabilities of commercially available atemporal GIS, we have developed a simple prototype temporal GIS based on PC ARC/Info. To extend ARC/Info by giving temporality to both spatial and attribute information, all spatial objects and attributes are time-stamped. The time stamp records two types of time, *valid time* and *database time*, and is stored as four additional attributes, *Vd_From*, *Vd_To*, *DB_From*, and *DB_To*. The time granularity, or the smallest time interval to be represented in a temporal GIS, which depends on the need of the particular application, is chosen to be the day.

A set of temporal query commands have been developed for the prototype temporal GIS using the

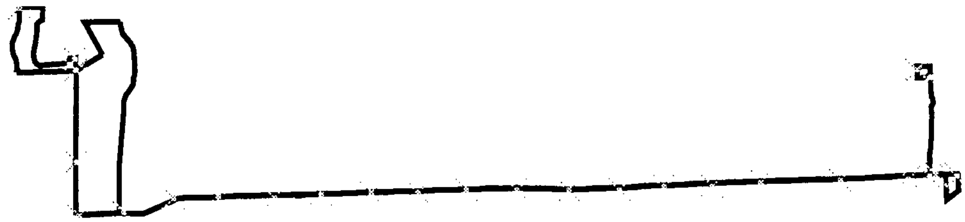
Simple Macro Language (SML) of PC Arc/Info. SNAPCOV is a command used to take a snapshot of the spatial objects contained in a coverage for a given world time. It takes as input a coverage name, a time slice (corresponding to a world time), and, optionally, a version time (or database time), and produces a new coverage for the specified time slice. SNAPINFO is similar to SNAPCOV but operates on the database tables associated with a given coverage. PERDCOV is similar to SNAPCOV. However, instead of giving information for one time point, it provides information about changes that occurred between two given time points. THISTORY generates a complete history for selected features or attributes in a coverage. The result will be a table showing all the changes in the features or attributes from their inception to current time. This complete historical information may then be used for trend analysis. Similarly, PHISTORY gives the history for a specified period of time instead of the entire life history of attributes. TDOMAIN reports the time period during which a database file (including .AAT, .PAT, and .DBF files) existed. TVERSION produces a temporal version of a given database file for a given database time.

AN EXAMPLE

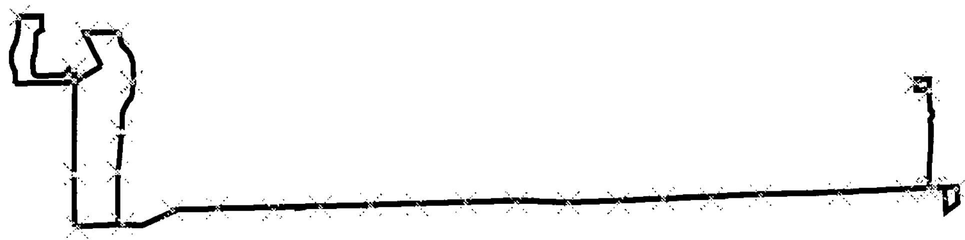
The geographic area in the example is a transit corridor along Southwest 40th Street in Miami. The bus route has undergone many changes. Using the temporal GIS query, changes in both the bus route alignment and the characteristics of the service area along the bus route may be examined. In **Figure S.2**, changes in bus Route 40 between June 15, 1986 and December 31, 1990 are shown. The map is generated by applying the PERDCOV command, which retrieves all the arc segments of the bus route and all the point features representing the bus stops that are effective (or valid) in the given time period.

In **Figure S.3**, changes in the population density and employment density in the service coverage area of Route 40 are given in both actual numbers and percentages of the changes. The numbers are given next to the bus stops for which the data has been generated. Circles group connected buffer zones not separable and the data are given for the entire cluster.

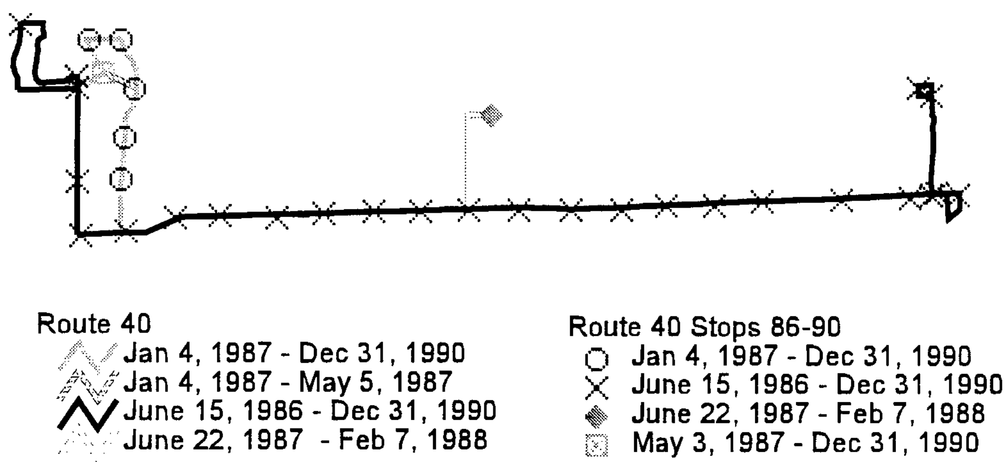
From **Figure S.3**, it may be observed that, at some locations, there have been significant changes in population and employment. In the majority of the cases, the decrease in population is accompanied by an increase in employment, which has been caused by heavy commercial developments such as new shopping centers and strip malls along the bus route. In fact, the total population and employment in the corridor has increased by 45.52 percent and 43.94 percent, respectively. In contrast, bus ridership has increased only slightly between 1987 and 1990. To understand the relationship between ridership and land use and demographics, a more detailed study is needed to consider many socio-economic and demographic factors. Detailed ridership data collected by traffic checkers that allow the determination of actual transit usage at bus stops are also needed.



(a) Bus Route 40 Alignment and Stops in 1986



(b) Bus Route 40 Alignment and Stops in 1990



(c) Changes in Bus Route 40 Alignment and Stops between 1986 and 1990

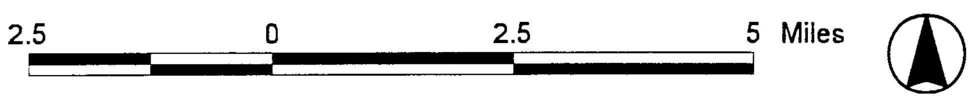
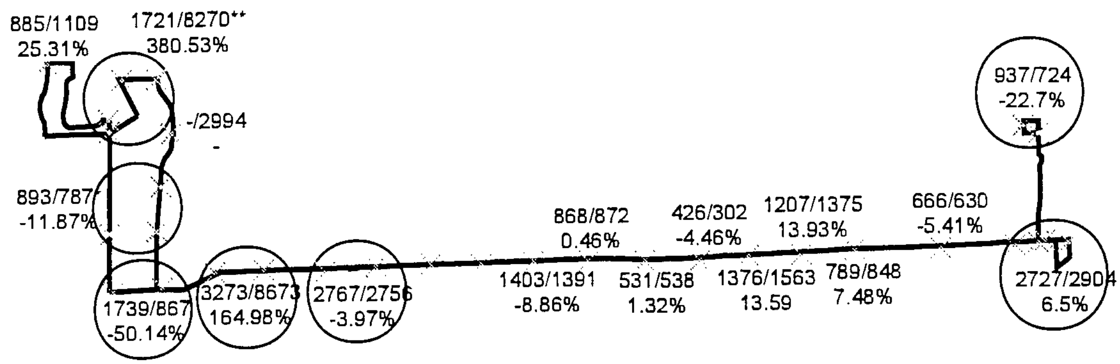
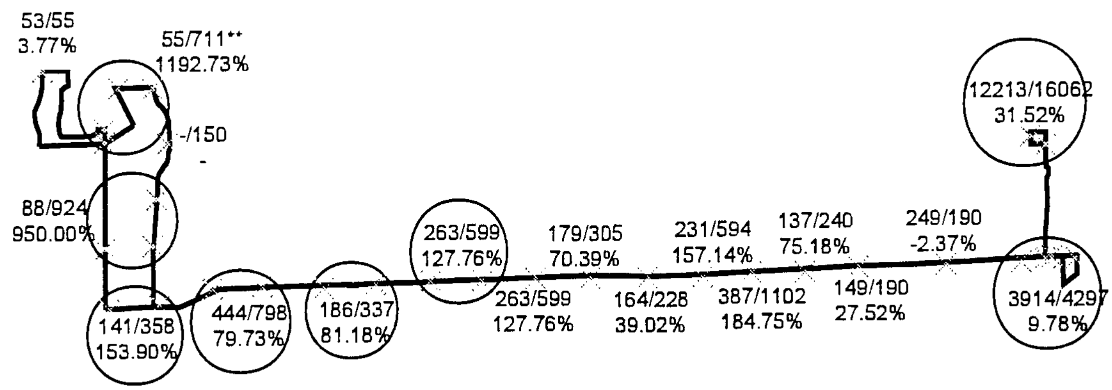


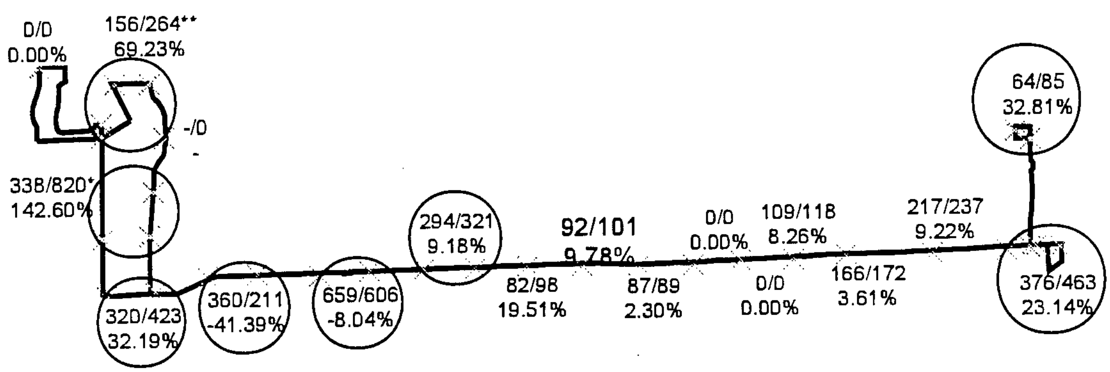
Figure S.2 Route 40 Alignment Changes between June 15, 1986 and December 31, 1990



(a) Population Change



(b) Employment Change



(c) School Enrollment Change

Notes: * Only one bus stop served the neighborhood in 1986 and two were added after 1987.
** Two of the bus stops were added after 1987.

Figure S.3 Changes in Population, Employment, and School Enrollment in Route 40 Service Area between June 15, 1986 and December 30, 1989

CONCLUSIONS

Many transit management tasks may benefit from a temporal GIS. The benefits are derived from the availability of historical data preserved by a temporal GIS, and the utility of these data to allow better transit planning, operations, marketing, customer service, and facility management. A temporal GIS provides the tools that allow the processing and understanding of real-time information, as well as the study and understanding of many complex relationships between various variables that affect transit service effectiveness and efficiency. Especially promising is the scheduling capability supported by a temporal GIS and the integration of GIS with knowledge-based systems. They will allow more advanced analyses to be performed, better decisions to be made, and productivity to be increased since less manual processes are needed to track events, monitor changes, analyze complex problems, and develop solutions. With a temporal GIS, therefore more accurate information about future transit environments, operating conditions, and political and financial constraints, a transit agency will be able to adjust its practices proactively in anticipation of changes instead of passively reacting to problems and challenges.

Many important technical issues remain to be addressed. These include data volume control, effective presentation of temporal changes, data models suitable for transit applications, process modeling, data maintenance, etc. Besides the technical issues, there are also many implementation issues that call for special attention. First, it is extremely important to realize the enormous benefits that a temporal GIS promises and begin immediate efforts to preserve historical data. Historical data availability is critical for the successful temporal GIS. For temporal GIS to be effectively used, careful analysis needs to be done to determine the short- and long-term objectives to be achieved. Accordingly, realistic data requirements including the types of data and the needed time resolution, strategies for data collection and maintenance, as well as practical and economical means to collect and process the data, may be developed to ensure accomplishment of the goals set for the temporal GIS applications.

Significant research efforts are still needed on temporal GIS and its application to transportation and public transit. The research areas include basic theories, data models, algorithms and analysis, visualization tools, potential applications for transit and transportation, data collection practices, and historical data preservation. The understanding gained through research will also help to develop temporal GIS data standards and define requirements for temporal GIS software for transportation applications.

1. INTRODUCTION

The use of GIS is rapidly growing because of its capability for storage, display and analysis of geographic data based on their spatial relationships. In the last several years, the GIS for transportation (GIS-T) software began to offer both analytical and modeling procedures common to transportation planning studies, in addition to providing the conventional GIS functions. GIS-T has found applications in a wide range of fields, including transportation planning, intermodal facility management, pavement management, bridge inventory and modeling, accident analysis, fleet management, transit service planning, etc. In the mean time, transit GIS applications continue to expand and grow in sophistication. As some have observed, the period of GIS-T discovery has come to an end and GIS-T has entered a stage of steady growth, with increasing attentions to enterprise GIS, GIS standards, and exploration of new applications.

Despite the rapid development and wide application of GIS and GIS-T tools, it appears that the development of GIS capabilities in dealing with temporal information is still limited. Current GIS software mainly supports cross-sectional spatial analysis, that is, spatial information may be analyzed for a fixed time point or time period for which information is assumed to remain unchanged. The reality is of course different, as population, economic activities, transportation facilities, travelers' behaviors, to name a few, all change with time. These changes and their interactions with the transportation system need to be understood and considered in transportation decision-making. With the current GIS technology, it is difficult to answer questions such as where and when changes occur, what patterns may be observed about the changes, and what may be the underlying causes. These questions, however, may be easily addressed by a temporal GIS that both stores the temporal information and provides spatiotemporal analysis tools. The need for and the benefits offered by a temporal GIS are evident. For instance, a temporal GIS would allow the relationship between land use patterns and travel demands to be analyzed over a long period of time. The data regarding the conditions of transportation infrastructures such as guideways, roads, and bridges may be continually collected and stored, and deterioration may be monitored and modeled. Transit operating data may be more efficiently stored and retrieved later for analysis. Transit system performance may be evaluated by considering the effects of decisions made regarding transit route layout, transit level of service, policies supporting transit, etc.

The development of temporal GIS, however, presents many challenges. In addition to the common database issues including database design, data creation and editing, database maintenance, security and currency, and data storage, a temporal GIS also has to answer questions such as how spatiotemporal information may be captured efficiently and effectively, how spatiotemporal information may be retrieved fast and completely, what types of analyses may be performed, and how the analysis results may be presented effectively.

This research is intended to explore the potential benefits of temporal GIS for public transit management and to study the issues related to temporal GIS applications to transit. We have developed a simple method to record the changes in spatial objects with respect to time using ARC/Info relational databases as well as means to query the spatiotemporal data, which provided a basis for understanding the requirements for a temporal GIS and problems associated with the construction of the temporal databases.

In the rest of this report, the research objectives are outlined and methodologies employed are first described in **Section 2**, followed by a section that provides a review of current transit GIS applications. In **Section 4** some basic concepts of temporal GIS and related work are described. Potential transit applications of temporal GIS are then discussed in **Section 5**. **Section 6** presents a prototype temporal GIS implementation consisting of a simple data structure design and a set of temporal query tools that are used to construct examples of temporal GIS applications. The examples are given in **Section 7.** Finally, conclusions and recommendations are provided in **Section 8.**

2. RESEARCH OBJECTIVES AND METHODOLOGIES

Despite the wide-spread use of GIS as a tool in various transportation areas, there is a minimal awareness among transportation professionals of temporal GIS technologies or their possible applications to public transit management, and to general transportation. The goal of this research is to gain a better understanding of the potential benefits of the temporal GIS technology to public transportation management, which include planning, operation, and maintenance, and what is required to implement temporal GIS applications for transit. As a result, the study should increase awareness of the need for temporal GIS and promote the consideration of incorporating temporal information into the enterprise GIS as early as possible. The objectives to be achieved include the following:

1. Understand the needs and tasks of public transit management and the potential benefits that may be brought by a temporal GIS;

2. Investigate the issues involved in the development of temporal GIS tools and software for transit applications;

3. Identify the problems associated with the development of temporal GIS databases and applications; and

4. Identify future direction of temporal GIS research and applications for public transit.

The research methodology used is a combination of literature reviews, software development, data collection, and data analysis. The following research tasks are completed:

1. Literature Review. An extensive literature review was conducted to examine the current GIS applications in transit and to identify similar works on the subject of temporal GIS applications in transit. Although there have been some efforts of performing spatiotemporal analyses, such efforts are almost exclusively limited to the areas of natural resource modeling and management. No transportation related applications have been found. Another aspect of this research effort is to determine the state-of-the-art of temporal GIS technologies, with the emphasis on data models and software tool development.

2. Software Development. To enable the demonstration of temporal GIS applications, software tools were developed to store, manage, and manipulate temporal information.

3. Data Collection. Transit data were collected from Metro-Dade Transit Agency. These include historical bus routes, bus ridership data including traffic checkers' reports, bus operating schedules, and demographic and socioeconomic data. Other data such as land use and property tax data were also collected, although not used for reasons that will be explained in the report.

4. Development of examples of temporal GIS applications. Two examples are developed. One involves the storage, retrieval, and display of changes in traffic analysis zones, which are the basic geographic units used for transportation planning. The other is the storage, retrieval, analysis, and display of bus service changes along with changes in population, employment, and school enrollment.

3. CURRENT AND POTENTIAL PUBLIC TRANSIT GIS APPLICATIONS

GIS applications have been implemented at many transit agencies over the past 10 years. A 1992 study by Schweiger provides an overview of these GIS applications in public transit nationwide. Schweiger conducted 74 interviews with 67 organizations across 30 states, including 46 transit agencies, and 21 Metropolitan Planning Organizations (MPOs). The results of this study showed that GIS was being used or being implemented at that time for a wide variety of applications. Among the 46 transit agencies, 21 have GIS, and of the 21 MPOs, 15 have GIS. In 1995, another survey was conducted by Harman (1995), 269 entities were contacted, and 202 survey forms were completed. Later, all transit agencies and MPOs in urban areas with a population of over 200,000 were interviewed. Nearly every transit agency (TA) with a fleet of 500 and above indicated that they were using GIS in some form or another. GIS is used in transit agencies mostly in areas related to transit planning, transit operations, such as scheduling and run cutting, marketing, fixed route and paratransit dispatching, customer services, and management. MPO GIS uses are mainly for forecasting ridership, service planning, and development of map products.

In this section, various current and potential GIS applications in public transit management are described. These applications, reported in publications, represent the current state-of-the-art, but certainly not the limit of the GIS technology.

3.1 Long Term Transit Planning

Azar and Ferreira (1995) examined the benefits of using GIS tools for developing transit ridership estimation models capable of forecasting changes in ridership that may be associated with changes in bus route alignment and other modifications to transit service characteristics. The main interest in their study was to obtain a model that could predict transit ridership along a route based on the socioeconomic attributes of an area, the physical characteristics of a bus route, and the attractiveness of "down-route" trip destinations using GIS. The Period Route Segment (PRS) Models, developed by Batchelder *et al.* (1983), was used for this purpose. This model estimates the A.M. peak period and the midday boarding in each direction for every segment of a route based on route characteristics and service provided. According to the PRS model, ridership on a segment depends on three factors:

1. A production factor related to the ability of an area to produce transit trips;

2. An opportunity factor representing the ability of areas down a route to motivate persons to take these trips along that route; and

3. A level of a service factor related to the quality of service provided along a route.

The PRS model requires computation of several variables that are spatially related. These variables, such as employment opportunities or people living within a quarter mile of a bus line or the stops that belong to routes that generate transfer trips, may be manually calculated or approximated from maps. A base map and 1990 census data for Boston, MA, were used to test the transit ridership estimation model. The 1990 TIGER/Line™ files and census block group boundaries were loaded into ARC/INFO® software along with population and employment location data from the 1990 census, selected ridership data, route alignments, and schedules for Metropolitan Boston Transit Authority bus routes. Using ARC/INFO GIS functions, the model displays the selected route, divides it into modeling segments, and shows the estimated A.M. peak period and midday ridership period on each modeling segment. Furthermore, the model estimates the total ridership on the entire route for both times.

A study is presented by Shaw (1993) that demonstrated the data and the analysis procedures required to conduct an urban travel demand analysis with GIS. This study uses the typical four-stage urban transportation modeling system (UTMS) as an example. It also describes the different models such as linear regression model for trip generation, gravity model for trip distribution, MNL model for mode choice, and the user equilibrium model for network assignment. From the example presented in this study, urban travel demand analysis can evidently benefit from GIS. However, some data (O-D matrix and trip generation rates table) required in the urban travel demand models are not currently supported by the topological data model employed in vector GIS.

Allen and Mukundan (1993) developed a process that used GIS to analyze different transit alternatives for major transit capital investment studies. Such alternatives included new fixed guideway facility, significant improvements in bus service frequency, new feeder bus routes, and new park-and-ride lots. The impacts of such alternatives were then evaluated.

Using GIS and artificial neural network (ANN) technology, the impact of demographics on fixed guideway ridership was studied by Lee et al. (Lee *et al.* 1995, Shen *et al.* 1996). Demographics, fixed guideway alignment and stations, and ridership were correlated with both traditional statistical methods and ANN methods. ANN methods gave better results with smaller errors. To examine the trend of the demographic changes and its impact on fixed guideway ridership was also intended but the effort was abandoned due to the lack of historical data in a GIS format. A similar effort of analyzing transit demand based on demographics was reported in Wensley (1995). GIS was used to compute demographic characteristics for varying sizes of buffer zones around transit routes and stops, display the Census Transportation Planning Package (CTPP) data of origins and destinations of work trips, and generate transportation network for demand modeling purposes. Analyses were performed for a many of transit properties including New York City, Cleveland, San Juan, and Boston.

The interaction between land uses and transportation and transit systems was studied in Eberlein and Brown (1991). In this study, transit and land use data were analyzed at the regional level using a GIS by relating the rail transit use patterns to siting of federal facilities in the Washington, D.C.

area. Recommendations were made to concentrate federal facilities or relocate some of the existing ones in order not to negatively affect the transit use and traffic congestion. This tool demonstrated that policies may be used as a tool to design land uses more rationally and promote transit use.

3.2 Service Planning

An application of GIS to bus routing is described by Chou (1995) regarding the design and application of a decision support system developed for bus routing, route sequence mapping, and passenger geocoding. This application, although specific to school bus routes, may be extended to include revenue service bus routing for both fixed route and demand response services. The school bus routing system consists of six operational modules:

1. A Single Routing Module allows planners to select either street segments or bus stops from a street map to generate his or her optimal route. The routing information includes the street address associated with each segment, the distance and estimated travel time of the segment at the assigned speed limit, and a turn code indicating if a turn is required at an intersection. A route may also be determined by selecting a sequence of bus stops.

2. A Walking Distance Maintenance Module identifies street segments that are within a user specified distance from a school. This model helps the school district to identify the students who live within a specific distance from schools and thus are not eligible for the school bus service.

3. A Bus Stop Optimization Module identifies the optimal sites for the location of bus stops based on travel demand.

4. A Passenger Plotting Module reads the passenger information file, geocodes it, and then plots their locations on the street map. The function of this module is to display the geographic distribution of any selected group of students in the school district. It also allows the user to retrieve the student file, specify any combination of selection criteria, such as student of certain school or within specific range of grades, then plot on the street map the residential location of all students that satisfy the selection conditions.

5. A Multiple Routing Module defines multiple routes based on information of passengers, bus stop location, and the bus fleet. The module assigns each available bus to serve a sequence of closely located stops until either the bus is full or the travel distance exceeds a limit.

6. A Complex Routing Module generates multiple routes with multiple destinations (schools) while each bus may be assigned to more than one route. Some constraints are incorporated into this module such as the availability of disability equipment, the maximum acceptable time a passenger may stay on board a bus, and the bell time of each school. This module also allows

students to go to one school on certain days and another school on other days.

The conceptual framework of the bus routing system is shown in **Figure 3.1**. Additional modules may be programmed to serve specific users. The routing system is designed to generate optimal solutions based on the existing locations of bus stops and the distribution of travel demand. For planning new bus services, the system optimal locations of bus stops may be identified according to the geographic distribution of the passengers. Other applications may require some user-specific or system-related constraints such as the seat capacity of each bus and the maximum loading factor for each segment. The data for this system requires a digital map of the street network, the location of schools and bus stops, a file of bus fleet, and a file of passenger information including each passenger's street address. The complex routing module requires additional information about any disability of each student and the equipment available on each bus assigned to the special education program.

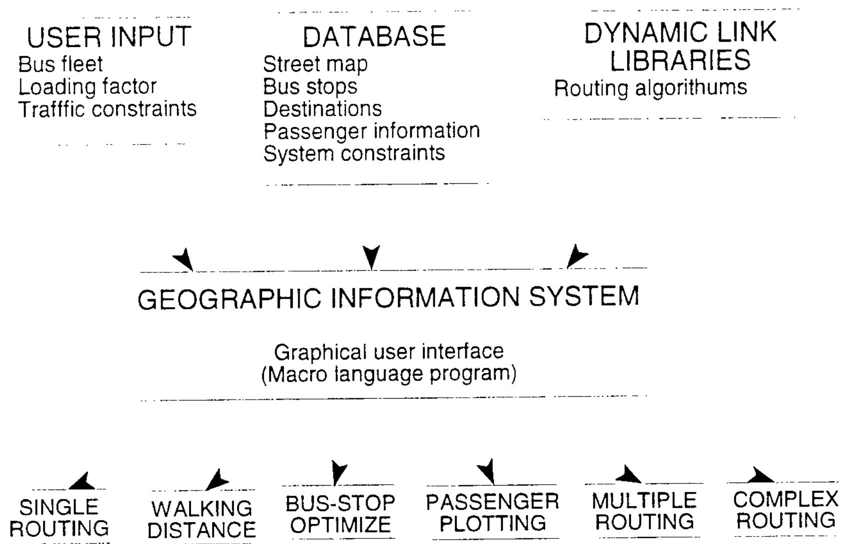


Figure 3.1 Conceptual Framework of Bus Routing System (Chou, 1995)

The use of GIS in planning transit service for people with disabilities was discussed by Javid and Prabhakar (1993). This application is much simpler than that of the school bus. The difference is to develop a method to estimate the number of people with disabilities within the catchment area (acceptable walking distance) or transit service area for estimating passenger demand. The information for building the database was obtained from TIGER/Line™ files, and from a questionnaire survey conducted as part of another study. Data from TIGER/Line™ files include county, state, census tracts, census blocks, groups of blocks, intersections, and roads. These data include total population and disabled population by block group. The origin destination trips of the people with disabilities surveyed from a previous study were entered a point database. To represent the transit routes, separate databases were built for each direction of the six fixed routes operated by the Logan Transit District (LTD), Cache County, Utah. The point database and the route database were then used to estimate the transit demand for each route and the entire network.

The GIS database may also be useful to schedule transit service to accommodate a planned event (Peng *et al.* 1995), such as a special event or a large festival. Once the location of the special event is identified and geocoded, the GIS can schedule special bus services to link the event location with the fixed route services and also to make changes on the level of service on the original fixed route services.

3.3 Transit Operations

In transit operations, vehicle dispatching, routing, and fleet management are a few of the activities in which GIS may offer help. For fixed route services, vehicle dispatching and routing are mainly for vehicle maintenance (e.g., returning a malfunctioning bus to maintenance facility), deadheading, and emergency responses. For paratransit, efficient dispatching and routing directly affect the operating cost, service effectiveness, and customer satisfaction. In Yang (1995), technical approaches to and issues related to dynamic vehicle routing problems (DVRP) are discussed. A prototype system is also introduced. According to Yang (1995), using GIS for paratransit routing and scheduling, vehicle miles may be reduced by 20 to 30 percent. GIS applications for transit operations including display of passenger boarding and other business performance on maps are discussed in Reilly (1997).

In recent years, automatic vehicle location (AVL) systems have been installed on transit vehicles in many transit agencies, which, by providing vehicle location information in real-time, allows the dispatchers to monitor the fleet continually, warn the drivers about delay in a schedule, and respond immediately to emergencies. Most AVL systems have a component that is a GIS-based display of vehicle location. Queries may be made regarding the exact location or address of a transit vehicle and its status. In Raj *et al.* (1995), a GIS-based emergency response system is described that gives the dispatchers accident/incident dependent, sequential and prioritized action plans when an accident or incident occurs. It also records the actions taken by the dispatchers and files incident reports.

Transit safety is very important to transit users. Due to traffic congestions, movement conflicts at, e.g., railroad crossings, and other potential disasters such as hazardous material spills, risks of accidents and incidents must be reduced. Panchanathan and Faghri (1995) discuss the development of a knowledge-based GIS for improving rail-highway crossing safety. The GIS interfaces with the USDOT model and a knowledge-based expert system, and, using qualitative and historical information, evaluates the safety at a given crossing. Many highway safety GIS applications have been developed that may be used for transit applications with minor modifications (see **Section 3.9.3**).

3.4 Service Monitoring

A study was conducted by Papacosta (1995) for the Honolulu bus system, Oahu Transit Services

(OTS), to monitor the schedule adherence for the fixed route bus systems operations using GIS. The data incorporated in this study include ride checks and point check surveys collected as part of a comprehensive operating analyses. Each bus trip sampled was computerized in a particular format and placed in a separate ASCII file. Each bus trip file includes information such as the date of survey, checker name, route number, direction, key and run, bus ID number, and seating capacity. A list of the bus stops with the corresponding arrival time and boarding/alighting is also included. A program written in C language converts the data into the Arc/Info file format. Program modules for this project were written using Arc/Info Macro Language (AML). The analysis program obtains and processes the necessary data for the required run. For example, when the user selects a route key, the program identifies the route structure and its corresponding stops. It then searches the database for all scheduled runs associated with that key, obtains the necessary raw data, and stores them in a temporary file for further processing. Any requested displays appear in separate windows on the output device. Therefore, they can be jointly viewed and examined.

3.5 Customer Information Services

GIS may be used as a powerful tool to give the transit users information about transit services on a digital map that may be used for pre-trip, in-terminal, or in-vehicle planning. Using a modem connection, travelers may connect their personal computers with the transit agency's telephone information center and display a transit map. By specifying the trip origin and destination, information such as a route(s) to be used, arrival time at each stop, transfer points, fares, nearest parking lots, ADA accessibility, etc., may be obtained. Automatic trip planning systems have been installed in many transit agencies. Among transit agencies with such a system are the: Winston-Salem Transit Agency in North Carolina, Los Angeles County Metropolitan Transportation Authority (LACMTA) in California, Tri-Met in Portland, Oregon, Metro-Dade Transit Agency (MDTA) in Miami, Florida, Metropolitan Atlanta Rapid Transit Authority (MARTA) in Atlanta, Georgia, and Central Ohio Transit Authority (COTA) in Ohio. Some of these systems are also installed in public accessible places such as universities, government offices, and shopping malls for planning non-home based trips.

In-terminal information systems provide schedule updates and transfer information for passengers. This information includes arrival and departure times, information on transfers and connections, information on other regional transportation services, and park and ride facilities. On board of a vehicle, information on routes, schedules, and connecting services is provided via visual displays and annunciations. Transit routes and schedules are needed to provide such information. For more accurate information, an automatic vehicle location (AVL) system may be used with GIS to provide planners, operators, and users with real-time information. Scheduled time and route information may be adjusted according to traffic delays, accidents or emergencies. In case of an emergency, a vehicle may be easily located and emergency vehicles timely dispatched.

Tri-Met installed kiosks for trip planning, mainly for visitors in the downtown area. The kiosks contain microcomputers and allow users to enter their destinations. They will then identify routes and provide directions. A display of bus routes serving the area in the vicinity of the user's origin and destination will be displayed.

3.6 Marketing

Henry and Sirota (1995) described an effort of identifying ways of increasing transit ridership on the Baltimore light rail system. Selected management level employees were asked to identify the areas with market potentials and develop recommendations to attract transit users. GIS was used to display and analyze ridership, origin-destination data, and CTPP data. Lycan and Orrell (1990) also described a GIS-based approach to analyze of the potential of bus ridership to Oregon Sciences University. Address matching was used to analyzed the accessibility of the university to the commuters. The results helped to understand the feasibility of modifying or improving the transit services for the commuters.

3.7 Facility and Real Estate Management

Facilities directly owned or managed by a transit agency typically include right-of-ways for fixed guideway systems, wayside equipment, storage yards, administrative and maintenance buildings, transit stops, stations, signs, parking lots, land parcels adjacent to transit stations or transit centers, and special structures dedicated to transit use including bridges, pedestrian walkways, and tunnels. Other infrastructures that are used for transit but not owned or managed include roadways, expressways, highway bridges, drainage systems, traffic signals, general traffic signs, seaports, airport, interurban train stations, railroad tracks, etc. In (Cipolloni 1993), the author discusses the use of GIS for improving the management of transportation facilities. An example of how New Jersey employed this technology to manage their traffic signs is also given in some detail.

Sathisan *et al.* (1993) demonstrated that GIS may be used for the management of rail infrastructure. This study addresses the development of a GIS-based system for rail infrastructure with respect to the key element and characteristics of a typical mainline railroad track, such as:

- Track alignment;
- Longitudinal gradient and elevation;
- Sidings;
- Bridges and culverts; and
- At-grade rail/highway crossings.

It also discusses the application of such a system for risk and routing analysis as related to hazardous material shipping. A GIS coverage of the rail alignment in Clark County, Nevada, obtained from the U.S. Census Bureaus's TIGER/Line file, was used as a starting point and to provide a base map. The next step was to relate all infrastructure characteristics to a specific milepost location. The accuracy of these mile posts was one-hundredth of a mile. Other data required for the development of the database were obtained from Union Pacific's Western District Condensed Track Profile (1985) and Western Area Condensed Track Profile (1990). After the development of the database and the graphical display of the rail infrastructure, probabilistic and quantitative risk assessments of alternatives were conducted to minimize the risk routes transporting hazardous materials.

3.8 GIS in Transit Agencies

Other opportunities exist for the use of GIS in transit planning, operation, and analysis. Some transportation organizations have become extremely active in the use of GIS. Smaller organizations have been less likely to invest the resource necessary to establish a GIS that will generate significant benefits (Harry 1995). The following discussion represents a selection of transit systems that use GIS in transit planning, operation, and/or analysis.

King County Metro Transit Municipality of Metropolitan Seattle

King County Metro Transit in Seattle, Washington is one of the most active users of GIS among transit agencies in the United States. In 1982, King County Metro developed an in-house GIS called TransGeo. As of July 1992, TransGeo continued to be a critical feeder system to Metro's automatic passenger counts system, ARIS/BUS TIME, commuter information system, mileage maintenance system, and the radio automatic vehicle monitoring/location system. In 1991, a GIS project team was established to carry out a GIS project that involves the assessment of the GIS needs of the agency and analysis of alternative GIS implementation strategies. As of today, GIS applications have included (CUTR 1996):

- Capital planning and development: display park-and-ride data against service patterns, volumes, and passenger volumes.
- Service planning: produce maps of selected service areas, and display route(s) proposals and information related to ridership demand such as population, employment, travel patterns, population, and employment densities.
- Market development: display employer sites against available transportation services and information such as transit service, park-and-ride, etc.; display and analyze demographic, census data, etc.

- Accessible services: geocode ADA applicant addresses and perform location related analyses.

- Coach and facility maintenance: provide route pattern maintenance (to track mileage by vehicle and route).

- Sales and customer services: use geocoding to create customer mailing lists for route-level marketing.

- Research and market strategy: create displays and other test materials for focus groups; geocode respondents' origin and destination to create a travel pattern database.

- Transit operations: create quick information maps/guides for operators to help answer customers' questions; provide timely and accurate maps for trainers and operators.

- Risk management, safety, and security: display and analyze accident locations by various attributes.

- Communications and community relations: use GIS to convey information to decision- makers and the general public.

- Rational transit project: calculate coverage of services against population.

- Environmental planning: display environment elements such as transit routes, sewer/storm systems, rivers, lakes, bays, housing patterns, etc.

Dallas Area Rapid Transit (DART)

DART's GIS is a critical planning and management tool for anticipating network service needs, and therefore, for improving existing and future ridership. GIS applications at DART are used in numerous divisions of the agency, including (Schweiger 1992, CUTR 1996):

- Paratransit;

- Automatic vehicle location;

- Enhanced customer services;

- Bus stops inventory management;

- Service planning;

- Data collection;
- Service scheduling; and
- System-wide analysis.

The purpose of developing and implementing a GIS at DART was to respond more quickly to customer requests, effectively track route changes, and to determine required additions and modifications of transit lines. DART's GIS is used primarily for service planning, customer assistance, and map and schedule production.

Los Angeles County Metropolitan Transit Authority

LACMTA is the largest transit system using GIS. However, unlike Seattle and Dallas, the LACMTA just recently began implementation of its GIS system. Although hardware installation began in 1991, GIS applications for transit planning did not begin until 1993. Implementation is ongoing and its completion is expected in 1996.

LACMTA is planning to use GIS to predict the future road congestion and the projected patronage on a proposed subway. Other areas of GIS applications will be providing solution to traffic problems, customer information systems, tracking and assessing industrial and commercial properties to support the Metro Rail Program (Peng *et al.* 1995).

San Diego Associates of Governments (SANDAG)

SANDAG has been using GIS since 1985, and has developed an extensive collection of spatial database (CUTR 1996). Transit planning and marketing are key functions of SANDAG's GIS. Databases of population, housing, employment estimate, crime statistics, and land use are maintained and used to produce historical, current, and forecasted profiles. The use of GIS in transit planning allows sophisticated analysis of complex transit-related queries using large databases. The use of TRANPLAN with GIS provides a powerful tool for transit modeling. Recent work includes the development of transit flow maps which provide users with a simplified visual representation of ridership volumes by route. Decisions regarding where to expand or reduce service may be assisted by these maps and plots. **Table 3.1** represents the different GIS application at SANDAG.

Table 3.1 Base Applications for Desktop GIS at SANDAG

Application	Description	Category	Database	Status
Transit Service Potential	Using a definition of potential transit ridership including employment, income, low auto availability, renter, age, and other variables, define areas undeserved or unserved by transit	Planning/Operations	Census data	Currently done with SANDAG's GIS
Socioeconomic profiles of areas surrounding transit	Socio-economic profiles of areas surrounding stops, routes, route segments. Allows staff to buffer an area within a specified distance to a stop or route	Planning/Operations /Marketing	Census data Employment Inventory Transit Coverage	Currently done with SANDAG's GIS
Physical characteristics of transit	Maintains physical characteristics of bus/trolley stops, displays ADA accessible stops, etc. (i.e., What is the distribution of accessible bus stops?)	Planning/Operations	SANDAG and operator bus stop inventories	Currently done with SANDAG's GIS
Route analysis	Analyze existing and planned routes by stop activity, capacities, analysis of passenger loads by route segment	Planning/Operations	Transit coverage, route alternatives, passenger counts, surveys	Currently done by individual operator
Title VI evaluation	Identify minority areas, transit accessibility, and minority routes for FTA/Title VI requirements	Planning	Census data, Passenger counts, Transit coverage	Currently done with SANDAG's GIS
Future Growth areas	Identify areas of forecast growth and relate these changes to transit (current and planned service). For example, what is the expected population growth within the service area of a planned light rail line?	Planning/Operations /Marketing	SANDAG population, employment, land use forecasts, Transit coverage	Currently done with SANDAG's GIS
Transit use by time	Identify route activity during peak versus non-peak hours, identify possible turnarounds	Planning/Operations	Passenger Counting Program, Transit Coverage	Not yet developed

Source: (Culp 1994).

Milwaukee County Transit System

Milwaukee County Transit System (MCTS) is operated by Milwaukee Transit Services, Inc. The GIS of Milwaukee County Transit is integrated with a computer-aided dispatch (CAD) and Automatic Vehicle Location (AVL) bus system (CUTR 1996). The Westinghouse system (SmartTrack) provides reliable two-way radio communication. Information from SmartTrack helps drivers and dispatchers proactively manage fleet operations and maintain arrival and departure schedules. Also, daily activities such as bus operator requests for vehicle repair and security assistance are tracked. Time point and schedule adherence information is also logged into a database so that the scheduling department can monitor trends in on-time performance.

Future applications for MCTA include the following:

- Installation of automatic passenger counters are planned for fifty buses by 1996;
- Options for the purchase of mapping/census software for the Planning Division was to be investigated; and
- Schedule adherence information will be available to planners for review of schedule running time.

Table 3.2 summarizes transit agencies using GIS for transit applications.

3.9 Other Transportation Related GIS Applications

In this section a general transportation GIS application is presented. The section is divided into four subsections. They are as follows:

- Transportation Corridor Planning;
- Urban Transportation Planning;
- Road Safety and Analysis; and
- Other General Transportation Applications.

3.9.1 Transportation Corridor Planning

Examples of using GIS in transportation corridor planning include studies in Dallas, Northern Virginia, suburban Atlanta, and Logan, Utah. Recent applications in North Carolina, within the Charlotte area, involve development of noise contours along roads to parcels that may be suitable

Table 3.2 List of Transit GIS Application Areas

APPLICATION AREAS	USERS
Transit ridership forecasting, service planning, market analysis	Baltimore MTA, Bay Area MTC, Bi-State, Chicago RTA, City of Phoenix, DART, DVRPC, GGBHTD, HGAC, Houston Metro, LIRR, MARC, NJTA, NOACA, NYCTA, NYMTA, Omaha-Council Bluffs MPO, Port Authority NY&NJ, Portland Metro, SANDAG, Seattle Metro, SEMCOG, SMART, Tampa Urban Area MPO, TTD, WashCOG
Map products design and publishing (for example: system maps, route schedules and maps, operator maps)	Bi-State, City of Phoenix, CTPS, DART, DVRPC, Houston Metro, MARC, Miami MPO, MTDB, NJT, NOACA, NYCTA, Omaha-Council Bluffs MPO, Port Authority NY & NJ, Portland Metro, RVTD, SANDAG, Seattle Metro, Tampa Urban Area MPO, WashCOG
Fixed facilities and real estate management (for example: bus stops, transit stations, park and ride lots)	Balt.. MTA, Chicago RTA, City of Phoenix, DART, DVRPC, GGBHTD, Houston Metro, LIRR, Miami MPO, NYCTA, NYMTA, RVTD, SANDAG, Seattle Metro, SMART
Telephone-based customer information services	City of Phoenix, DART, DVRPC, NOACA, NYCTA, Seattle Metro
Transit scheduling and run time	DART, DVRPC, NJT, RVTD, Seattle Metro
Ride matching (for car and van pools)	DART, MARC, Miami MPO, Seattle Metro
Automatic vehicle location	DART, NJT, Seattle Metro
Transit pass sales	DVRPC, MTDB, Seattle Metro
Paratransit schedule and dispatching	TTD
Improved transfer points and connections	NYCTA

Source: (Schweiger 1992)

for industrial development as opposed to residential development. Tennessee also developed a GIS virtual reality to view how newly proposed roads would fit into the landscape.

Hartgen and Li (1993) presented the use of GIS in transportation corridor planning. North Carolina uses GIS to identify the major impacts of I-40, a 120 mile highway connecting Wilmington to Raleigh. GIS was used to provide recommended actions and strategies for governmental and transit agencies. It was also used to reduce negative impacts and maximize positive impacts. Extensive information was used in this study including:

- Demographic and socioeconomic data for all counties along the route;
- Traffic conditions;
- Population and household statistics;
- Information describing the business responses to telephone surveys; and
- Citizen information obtained from public hearings and forums.

This information was used with GIS to analyze the extent to which each of the 22 exits on I-40 were accessible from surrounding communities and other traffic corridors and which communities within the corridor would be affected negatively by greater accessibility to big cities. During this project GIS-T served as a basic tool for facilitating the communication between planners, data gathering, citizens, and policy makers.

The application of GIS-T in the Carolina Parkway study was a perfect forecast for transportation demand and network modeling. This project was part of a transportation study intended to coordinate land use and transportation planning in a way that creates an attractive, efficient regional transportation system supporting economic development objectives. The goal of this study was to develop a series of traffic and land use forecasts for the years 2010 and 2030, with and without the parkway. Several comparative analyses were prepared, showing traffic on critical road segments in the area. Tables for vehicle miles traveled, speed, vehicle hours traveled, and emissions were also developed.

3.9.2 Urban Transportation Planning

In order to model travel demand using the Urban Transportation Planning Process (UTPP), transportation analysis zones (TAZs) must be developed. These structured zones are used in transportation planning and forecasting models at regional and subregional scales. However, when conducting site impact analysis, if the region being modeled is large, planners often use a subarea to perform detailed analyses of a smaller area. By aggregating zones outside the specific area of interest using GIS, organizations can save considerable time and expense from traditional methods. To help minimize the introduction of error into transportation planning models, various criteria for delineating and aggregating zones have been suggested. These criteria were summarized by Bennion and O'Neill (1992) as follows:

1. make zones as homogenous as possible;

2. maximize interaction between zones;

3. avoid irregular or elongated shapes;

4. avoid creating zones within zones;

5. use census boundaries as much as possible;

6. employ other political, historical, and physical boundaries as needed;

7. aggregate TAZ's only at adjacent zones;

8. construct zones so that roughly equal number of trips are generated and attracted between each pair of zones; and

9. establish a maximum number of trip ends per zone.

Developing a process for aggregating TAZs within a GIS framework promotes standardization. Since transportation databases are increasingly being built in GIS, the GIS seems a logical place in which to design and aggregate TAZs. GIS graphical capabilities greatly facilitate visual inspection of different aggregation. The framework of a TAZ aggregation model is presented in **Figure 3.2**. It demonstrates the use of spatial analysis tools in a GIS by modeling some of the aggregation criteria and the use of fuzzy C-varieties (FCV) algorithm as an alternative to a thematic mapping approach to model the homogeneity criterion. For more details, refer to Bennion and O'Neil (1992).

Choi *et al.* (1995) also presented a GIS-based method for designing TAZs. The method employed an indexing method to group homogeneous spatial units to form TAZs. The method involved two steps: establishing first the topological relationship between basic spatial units, then integrating the units into a spatial database. Attribute values of the new TAZs were computed from those of the original spatial units after the integration.

Anderson (1992) presented an application of GIS to transportation planning for the Montgomery County in Maryland which is one of the early users of GIS technology for integrating transportation planning database. For transportation modeling development and data management, a GIS Spatial

Analysis System (SPANS) was acquired. SPANS was used to produce maps of TAZ level input, to provide land use data input to a series of suburban planning modeling. It was also used in the analysis of the household travel survey especially regarding the time-of-day travel behavior. The input data for Montgomery County includes 255,000 recorded county tax assessor parcel file, along with a file containing all approved subdivisions in the county, and vector graph files of parcel boundaries. Also included are TAZ boundaries, MetroRail and commuter rail stations, TIGER/Line street vector file, and sidewalk and street mileage file.

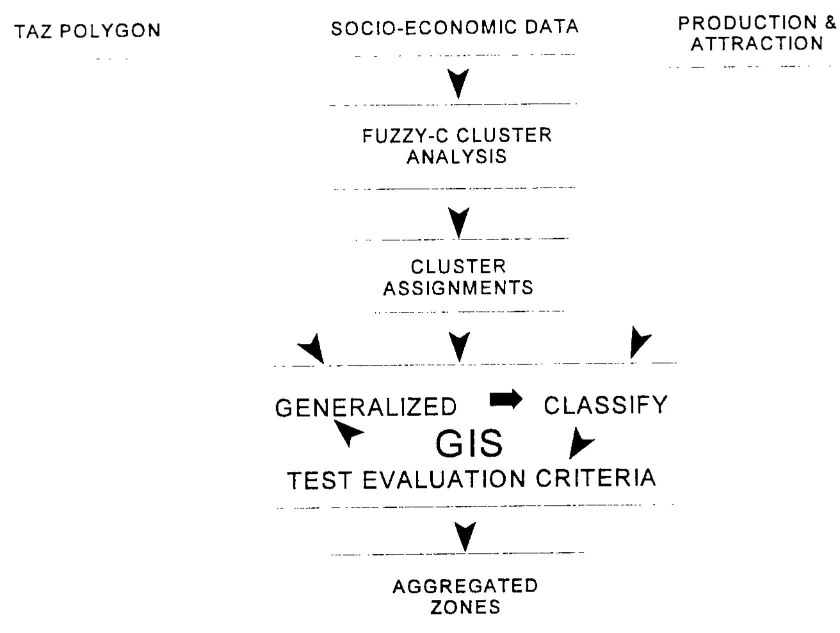


Figure 3.2 Flowchart of TAZ Aggregation Model (Source: Bennion and O'Neil 1992)

3.9.3 Road Safety Analysis

The use of GIS for road safety analysis and management was presented by Peled and Hakkert (1993). This application was implemented in Haifa, Israel. Road safety analysis may be divided into three different processes:

- Identification of a problem;
- Diagnoses of preventative measures; and
- Selection of a solution.

Among the selective approaches are:

1. Mass action which is associated with the raising of engineering standards on a specific subject

such as lighting, friction, guardrail, and much more;

2. Single site and route actions are associated with the identification of safety problems on a specific route or a segment of a route; and

3. Area action that deals with problems associated with the geographic area such as a neighborhood, a region, a district or a municipality.

The data for this study was collected from different sources. A data file compiled by the Planning Department of the Israel Police was suitable for work only at the municipal level because it has no location code. A data file was prepared by the Central Bureau of Statistics that compiled accident data by urban area, rural area, and towns. In this file, accidents for each town are associated with a road section or intersection. A local accident file specific for Haifa, was fed directly from information supplied by the local police department. Difficulties facing the police department in collecting accident data were inaccuracies in data, lack of information, and incomplete or untimely reporting of accidents.

Accident data alone was insufficient for the analysis. Accident data needed to be analyzed to consider the time, location, and the geometric of the road where the accident occurred. In this context GIS was the solution for better accident and road safety analysis. The two major databases involved in the road safety analysis are the road system layout and accident information. A few other databases are also used, including intersections positional and physical characteristics, traffic counts, intersection related data such as signals and signal programs, traffic sinage, pavement markings, and public transportation services and routes.

Using GIS software (ARC/INFO), two layers of road system positional data (streets and intersections) and one layer of accident were created. The accident layer is complemented by two additional non-georeferenced (tabular) data files of vehicle and casualties involved in the accident that are related to and controlled by the accident layer. A special landmark layer was also defined to elaborate on analysis pertaining to attraction like schools, cinemas, supermarkets, etc. Photographs for several intersections and links were scanned and added to the system in order to develop a tool allowing users to view places of interest such as hazardous intersections, bus routes, etc.

This GIS is capable of generating reports in a tabular format or map format. These reports enable managers to understand the overall accident situation in their area or at a particular location, and how it is changing at frequent intervals. Furthermore, they allow the staff members to determine traffic operational and capital investment solutions. These reports establish priorities for improvements on a regular basis. The geographic accident database described above is structured in such a way that the total number of accidents and accident rates at an intersection, on a street segment, or an entire street length, or in a specific area may be determined. The information obtained from the periodic reports and map displays, combined with an accessible database can assist staff members to respond efficiently to citizens' complaints.

In 1980, the Ohio DOT (ODOT) started developing a GIS (Gebhardt 1992). It was designed initially to display accident reports to the nearest one hundredth of a mile on maps of state, county, township, and municipal jurisdictions. All jurisdictions were digitized with total road millage of approximately 112,000 miles. Another task was to relate all digitized roadway mileage to the truly traversed roadway mileage used in the Road Inventory. By adding inventory data to the database, ODOT were able to perform analyses for the desired information which could be displayed graphically with plots or interactively on screen.

The Kansas Department of Transportation (KDOT) is developing a GIS accident analysis system using a CAD package and accident data files (Schweiger 1992). The city of Boulder, Colorado, was in the process of implementing GIS for transportation management (Schweiger 1992). The end product would allow access to traffic counts. Furthermore, it would provide needed information on accident, traffic control device, traffic safety problems, and maintenance needs.

3.9.4 General Transportation Applications

The Southern California Association of Governments (SCAG), the planning agency of the Los Angeles metropolitan region, was developing a land use transportation model to assess long-term growth patterns using ARC/INFO as a GIS environment to integrate the database. The database will include a digitized master plan of all communities in the region, an accurate representation of the street network, the exact location of most employers, and land use data (Prastacos 1992).

In 1989, the Metropolitan Transportation Authority (MTA) in New York City used TransCAD to support data management, modeling, and decision-making for transportation planning. The data collected during this project were used for the highway and subway networks with census tract polygons containing information on population, income, and other socioeconomic characteristics (Prastacos 1992).

GIS may also be used as a tool for highway infrastructure management as well as for land use information. The applications of GIS in highway infrastructure management reported in (Petzold and Freund 1990) include:

- travel demand forecasting;
- accident analysis;
- land use and right-of-way;

- environmental and economic impact; and
- transportation system management.

This study for Petzold and Freund (1990) mentioned that at the state level, two statewide GIS were in the implementation stage. One of them is the Wisconsin DOT's implementation of a GIS for highway infrastructure management which targets pavement management for initial application. The other is the North Carolina DOT's implementation of GIS for pavement management, planning and research, map publication, bridge maintenance, and field office support.

The Office of Policy Development (HPP-1) was the first office within the Federal Highway Administration (FHWA) to use a GIS for highway policy analysis (Stokes and Marucci 1995). HPP-1 started constructing its database in the mid-1980s and completed the database in 1988. The database coded 370,000 miles of highways. The attributes of the database include FHWA functional classification, route number, length, median type, access control type, number of lanes, and pavement type. Other databases in the GIS include interstate truck volumes, state boundaries, congressional district boundaries, airports, military installations and bridges.

Among the leading DOTs in the implementation of GIS besides Wisconsin and North Carolina was Pennsylvania DOT. It formed a steering committee consisting of several state agencies in charge of undertaking research to develop a strategic plan to implement GIS by the agency involved. GIS application in PennDOT is expected to follow the traditional areas of agency responsible for pavement management, traffic engineering, safety, planning and programming, bridge rehabilitation, etc. (Basile *et al.* 1992). The first application for data retrieval was related to the highway safety program, in which accident records can be displayed graphically in many ways on the state highway system. The display of the accident was very helpful for police and emergency medical services. Data integration involved the use of two or more databases to develop the required information. For example, accident records may be combined with road data to view an accident of a certain level of severity in relation to pavement conditions.

A study was done by Hsiao and Sterling (1992) to examine how geographic information system techniques were applied to analyze commuter rail survey data from which the upcoming intercounty rail service design may be projected and tailored. The application in this study demonstrated that GIS provided an efficient approach for transportation data analysis, particularly in the area of origin-destination data analysis. This study focuses on proper parking supply and traffic flow at rail stations, including the riders' origins and their boarding stations tabulated in O-D tables. These O-D tables were used as input to a network assignment for displaying traffic impact on the street network at rail stations. As a result, O-D trip tables were applied to the travel forecasting model for network assignments to the peak-period link volume. It became possible to gauge the distribution pattern of a rider's origin in relation to boarding stations. By analyzing the network assignment, it was found that most people traveled three to seven miles from their homes to the rail stations. The authors concluded that the GIS provided a flexible approach for data analysis for the specific purpose. Moreover, both short-term commuting service design and long-term range transportation planning activities may be developed based upon a common GIS database structure, from which specific information can be queried to address a unique project purpose.

Another application of the use of GIS in transit can be the development of an intermodal transportation plan. The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 requires that each state prepare a statewide intermodal transportation plan in mid-1995. Louisiana along with Alaska, Florida, New Mexico, Ohio, and a consortium of six New England states were selected to develop modal plans. The following discussion includes the organization, development, and management of the GIS and MIS (management information system) systems related to the intermodal plan for the State of Louisiana. The study included Louisiana in detail, U.S. States were divided into several regions, and several major trade locations worldwide. In this study, Movassaghi and Parlee (1995), Louisiana Department of Transportation and Development took into consideration not only the passenger movements, but also the cargo movement including road, rail, waterway, and air travel. Data was collected by determining the type, level of detail, and the methodology to perform the analysis. The data collected included network and flow data (base-line 1990 and forecasts 2020). Network data include demographics, land use, highway network, rail network, air network, and waterway network, while flow data include node network for passenger and cargo movements. Other non-spatial data is stored separately in MIS. Such data include ozone and carbon monoxide concentration in air, major imports and exports of various regions, emissions by vehicle type, fuel consumption by vehicle type, operating cost by mode, freight shipment rates by commodity, regulation and legislative acts, results of interviews with transportation users and providers, and average vehicle occupancy by mode. The study concentrated primarily on the intercity movements. The database development evolved into analysis and mapping results for future flows of passenger and cargo. These results were then displayed on maps, and based on which additional highways were proposed.

In a study for the Center Region of Pennsylvania, Matzzie and Rogers (1991) utilized MapInfo GIS in conjunction with MINUTP transportation modeling system. Transportation network modeling generally involve a large number of elements. Usually there are several hundred traffic analysis zones, and thousands of links and nodes, depending on the geographic extent of the area of study and the degree of detail incorporated into the model. MINUTP is a derivative of the UTPS software package that runs on mainframe computers. It includes two graphic interfaces that provide a powerful tool for viewing and editing transportation networks. Moreover, it provides a colored hard copy output of a network with different attributes for each link. Although MINUTP provided the ability to visualize the network and help the user in model calibration, interpretation, and communication of the model, it did not show either the boundaries of the TAZ nor the network in relation to physical features. By using GIS as a database management tool and applying location codes to all records, information may be overlaid that will address a variety of location-oriented questions.

A study was done for the Regional Transportation Commission (RTC) in Clark County, Nevada by Lima *et al.* (1992) to develop a comprehensive regional transportation database using GIS. The development of a GIS system was thought to be a tool for analyzing the impact of competing arterial and highway projects and understanding regional traffic patterns. The first step for the development of a regional database was to identify the transportation functions to determine the data needed for the final products. Although the potential functions were transportation improvement, detailed capacity analysis, accident analysis, and cost effectiveness analysis, functions such as traffic volume analysis, transportation modeling, network analysis, planning LOS, transit network planning, and hazardous material routing were also required.

The RTC GIS/T communication flow chart shown in **Figure 3.3** illustrates the general data communication flow from various data sources to ARC/INFO to output. The data flow was divided into five main parts:

1. Database to GIS or Planning Models;

2. TRANPLAN to GIS;

3. GIS to TRANPLAN;

4. External GIS to RTC GIS; and

5. GIS to Maps.

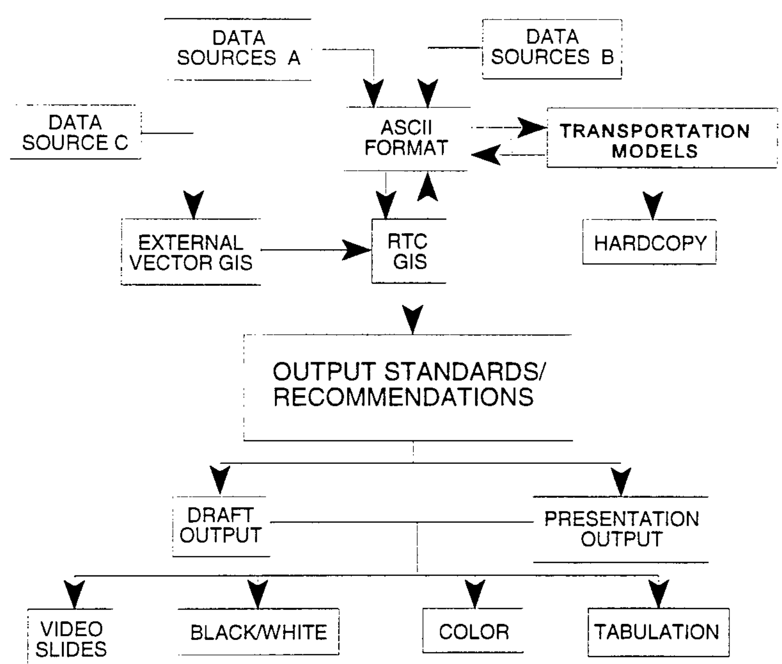


Figure 3.3 RTC Database / GIS Communication Flow Chart (Source: RTC 1991)

According to the authors, this project was successful in terms of defining a regional transportation GIS/T concept and demonstrating potential regional transportation applications. It demonstrated how to link the regional transportation model to Clark County GIS. RTC was in the process of implementing the major project recommendations including the provision of linkage between the transportation model and GIS in the development of macro commands to provide a user friendly interface which is now an available feature of ARC/INFO, implemented in SML and AML.

Other technologies will become an important element of GIS such as the Global Positioning System (GPS) discussed by (George 1991). The use of GPS will enable transit operators or transportation professionals to quickly determine the location of interested features on the earth's surface that constitute the spatial data in GIS database. GPS-derived data may be field recorded and inserted directly into a computer database without further processing. The Texas State Department of Highway and Public Transportation (SDHPT) has installed five automated GPS continuous tracking stations, located in Dallas, Austin, San Antonio, Corpus Christi, and Houston, to facilitate existing and future GPS operations. Among the non-highway transportation users, the railroads have already considered the possibility of using GPS to keep track of the railroad cars and to keep real-time accurate positions of their trains. The use of GPS with GIS is now being tested by the U.S. Coast Guard for harbor navigation. Moreover, FAA is evaluating GPS for both airborne enroute navigation and precise terminal approach applications.

4. TEMPORAL GIS

A fundamental difference between a conventional GIS map and that of temporal GIS is that the former describes a static state of the physical world while the latter a dynamic state, a series of which depict the history of the physical world being modeled. Current GIS technologies provide static data models and tools that support the capture, query, analysis, and display of geographic information for a fixed time point. When data are captured, they are assumed to be reflecting the present state of the world and used for various analysis tasks until new data become available and the GIS databases are updated with the new data superseding the old. The old data, however, are most often thrown out, or, if not discarded, archived on a magnetic media. Since existing GIS software does not support the storage and analysis of temporal information, such historical data are difficult to maintain or use. Some GIS software such as STORM™ by Environmental System Research Institute, Inc., provides limited data management tools to maintain history of database transactions by allowing the storage and retrieval of different versions of GIS map layers. The database time, however, only tells when a change has occurred in the computer storage and does not provide information regarding when it has happened in the real world, thus missing the link to reality. At present, to include temporal information and make temporal analysis possible in existing GIS software packages, extensive customized software development is required.

To provide a background of temporal GIS, in this chapter some basic concepts of temporal GIS are discussed. The next section describes the basic functions of a temporal GIS. **Section 4.2** briefly discusses the concept of time and modeling of time in temporal GIS. **Section 4.3** presents major data models so far developed for temporal GIS. **Section 4.4** summarizes the current temporal GIS applications. Since most transportation applications involve the use of road or other transportation networks, vector GIS is usually more suitable than raster GIS. Therefore, in the discussions that follow, we will focus our attention on vector spatiotemporal data modeling issues.

4.1 Functions of a Temporal GIS

According to Langran, the fundamental functions of a temporal GIS are inventory, analysis, updates, quality control, scheduling, and display (Langran 1992). Inventory is the storage of complete descriptions of the study area, which include changes in both the physical world and in computer storage. These changes may be simply temporal, or both spatial and temporal. For instance, a given bus route may be represented in a GIS database by a set of spatial objects, in this case lines, with attributes such as route number and total ridership. The bus ridership for different time, day, month, and year is temporal information that reflect the changes in the attribute value of the bus route. The different alignments of a bus route, on the other hand, is spatiotemporal since the spatial objects themselves have changed with time.

Analysis in a temporal GIS, in addition to spatial phenomena, involves the investigation of the changes in spatial patterns with time and the causes or effects of such changes. For instance, one temporal analysis may be to examine the long term trend of ridership for a bus route. The examination may be performed on total ridership, or, if disaggregate information is available, on passenger counts for specific loading points. Another analysis may involve study of both bus network change over a period of twenty years, e.g., and the change in urban patterns. Typical questions to be answered by a temporal GIS include when changes occur, where they occur, in what spatial and/or temporal pattern they occur, and why they occur. Although some analyses may be performed manually using the conventional GIS technologies, they may be accomplished easily and more systematically with temporal GIS technology.

Updates are concerned with ensuring that the database provides the most current information about a study area. Two types of GIS are distinguished by Dueker (1979) and Langran (1992). One is *nonroutine* or *ad hoc* GIS, which is intended to seek answers to a particular question or solutions to a special problem. Such a GIS database is often abandoned after the original objectives are accomplished. There is, therefore, no need for updating this type of GIS. The other type is *routine* GIS and is intended as a permanent repository of information on which an organization's operations depend. GIS databases of this nature require updates. Updates not only require new data to supersede old data, but also continue the maintenance of the old data for future use. To this end, it is often necessary to maintain a logical link between the old and new data. This temporal topology preserves the information about the evolution of spatial objects and may be used to trace the history of a particular spatial phenomenon.

Quality control provides a means to minimize the chance of errors by checking the validity and consistency of the database. In a temporal GIS, new data may be verified against historical information about the real world phenomena that they describe. However, such verification and validation most times will have to involve human judgements since it will be difficult to distinguish errors from changes when comparing data of two different time periods.

Scheduling is a mechanism that may be implemented in a temporal GIS and allows predefined actions to be triggered by events such as changes in data or the elapse of a certain time period. This feature is useful in many transportation applications, especially those that are related to operations and control. Even for applications that are less time-sensitive, such as transportation planning, a temporal GIS may signal the need for a new model run due to significant changes in road network or land uses.

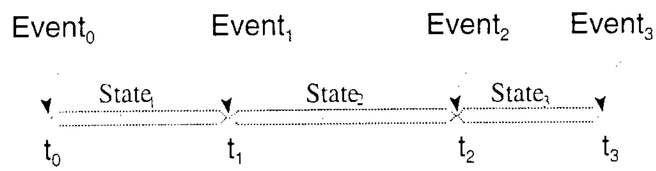
The last but not the least function of a temporal GIS is display and map production. In addition to the display functions provided by a conventional GIS, display in a temporal GIS also involves the generation and presentation of the temporal changes that may be qualitative as well as quantitative in nature. Muehrcke (1978) describes four types of temporal information that may be displayed regarding changes: where (qualitative), how much (quantitative), composite change (paths, time sequences, cycles, etc.), and space-time ratio (travel speed, rate of change). Adding a dimension to the information makes the display on a two-dimensional map more difficult. Existing techniques for temporal information display include map series of different time periods, text, graphics, and digital amendments to a base map, static maps with thematic symbols depicting a temporal theme, and animations that use a scaled time and space model to show dynamically the sequence of states of a spatiotemporal phenomenon (Langran 1992). More sophisticated mapping techniques need to be developed for temporal information display. While animations have been favored in display changes in land use or vegetation, and in movements of storms in weather forecast, they are of a highly qualitative nature and unable to convey precise quantitative information. For transit and general transportation applications, operations information such as vehicle locations tends to be more suitable for animations while planning information more suitable for static maps with temporal themes.

While no generic temporal GIS software is available, prototype temporal GIS programs have been developed for various applications, most of which are related to natural resource management and environmental modeling. Due to the lack of experience with temporal GIS and therefore limited understanding of its applications and potentials, the potential functions of a temporal GIS have only been explored in a limited manner. Prospective users are often unable to fully specify the functional requirements of a temporal GIS for intended applications. In prototype implementations of temporal GIS, functions have included storing temporal information, retrieving temporal information, determining the relationship between two events (such as before, after, during, overlapping, etc.), comparison of two map series, interpolation of two or more map series, and temporal visualization through animation. While most of such functions are common to most temporal GIS applications, specific applications are likely to produce their own functional requirements, thus new temporal GIS functions.

4.2 Modeling of Time

One view of temporality is to consider it as a sequence of states "punctuated by events that transform one state into the next" (Langran 1992). Each state represents the knowledge we have about the physical world for that given period of time. The time point when updated information is obtained becomes the "event" that changes the state of the modeled phenomenon and marks the beginning of the *valid time* (or *world time*) for the database records describing the new state of the phenomenon. For instance, when a new census is taken, new information about population becomes available and this results in a change in the GIS database. The event that caused the change is the census sampling and compiling and the states are the populations at different time periods. The *world time* or *valid time* may be represented by a pair of attributes: *valid_from* and *valid_to* that are attached to the spatial objects. **Figure 4.1** illustrates the concept of states, events, and valid time.

The above understanding of events and states is, however, somewhat static. It assumes that events are instantaneous or their durations are insignificant. For instance, census is taken every ten years, compared to which the time spent on sampling and compiling the data is



	valid_from	valid_to
$State_1$:	t_0	t_1
$State_2$:	t_1	t_2
$State_3$:	t_2	t_3

Figure 4.1 Temporality as States of a Phenomenon Separated by Events

considered relatively small and does not result in a noticeable inconsistency in the data, since the overall population and socioeconomic conditions do not change rapidly. There are many occasions, however, when a phenomenon is less static or stable than population and is an event that has a shorter but defined and dynamic life span. Examples of such phenomena include wildfires, traffic congestions, or a vehicle trip. For such phenomena, events will have their own lives, life spans, and, therefore, world time or valid time. The view that temporality is a series of states marked by instantaneous events is, therefore, unable to fully describe the changes that occur around us. A different approach is to consider events as having some duration rather as durationless time points (Allen 1983, Freksa 1992). Information may be incomplete regarding the beginning and ending of an event, but logical relationships may be maintained. Fuzzy logic may also be used to model the imprecision of the beginning and ending of an event (Dubois and Prade 1989).

Another time dimension independent of the *valid time* is the *database time* or *transaction time*, which is the time when a database transaction is completed. Database time is important not only for maintaining database history but also for maintaining a history of the usage of the data for analyses and, subsequently, decision-making.

Sometimes, the time when a phenomenon manifests itself and the time when observation or measurements are made about the phenomenon do not coincide. In other words, we may be measuring a phenomenon sometime after we became aware of an event that caused the phenomenon. One example is a flood area, which may be measured a few days after it actually happens. The need to model the *measured time* or *observation time* depends on whether the phenomenon is stable or if the changes that occur between the time when an event occurs and when the measurements taken are significant.

All of the above and possibly more types of time that we may wish to model reflect the fact that time is multidimensional (Snodgrass 1986). These different time dimensions are also most often independent of each other although there may exist some logical relationships between them. For instance, measured time, if applicable, will always lag behind the valid time. For more time dimensions and time modeling, readers are referred to Allen and Hayes(1985), Anderson (1982), Clifford and Warren (1983), Snodgrass (1992), and Van Benthem (1982).

Besides different time concepts, another important issue in modeling time is the temporal resolution. By temporal resolution we mean the smallest time interval to be represented in a temporal GIS database. For instance, we may choose the unit of time to be a year, month, day, hour, minute, second, or an even smaller unit. As an example, demographic and socioeconomic data may be satisfactorily dated by year while for vehicle tracking a time unit of minutes or even seconds may be necessary. Therefore, the choice of temporal resolution is mainly a function of intended applications, but is also constrained by data availability and data volume. Sometimes, due to the lack of existing data, a temporal resolution may be less than desirable. Techniques such as interpolation may be used sometimes to estimate data for an intermediate time slice. These techniques, however, should be applied carefully to ensure that the interpolation function reflects the trend of changes. While a higher resolution is often desired, it also increases the data volume significantly. Consider a database with a temporal resolution in hours and another with one in seconds, the data volume for the latter database may be up to 3,600 times larger, depending on the actual data model used. Although computer technologies have advanced close to the point that storage will not be a constraint anymore, such large volumes of data still create a burden in terms of data management, maintenance, organization, and retrieval. The choice of a temporal resolution is, therefore, sometimes one that involves trade-offs, demanding the balance of the application needs and data management and performance requirements.

4.3 Modeling of Temporal Data

In this section, we only discuss the modeling of temporal data. Models for spatiotemporal data will be discussed in the next section. Many schemes have been proposed to model the event time in a temporal database. For instance, <[25, 32] red. [33, NOW] blue> may be used to describe the attribute COLOR (Gadia and Nair 1993). The expression means that the color was red during the time period from 25 to 32, and changed to blue at time point 33 and remains blue until the present time. Other methods for modeling the time may be found in (Langran 1993, Snodgrass 1992, Segev and Shoshani 1987, Story and Worboys 1995, Soukeras and King 1994).

Every time there is a change in the database, a new version of the information will be produced, which is referred to as *versioning* in temporal database literature. Apparently, generating a new version for the entire database for every change is unrealistic. For relational databases, information is organized and stored in a set of related tables with each column in a table containing values of a given attribute for different instances of an object or feature and each row a complete description or record of an object. Accordingly, new versions may be generated for tables, records or tuples, or attributes. **Table 4.1** shows a sequence of hypothetical events that occurred during the time period from *5/1/88* to *12/1/90*. **Tables 4.2** through **4.4** give the database relations for the three different versioning strategies. It may be seen that versioning at the relation level often results in large volumes of duplicated data. Data duplication is reduced for versioning at the record or tuple level. Versioning at the attribute level eliminates redundant information completely, but it also results in a variable length of records.

Table 4.1 Sequence of Events

	Feature	X	Y	Effective	Comments
database as 3/1/85	Stop 1	45	67	2/23/85	
	Stop 2	45	68	2/23/85	
database modification as on 5/1/86	Stop 3	46	68	4/16/86	(added)
database modification as on 12/1/90	Stop 1	45	66	11/17/90	(altered)
	Stop 4	48	68	11/22/90	(added)
	Stop 5	50	68	12/20/90	(added proactively)

Table 4.2 Versioning at Relation Level

Database Time	Feature	X	Y	Valid Time	Comments
3/1/85	Stop 1	45	67	2/23/85	
3/1/85	Stop 2	45	68	2/23/85	
5/1/86	Stop 3	46	68	4/16/86	
12/1/90	Stop 1	45	66	11/17/90	(altered)
3/1/85	Stop 2	45	68	2/23/85	
5/1/86	Stop 3	46	68	4/16/86	
12/1/90	Stop 4	48	68	11/22/90	(added)
12/1/90	Stop 5	50	68	12/20/90	(expected)

Table 4.3 Versioning at Record Level

Database Time	Feature	X	Y	Valid Time	Comments
3/1/85	Stop 1	45	67	2/23/85	
3/1/85	Stop 2	45	68	2/23/85	
5/1/86	Stop 3	46	68	4/16/86	
12/1/90	Stop 1	45	66	11/17/90	(altered)
12/1/90	Stop 4	48	68	11/22/90	(added)
12/1/90	Stop 5	50	68	12/20/90	(expected)

Table 4.4 Versioning at the Attribute Level

Feature, DBF, DBT, VTF, VTT	**X**, DBF, DBT, VTF, VTT	**Y**, DBF, DBT, VTF, VTT
Stop 1, 3/1/85,*, 12/1/90,*	**45**,3/1/85,*,2/23/85,*	**67**,3/1/85,12/1/90,2/23/85,11/16/90 **66**,12/1/90,*,11/17/90,*
Stop 2, 3/1/85,*,2/23/85,*	**45**,2/23/85,*,3/1/85,*	**68**,2/23/85,*,3/1/85,*
Stop 3, 5/1/86,*,4/16/86,*	**46**,5/1/86,*,4/16/86,*	**68**, 5/1/86,*,4/16/86,*
Stop 4, 12/1/90,*,11/22/90,*	**48**,12/1/90,*,11/22/90,*	**68**,12/1/90,*,11/22/90,*
Stop 5, 12/1/90,*,12/20/90,*	**50**,12/1/90,*,12/20/90,*	**68**,12/1/90,*,12/20/90,*

Note: DBF - database time from, DBT - database time to, VTF - valid time from, VTT - valid time to.

Versioning at the relation level often results in a high degree of duplication, especially when only a few records are changed. The database operations such as query will be, however, the simplest, since an entire database table may be retrieved based on a given time slice. Versioning at the record or tuple level will reduce the degree of duplication, although data duplication is still not completely avoided. This is because if only one piece of information in a record is changed, the entire record, which may contain a few dozen pieces of information, will be replicated and the rest of the record will be duplicated. The query now requires a little more processing. Finally, versioning at attribute level results in the most compact database but the associated operations are also the most complex. Apparently, the fundamental problem is the space and time trade-off. A database, therefore, must be carefully designed to achieve the balance between storage and processing.

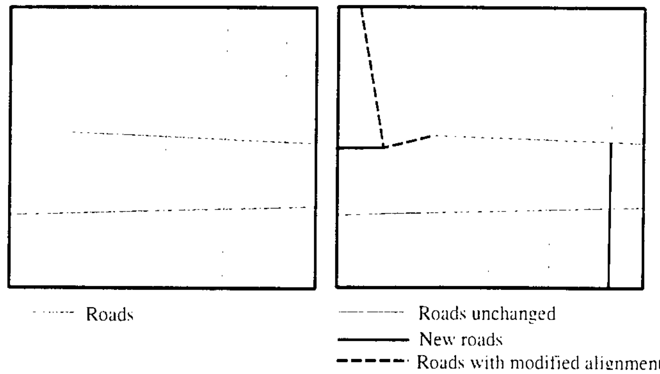
4.4 Temporal GIS Data Models

In this section, we describe some proposed data models for representing spatiotemporal data in a temporal GIS. Spatiotemporal data are those that reflect changes in spatial features, which include changes in the geometry and location of a spatial feature or spatial topology. In contrast, temporal data are those that reflect changes only in the attributes of spatial features while their shapes, positions, and topology remain the same. Modeling of temporal data is dealt with in **Section 4.5**, separately.

Static Models

Static models refer to those GIS data models that describe stable phenomena that have relatively clearly delineated states as marked by events of which the life span or during is less important (see **Figure 4.1**). The states change due to events in which both spatial objects and/or their attributes may change. The major temporal GIS models proposed are the snapshot model, update model, space-time composite model, 3D/4D model and integrated model. The snapshot model, which is supported by the current GIS technologies, stores spatiotemporal information by a series of map layers depicting the same phenomenon over the entire space, one for each time slice (Langran 1993, Peuquet and Wentz 1994). For instance, for transportation planning, there is a need for demographic statistics. Such data for different years may be stored in several map layers, e.g. pop80 and pop90, respectively, with pop80 containing the 1980 census data and pop90 the 1990 data. It should be pointed out that not only population and its spatial distribution will change, but the census statistical units such as census tract definitions may also change. Such change may involve change in numbering scheme, or redefinition of the tract boundaries. **Figure 4.2** shows two snapshots of a road network in an area captured at two different times. Snapshot models have a serious shortcoming, which is a high degree of data duplication. In many cases, changes may be relatively few, which means large volumes of the data are unnecessarily stored. Another problem with the snapshot models is that they do not provide temporal connections, or *temporal topology*, between the features from two different snapshots. In other words, while the differences between two snapshots may be analyzed, the relationship between individual features are either not captured or difficult to establish. As a result, it is difficult, for example, to determine that a roadway alignment has been modified unless they happen to have the same identifier, which is a rare case. Because a snapshot captures data for an entire study area, update is rather expensive therefore temporal resolution is often low, ranging from annual update to centennial update (as in the case of census data). Since there is no means to time-stamp individual features in one snapshot, temporal resolution is further degraded. As shown in **Figure 4.2 (b)**, there are three changes in the road network, two new road segments and one with modified alignment. Information regarding when these changes occur, however, is missing.

The update model stores only one full version of a data set, with new information added as updates (stored separately) whenever changes occur (Langran 1992, Peuquet and Duan 1995). **Figure 4.3** illustrates the same road network evolution as shown in **Figure 4.2** using an update model. It is possible in an update model to time-stamp all the changed features. Temporal resolution is therefore improved. There are no established rules regarding how the updates should be stored, in a single file or multiple files, or the number or size of the files, which should be determined to minimize the search time when temporal queries are requested. Alternatively, an update model may be replaced by backward-oriented amendments to a base state where the most current information is saved as a complete coverage while changes occurred in the past as separate coverage(s) (see **Figure 4.4**). Backward-oriented update model is perhaps more efficient since most analyses are likely to involve comparisons between present state to past states.



(a) (b)

Figure 4.2 Road Network Changes in a Snapshot Model

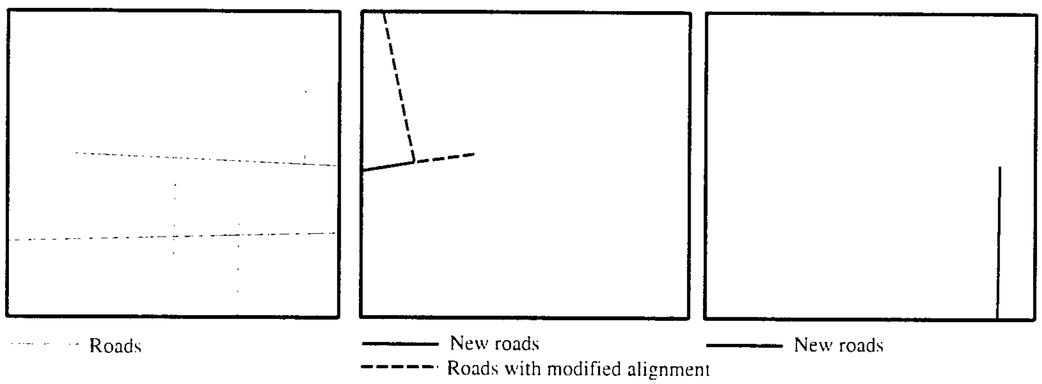


Figure 4.3 Road Network Changes in an Update Model

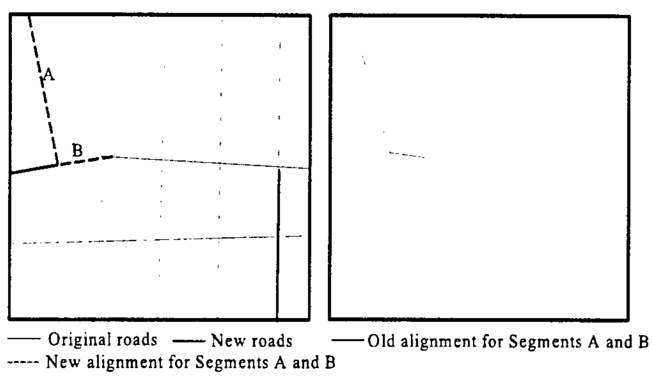


Figure 4.4 Road Network Changes in a Backward-Oriented Update Model

The update model is in many ways an improvement to the snapshot model. It is, however, more complex in terms of data management and is not supported by current GIS software. It is possible to implement an update model as an extension to commercial GIS software. For instance, a prototype temporal GIS is reported in (Candy 1995), which is built on an update model on top of

Arc/Info using ArcTools and Arc/Info Micro Language (AML).

The space-time composite model is similar to the update model but stores both past and present data in the same layer and constantly maintains the topology (Langran and Chrisman 1988). This model allows historical information to be preserved by identifying spatial units that have unique attributes and existence in terms of time. **Figure 4.5** and **Figure 4.6** show how changes in a road network and in a traffic analysis zones appear in a space-time composite model, respectively. **Table 4.5** describes some of the attributes of the polygons representing the TAZs of 1980 and 1990. Evidently, this model runs into the problem of spatial objects being decomposed progressively into smaller objects and their identifiers having to be retroactively changed. For instance, in **Figure 4.5**, because of the realignment of road segment *1*, represented as segment *9* in **Figure 4.5(b)**, both the new and old segments *1* and *9* are divided into smaller line segments: *1, 2, 6, 7*, and *25*. Even though old and new segments *1* and *9* do not exist in the same time period and therefore do not have spatial contacts, in the space-time composite model they appear to intersect with each other, which is an undesirable situation. Intensive computation would also be involved when a snapshot of the database is to be obtained since spatial features have to be merged to recreate the topology. In addition, the identification numbers for the old line segments have to be changed. This same problem also exists for polygon data.

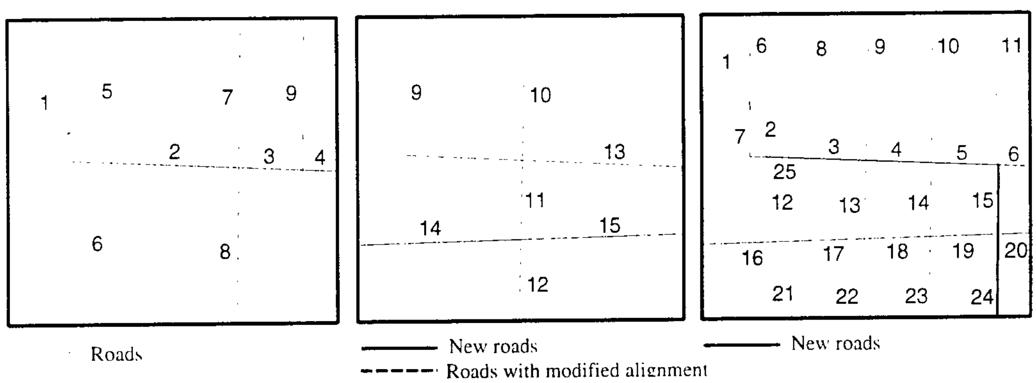


Figure 4.5 Linear Feature Representation in a Space-Time Composite Model

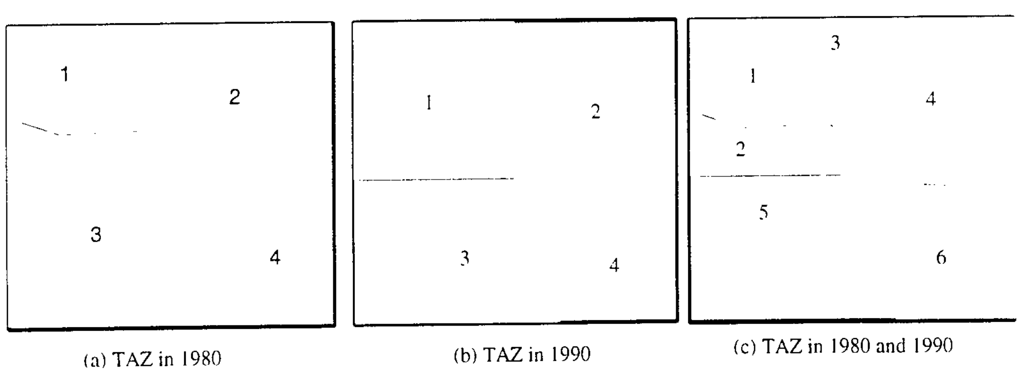


Figure 4.6 Polygon Representation in a Space-Time Composite Model

Table 4.5 TAZ Definitions in 1980 and 1990 in a Space-Time Composite Model

Polygon ID	1	2	3	4	5	6
TAZ_ID	1	1	1	2	3	4
Old TAZ ID	1	3	2	2	3	4
From	1970	1980	1980	1980	1980	1970
To	1990	now	now	now	now	now

The 3D/4D model treats time as a dimension in addition to the spatial dimensions. Every spatial object including points, nodes, arcs, and polygons would be defined by coordinates in the space of either *(x, y, t)* or (*x, y, z, t*) (Hazelton *et al.* 1990). This data model is much more complex and requires a GIS to be developed from scratch. No implementation of this data model has been reported so far. However, it offers the full temporal topology since time is being treated in the same way as a coordinate. Therefore, just like questions such as which objects are connected or adjacent to each other may be answered by existing GIS, questions may also be asked regarding which objects are temporally connected.

The integrated model combines some of the aforementioned models to take their individual advantages and overcome some of their disadvantages (Peuquet 1994, Kelmelis 1991, Osborne and Stoogenke 1989). All these data models have their own attractiveness and shortcomings, and the theories were better developed for some than for others. Some require developing new temporal GIS software from scratch and others allow existing GIS software to be extended to provide some forms of support for temporal information.

Dynamic Models

Static models based on the concept of time series are not well equipped to deal with spatial phenomena that are local, change fast, and have their distinct characteristics. Examples of such phenomena include weather systems, wild fires, floods, chemical or oil spills, traffic congestions, vehicle tracking, etc. In the study of such phenomena, or events, the processes are more important than are the spatial attribute distributions. It is often of interest to study the origin of an event, its changing shape and traveling path, its characteristics such as intensity and speed of movements, its relationships to other events, and its transitions and life span. These events, therefore, may be treated as real world entities that have a set of unique characteristics with a temporal dimension. The concept of time objects are intended to model such phenomena, from which event-based spatiotemporal data models are developed. Raper and Livingstone (1995) proposed an object-oriented approach to model geomorphological systems. Geomorphological phenomena are represented by objects that are described by form, process, and material objects, which, in turn, are represented by attribute objects (**Figure 4.7**).

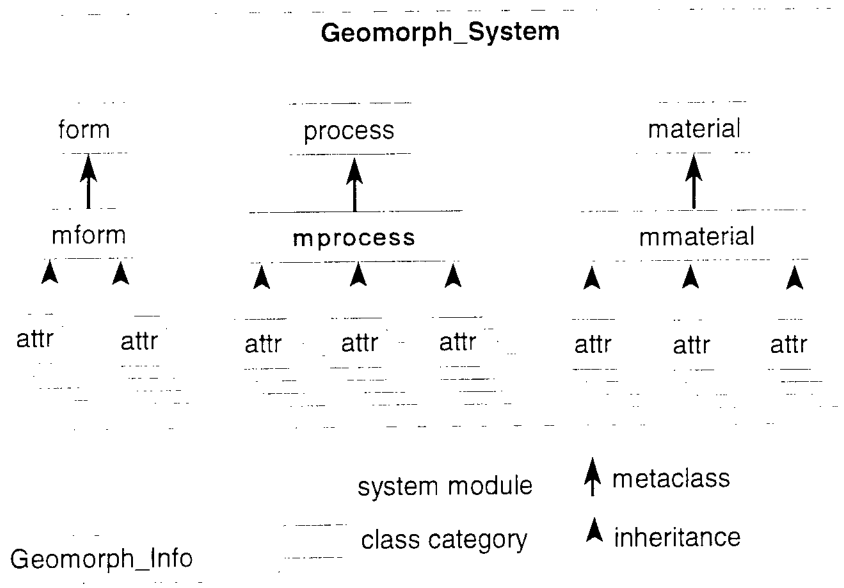


Figure 4.7 Object-Oriented Data Model - OOGeomorph (Raper and Livingstone 1995)

The three domain model is developed by Yuan (1994a). Three domains are semantic, temporal and spatial domains (**Figure 4.8**), in which semantic, temporal, and spatial objects are defined. The three domains support four data schemata needed for wild fire modeling: snapshots representing states, fire entities process, entity snapshots changes, and fire mosaics the history (**Figure 4.9**). Time is modeled as a temporal object instead of being an attribute of a location, as in snapshot models, or spatial entities as in update and space-time composite models. Any phenomenon may be modeled by dynamically linking the three types of objects with location-centered, entity-centered, or time-centered perspectives. Changes that may be modeled include attribute changes, static spatial distribution, static spatial changes, dynamic spatial changes, mutation of a process, and movement of an entity.

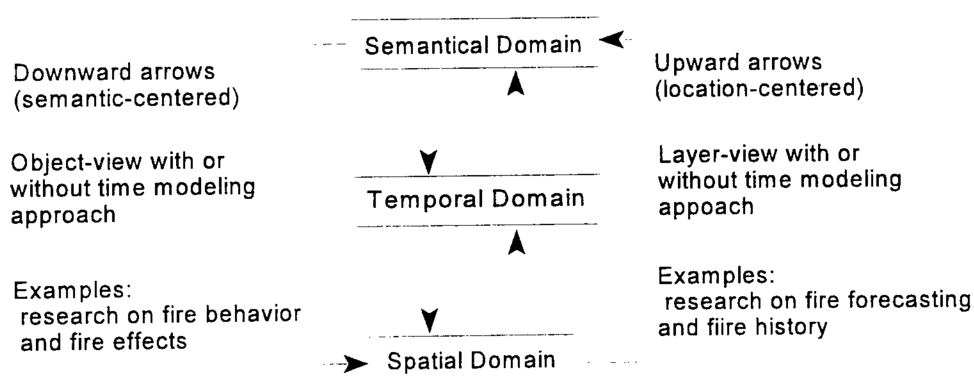


Figure 4.8 The Three Domains Model (Yuan 1994a)

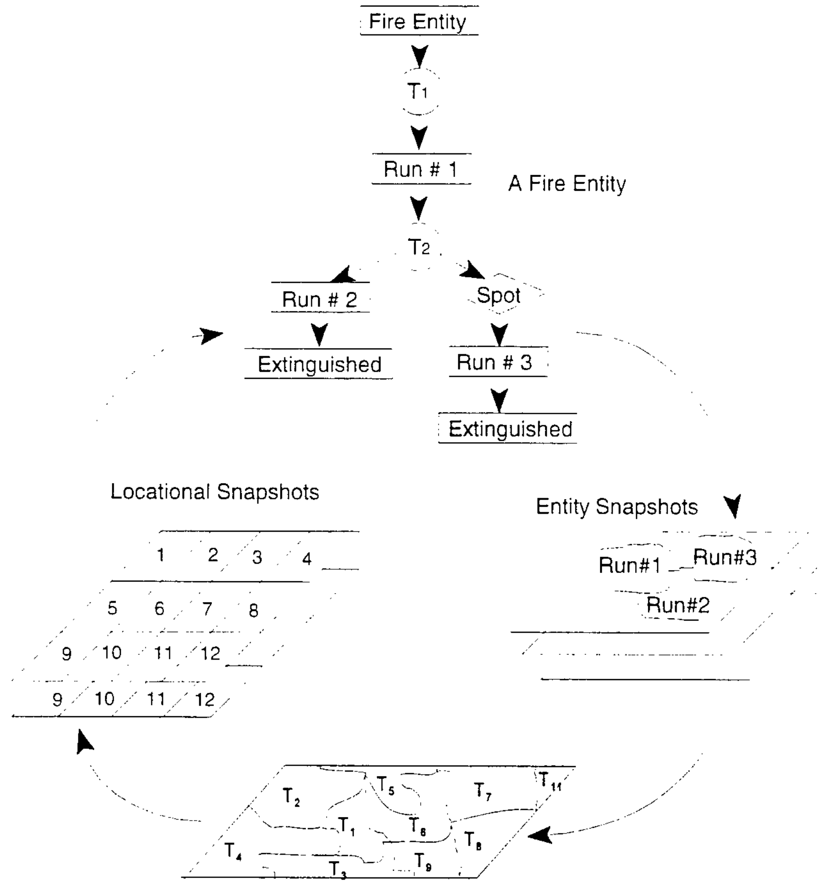


Figure 4.9 Four Data Schemata for a Wildfire Information Cycle (Yuan 1994a)

Temporal GIS theories as well as data models continue to be developed. Depending on specific applications, various data models have their advantages and disadvantages. At present, there is little understanding about potential, suitable temporal GIS models for transportation and transit applications. Systematic studies, therefore, are needed to carefully analyze the functions related to transit management activities, including planning, construction, operation, and maintenance, and to identify the potential data models. While it is anticipated that future commercial temporal GIS software may begin to provide a limited number of data models, these data models may be inadequate or inconvenient to use for particular transit or transportation applications. Therefore, the special data modeling needs have to be studied to allow either adaption of commercially available temporal GIS data models, or to develop additional data models.

5. POTENTIALS OF TEMPORAL GIS FOR TRANSIT MANAGEMENT

The public transit management has many facets including transit planning, service planning, transit service quality monitoring, transit service evaluation, marketing, customer services, and evaluation of impacts of transit on land use. Due to the continual change in the urban patterns, economy, and population with time, there has been a steady increase in the demand for transportation. Although automobiles are the dominant means for personal travel today and will remain so for a long time to come, urban sprawl, congestion, and other problems related to automobile uses have increasingly raised the awareness of the needs for developing a good public transportation system. Public transportation management, like transportation science and engineering in general, however, is still as much an art as a science after a history of more than a century. There are many phenomena, such as transportation and land use interactions and transit impact on economy, that we do not currently understand or understand well. Temporal GIS promises to help make transit management and policies more effective and efficient by providing a tool to study the history to learn important lessons. In this section, various aspects of transit management are examined to explore the opportunities of benefiting from a temporal GIS, either by making historical information available for public access or by improving management practices with better knowledge about the changing trends. The discussions are not intended to be a complete examination or enumeration of the potential applications of temporal GIS for transit, but rather selected examples to demonstrate the usefulness of a temporal GIS and inspire more ideas. The issues related to their actual implementations include complexity, effectiveness and associated difficulties need to be studied in more detail. The areas that will be examined include:

1. Transit planning;
2. Service planning;
3. Travel information; and
4. Transit service evaluation.

For each of these areas, a description of the management task is first described, and examples of potential temporal GIS applications are presented and discussed. We emphasize that we are not suggesting that all these applications are only possible with a temporal GIS. A few applications may be implemented using the conventional GIS technology. However, a temporal GIS will make the data collection, storage, maintenance, and analysis much easier and more efficient. Without a temporal GIS, a manual process that is extremely slow, cumbersome, and error prone will make many analyses impractical.

5.1 Transit Planning

Transit planning is the process of determining the needs for transit services and facilities. Planning is divided into long-range planning, short-range planning, and service or operations planning. Long range planning may include, in addition to determining the demand for transit services, items such as acquiring new vehicles, changing the general configuration of the network, planning major capital facilities, and introducing new transportation modes.

One objective of transit planning is to determine the demand and the need for transit services by estimating the expected number of users in a transit service area. While many efforts have been made to develop transit demand modeling techniques (see, e.g., Peng et al. 1997, Azar and Ferreira 1995, Segedy 1997), transit ridership forecasting remains an important component of the traditional four-step transportation planning process (trip generation, trip distribution, modal split and network assignment). Transit patronage forecasts are the product of a sequence of models used to analyze and predict the aggregated travel volume in an urban area, the geographic distribution of trips-making, the level of transit use in specific corridors, and ultimately, patronage on individual routes. The transit demand modeling process is divided into estimating the number of transit trip ends by geographic areas, often divided into analysis zones, transit trip distribution, transit interchange, transit assignment, and transit link volumes. The four steps of the traditional urban transportation models, trip generation, trip distribution, modal split, network assignment, and their significance to transit planning are briefly described below (Meyer and Miller 1984).

Trip Generation

For planning study purposes, an urban area is divided into small study zones, called traffic analysis zones (TAZs). Trip generation is the prediction of the number of trips produced and attracted to each zone, that is, the number of trips generated within the urban area. In other words, the trip generation phase predicts total flows into and out of each zone in the study area, but it does not predict the origin of the incoming flow or the destination of the outgoing flow. Trip ends are classified as being either a production or attraction, as shown in **Figure 5.1**. Trip production is defined as the home end of a home-based trip or the origin of a non-home-based trip, while trip attraction is defined as the destination of a non-home-based trip. Variables used as predictors of trip productions include household income, automobile ownership, number of workers per household, residential density, and the distance of a zone from the central business district (CBD). Trip attraction predictors include employment levels, floor space, and accessibility to the work force. Trip generation models use the previous variables to predict the number of trips generated from and attracted to each TAZ.

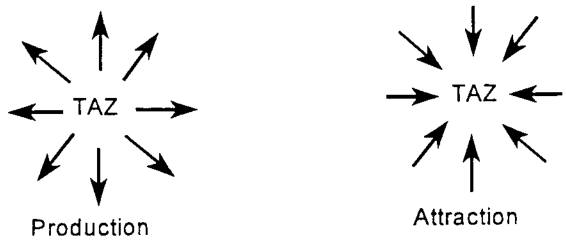


Figure 5.1 Trip Production

Trip Distribution

Trip distribution is the process of distributing the zonal trip ends in order to predict the flow of trips from each production zone to each attraction zone as illustrated in **Figure 5.2**.

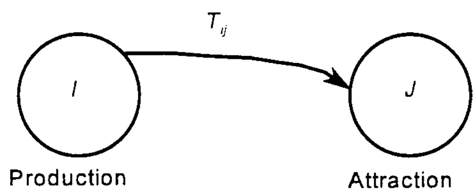


Figure 5.2 Trip Distribution

The most commonly used model for trip distribution is the gravity model, which has been in existence over 100 years as one of many types of trip distribution models. The gravity distribution model is based on the concept that the desirability of traveling to a particular zone is directly related to the amount of activity taking place in that zone, and inversely related to its perceived spatial separation from the production zones. This spatial separation is measured in terms of travel time, distance, monetary out-of-pocket cost, etc., between zones. The purpose of this model is to find out the travel pattern between zones, which may change over time.

In many ways, the distribution of home-based work (HBW) trips is the most important in the transportation modeling process. HBW trips account for the majority of trips made. They usually determine peak-hour usage, and are often the trips for which transportation facilities are designed. The data source of the HBW trips is the Census Transportation Planning Package (CTPP). CTPP is a set of special tabulation of 1990 census data tailored to meet the data needs of transportation planners. The data includes characteristics of persons, workers, and housing units.

Modal Split

The function of the modal split (or modal choice) module is to identify the mode, or means of travel, for trips generated by the generation module and distributed by the trip distribution module. The model also predicts the percentages of flow that will use each of the modes that are available for travel between each origin destination pair and provides estimates of linked trips by mode, as shown in **Figure 5.3**. The probability of choosing a particular mode of transportation is a function of level of service and cost variables and a traveler's perception about them. Variables considered in some models to determine transit mode choice may include walk access time, automobile access time, out-of vehicle wait time, transfer time, number of transfers, transit fares, vehicle operating cost, and parking cost. Other factors that may be used in the modal split model include auto ownership household income, household size, age, occupation, population density, and distance from the CBD.

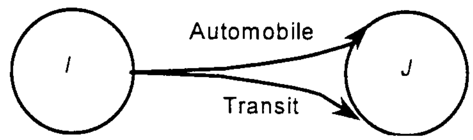


Figure 5.3 Modal Split

Trip Assignment

The last step in the UTMS sequence is the assignment of the predicted modal flows between each origin-destination pair to actual routes through the given mode's network as shown in **Figure 5.4**.

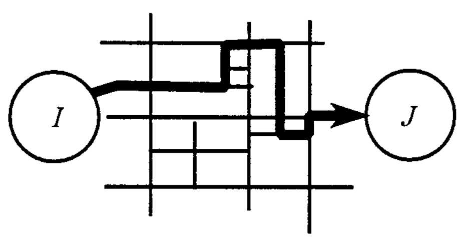


Figure 5.4 Trip Assignment

Trip assignment is divided into transit assignment and highway assignment. Transit assignment is the process of allocating transit trips estimated in the mode choice model to the transit network. Unlike trips estimated during the mode choice step, assigned transit trips may be identified by all modes which must be used to get to a destination. For example, a trip that involves walking to an express bus stop, going to the downtown area by bus, and transferring to the Metro were considered as two trips in transit assignment summaries. Transit trips are estimated for local buses, premium transit (rapid transit) with walk/local bus access, and all transit with auto access. Overall, the transit assignment process results in estimated peak season weekday travel by transit. Although the mode choice model may be able to accurately estimate mode shares, estimates for individual modes may deviate noticeably from observed ridership.

Highway assignment is the process of allocating vehicle trips to the minimum impedance path between each pair of zones in the study area. Evaluation of the highway assignment model is based on a comparison of observed traffic counts to model estimated volumes. Since the trip assignment models depend on the transit and highway network configuration, any changes in the network configuration will affect the trip assignment models.

Temporal GIS Applications

Table 5.1 summarizes the factors that impact transit demand and are typically used in transit demand modeling. Almost all the factors change with time except the distance between a particular geographic area and CBD or other activity centers, although change in definition of TAZs will result in changes in distances of TAZs and the CBD and activity centers in the GIS database. Therefore, most of the information is spatiotemporal in nature.

There are several possible benefits that may be derived from a temporal GIS. First, TAZs and transportation facilities need to be inventoried. A temporal GIS will offer an effective and efficient means for recording changes in TAZs and transportation networks and facilities. As shown in **Section 4.1**, the definition of TAZ may be maintained using an update model, in which the current TAZs will be stored as a complete coverage. Historical changes including the redefinition of the boundaries of a relatively small number of TAZs, TAZ identification numbers, and socioeconomic statistics may be saved as amendments. The capability of handling spatiotemporal information allows the model output to be validated by comparing current and historical data. Although this may be accomplished without a temporal GIS, a temporal GIS will make the task much easier.

Another use of a temporal GIS is data validation and model calibration and validation. Due to the large volume of data required and extensive effort required for data editing, errors are difficult to avoid. Model input data and economic forecast data may be validated with historical data. Significant differences may raise a flag of possible data errors, which may be examined either manually or with the assistance of a knowledge-based system integrated with the GIS. Similarly, vehicle traffic counts and actual transit ridership counts, which are used to validate the output of the traffic assignment module, may be checked for fluctuation due to temporary causes such as road construction or special events.

Historical data are also useful in model improvements or even developing new models. With historical data available, relationships between land use, demographics and trip generation, transit level of service and congestion level and transit ridership, may be analyzed and better understood. This improved understanding will allow the models to be improved to more accurately forecast travel data. In recent years, behavioral travel demand modeling has attracted much attention (Oppenheim 1995). The basic viewpoint adopted in modeling urban travel demand is that travel in an urban area is best understood as the result of various decisions by individual travelers regarding, for instance, whether to travel, where to go, which mode to use, and which route to take. Person trips in turn may be estimated on the basis of assumptions about individual objectives, opportunities, and constraints. An example is estimating home-based work trips in areas where a large number of retirees live.

Table 5.1 Factors Impacting Transit Demand

Factor	Rate of Change
Demographic	
population density	Normally slow, there may be sudden changes under special circumstances such as new residential developments and natural disasters
number of workers per household	
household size	
age	
occupation	
Socioeconomic	
household income	Household income and auto ownership change of a relatively slow rate. The rate of change for others vary depending on the degree of saturation for development and commercial activities in an area.
auto ownership	
floor space	
employment types	
employment density	
school enrollment	
Geographic	
distance to CBD	stable except when TAZ definition changes, distances in computer representation will also change.
distance to activity centers	
natural terrain	
Transportation Facilities	
roadways, freeways, fixed guideways	transportation facilities change when a new facility is constructed or an existing one is modified (e.g. adding new lanes to roads). Travel cost, parking availability, and highway and transit level of service may also be influenced by economy and policies as related to gas price, transit fares, highway tolls, parking fees, and transit service frequencies.
travel time	
monetary out-of-pocket travel cost	
pedestrian/bike paths	
parking availability	
transit level of service	
highway level of service	
safety	

Using the traditional modeling techniques, the fact that there are few home-based work trips from such areas is ignored, which is a consideration in behavioral travel demand modeling. Since aggregated travel behavior for an area will evolve over time, this approach requires tracking the evolution of travel behavior or the establishment of a travel behavior model. A temporal GIS may be a useful tool for such a purpose. For instance, the percentage of retirees and their average age may be recorded in a temporal GIS database and updated automatically if required. Similarly, the number and age of children in households in an analysis zone may also be tracked, which is important information for determining trip purpose and chained trips.

By using temporal GIS to model urban growth, transit plans may be made to phase transit service expansions to new areas. Stored in a temporal GIS database, questions about these future transit plans may be easily answered and difficulty in coordinating different public and private projects may also be reduced. The latter can only be achieved with a region-wide temporal GIS, in which different public agencies share their project information. With the scheduling capability of a temporal GIS (see **Section 4**), it is also possible to maintain and update the time tables for the implementation of various projects and determine the effects of changes in one project on transit projects.

Another important benefit of a temporal GIS is to learn how decisions made in the past impact the transportation system and what decisions should be made in the future. Has a particular policy or transportation program been effective to achieve the original set goals? Do changes and trends of demographics, land uses, socioeconomic conditions, and transportation facilities agree with our past or current expectations and assumptions? A temporal GIS will allow information such as changes and trends of changes as well as impacts of decisions and policies to be viewed easily.

Transportation modeling is a complicated subject, which is both a science and an art. A temporal GIS provides the basic infrastructure that is needed to improve the theories and techniques for modeling. The actual implementation of any of the GIS applications mentioned above and possibly more will require much research and development effort. Most importantly, however, a temporal GIS will allow implementation by making the historical data available as the foundation of applications.

5.2 Service Planning

Given the transit demand in an area, service planning involves the development and improvement of service plans, which include the determination of types of services to be provided, layout of routes (for non-fixed guideway systems), development of service schedules, and evaluation and modification of service. Service planning also deals with changes in land use, travel patterns, and resources. While service planning should reflect the specific needs and operating requirements of the urban areas due to its scope, it does not include actions such as acquiring new vehicles, changing the general configuration of the transit network (e.g., from grid to radial), planning major capital facilities, and introducing new transportation modes. Analyses of these options usually fall in the domain of transit planning.

Service planning objectives should balance the amount and type of services provided with the net cost of service and emphasize tailoring transit services to major activities. Planning factors should include past and current operating data such as ridership, service coverage, farebox recovery rate, land use, population density, employment rate and locations, street layout, and the availability of other transportation facilities. These factors influence the pattern of transit system services and the opportunities for change and improvement. A well-designed service should maintain the following:

- An up-to-date route system consistent with current demands and easily understood by riders;
- convenient schedules;
- reliable services;
- coordinated transfer opportunities in the same mode or with other transit services;
- amenities at stops and stations;
- reasonable fares; and
- park-and-ride facilities where appropriate.

Factors and considerations that are included in route planning are presented in **Table 5.2**.

Service planning processes should include different types of system modifications that are grouped at various levels (Wilson and Bauer 1984): system or area coverage level, route structure level, and schedule level. At each level, a distinction may be made between actions tending to increase cost and ridership and those tending to decrease cost and ridership. These actions are presented in **Table 5.3**. Their adoption will depend on budget changes or other system resources. In some cases, the actions may bring mixed results, in which case the system is fine tuned to improve attainment of the objectives of the system. Actions at the area coverage level are the most disruptive for the public and need close examination and analysis. Actions at the route structure level are less disruptive than changes in system coverage and require careful planning because some riding patterns may change. At the scheduling level, actions will affect the waiting times and schedule adherence of a route.

For bus services, modifying the route structure may not be easily accomplished, especially when service reductions such as route abandonment, shortening, or reduced service frequency are involved. This makes it more important to be able to accurately determine the long term market potential of a proposed or existing route. The market potential is best determined with the aid of a temporal GIS that allows the ridership development history of an existing route or those routes with similar characteristics to be examined in conjunction with historical demographic, socioeconomic and other relevant information. Although political influences are unavoidable in such cases, transit agencies will be able to present more convincing evidence to support their recommendations.

Table 5.2 Route Planning Factors and Considerations

Factors	Considerations
Residents' accessibility to route	- Percentage of population within walking distance of a bus stop (1/4 mile).
Diversity of destinations served	- Number of activity centers connected. - Transfer opportunities provided.
Efficiency of routing/directness	- Bus travel time vs. auto travel time. - Minimization of loops.
Route safety	- Street width/pavement conditions. - Road conditions in adverse weather. - Safety of travel lane stops. - Pullout and shelter facilities. - Manageability of turns.
Responsiveness to the public	- Public input in forms of service request, survey responses, etc. - Potential pressure & political feasibility.

Source: A Guide to Land Use and Public Transportation, Department of Transportation, 1989.

Transit ridership varies seasonally and is affected by changes in land uses, special events, and accessibility. A temporal GIS database maintaining the historical data on route structure, service schedules, fare structure, ridership, land uses, special events, travel time, road conditions, etc., will allow tracking of the trend in ridership and analysis of the impact of various factors on transit ridership and transit trip patterns. Such information will allow transit agencies to be prepared for changes well in advance by developing strategies and measures to ensure that transit services are provided in a most effective and efficient manner. In general, this proactive approach to service planning and to transit management promises more efficient services and higher user satisfaction, thus higher transit ridership.

Table 5.3 Summary of Generic Actions by Level

Levels	Actions
Area Coverage Level	• New route • Route extension • Small set of route replacements • Route abandonment • Shortening a route • Route realignment
Route Structure Level	• Route Splitting • Zonal service • Express/local service • Linking two routes
Scheduling Level	• Changes in route frequency • Changes in departure times of individual trips • Changes in layover times, positioning time, etc. • Modify running times • Partial deadheading

Source: Short Range Transit Planning: Current Practice and a Proposed Framework, Department of Transportation, June 1984.

One important aspect of service planning is to accurately determine the running time for bus or paratransit services, therefore, a realistic and accurate service schedule may be established and maintained, which is extremely important to have transit services regarded as reliable and keep the confidence of the users. Running time, however, changes with location as well time and season. Running time will be significantly higher near activity centers, in a CBD or during peak hours when congestion is more pronounced. In addition, due to changes in land uses and increasing roadway congestion level, running time also changes for the same route segment and same time during a day over a longer period of time. A temporal GIS database may be used to record the actual running time of the buses. The information will include a bus identification, route number, run number, running time during different times of the day, at different time points along the route, bus schedule, and incident reports for that run. Based on these data, statistical models or other methods may be used to determine, e.g., the average running time for each segment of the route as determined by time points while avoiding bias in the data introduced by special events or incidents. Service schedules may then be established based on the results of the analysis. This concept has been studied by Abkowitz and Engelstein (1979). Its system-wide application and regular use is made possible with both a temporal GIS and AVL. The latter is becoming installed in more and more transit agencies in the recent years and this trend is expected to continue. AVL will record the data while the temporal GIS will store, analyze, generalize, and maintain the data. A temporal GIS will be able to organize the data more efficiently as it has a built-in capability to handle both time and location, which are the essential information provided by AVL data. This application has the potential to improve service quality and reduce operating cost through better fleet managed.

Table 5.4 shows different spatial features and attributes that may be stored in a temporal GIS database for service planning purposes. It needs to be pointed out that the classification or grouping of information is informal and is not a suggestion as to how the database should be designed. It is, however, interesting to note that by using object-oriented program techniques, the representation of certain types of information such as run time, schedule, and ridership counts, will be much easier and clearer conceptually clearer than if a relational database is used.

Some examples of spatiotemporal queries in a temporal GIS related to service planning may include:

1. How did bus Route 40 alignment change between 01/01/1987 and 12/31/1990?

2. How did the changes of Route 40 alignment respond to changes in socioeconomic data?

3. How did the ridership change at bus stop *X* between 01/01/1991 and 01/01/1992? And what might be the causes for this change?

4. Have the schedule and frequency responded well to the transit demand? Is there evidence that ridership was positively or negatively impacted by transit level of service?

5. How have changes in bus stop locations affected ridership?

6. How fast have population density and employment been changing in a service area? How soon will population density exceed the threshold that demands services to be provided? What are the causes of the changes? Will the changes continue in the future?

7. Where and when will a major activity center be moved to another location? How have the characteristics of the activity centers changed within 1/4 buffer around Route 40 stops between 1986 and 1996?

Table 5.4 Data Needed for a Temporal GIS-Based Service Planning System

Information Type	Comments	Description
route structure	may change spatially as well temporally	route alignment, roadways, road conditions, speed limit, incident statistics
transit stops		time point, shelters, # of routes
roadways		level of service, traffic counts, road configuration
activity centers	it is useful to trace the movement of major trip generators	location, size, and type of activity centers
demographics	the definition of TAZ may change	population density, age, income, auto ownership, etc.
election districts	district boundary may change	boundary of districts, elected officials, population, racial makeup, tax contribution, etc.
municipalities	boundaries may change	population, elected officials, tax contribution
transit ridership		ridership counts by time, day, month, season, route, stop
transit schedules		service period, headways, time points
run time history		route number, run number, run time, schedule deviation at time points
incident records		time, location, and description of incidents
customer comment records		description of complaints, commendations, or suggestions including specific time and location as relevant

5.3 Travel Information

Providing accurate travel information is increasingly recognized as a critical element in improving transit service quality and attracting riders. Travel information may be provided through publications, kiosks located at public places, radio stations, TV broadcasts, telephones, and, more recently, the

Internet. Most frequently requested and desired travel information include transit routes, schedules, fares, and directions on how to get from one point to another. With the installation of an AVL system on transit vehicles, real-time information is also possible, which allows a passenger to know where a bus is and how soon it will be at a particular location.

There are two important benefits that may be brought by a temporal GIS. One is its real-time processing capability that allows fast queries about the actual schedule of a transit vehicle. In addition to transit schedules, the user may also receive real-time traffic information, which may assist him or her in decision-making regarding mode choice. The other is to collect additional data about transit trip making by recording each request of information made through telephone, the Internet, or a kiosk. The information may include the time and location of the requests, as well as the actual request made, such as origin-destination data, transfer information, or schedule information. Such data will be useful to determine the usefulness of the information system, ways to improve it, the best places to locate information access devices, and travel patterns. The origin-destination data will be valuable as supplement data for service planning. **Table 5.5** shows the data needed for providing travel information and collecting data for improving the information system and the transit service.

Table 5.5 Data Needed for a Temporal GIS-Based Travel Information System

Information	Comments	Description
transit route structure		route alignment, roadways, road conditions, speed limit, incident statistics
transit stops		location, amenities, ADA accessibility, transfer
activity centers		
schedule		vehicle expected arrival time and delay time
transit vehicle location	may be in real-time	
security	crime information may be used to select the best routes	
type of information requested		routes, schedule, fare, transfer, directions, etc.
time of request		
length of interaction	to measure the quality of service	
origin-destination survey		origin, destination, route taken, time of travel

5.4 Transit Service Evaluation

Service input, output, and consumption figures measure three important aspects of transit operations: efficiency, effectiveness, and overall performance. The purpose of any performance-based allocation procedure is to give agencies of all sizes the incentives to improve their performance. According to Fielding (1987), efficiency measure how well resources such as labor, equipment, facilities, and fuel are used to produce output measures such as revenue vehicle hours or revenue vehicle miles. Effectiveness measures transit productivity as measured by passenger trips or passenger miles per vehicle mile or per vehicle hour. Overall performance indicators integrate efficiency and effectiveness measures with costs of service input related to consumption. Transit management is responsible for achieving efficiency and is held accountable for it, while effectiveness is more difficult to evaluate.

Transit performance measures are used for both internal and external purposes. Internally, these performance data may be used to ascertain progress toward transit service goals and objectives, to assist in evaluating the transit system's overall performance, and to provide a management control system for monitoring and improving transit services. Externally, they can facilitate the accountability sought by government funding agencies and demanded by legislators, regional and transit authority boards, and the general public (TCRP 6, 1994). For instance, the Southeastern Pennsylvania Transit Authority (SEPTA) and Port Authority of Allegheny County (PAT), the two largest transit system in Pennsylvania, together receive about 95 percent of the state transit operating funds, which are allocated based on the historical need. As specified in the state laws, SEPTA is required to achieve a 50 percent revenue-to-cost ratio to receive its full 70 percent of state funds, and PAT is required to recover 46 percent of its cost from fare revenue to receive its full share of 25.3 percent funding from the state. For every percentage point, these systems fall short of their cost recovery ratio, they lose 1 percent of state funds (TCRP 6, 1994). In order to maintain the previous fare recovery ratios, temporal GIS may be used to identify the weak segments of the transit system and the reasons for low ridership. Keeping transit data in a temporal format will allow transit analysts to monitor and track the performance of the transit system in order to meet the required goals and objectives.

Carter and Lomax (1992) formulated performance measures and indicators to assist in selecting appropriate measures and indicators for assessing and comparing systems, which are shown in **Table 5.6**. Such performance data may be managed in a temporal GIS database. The spatiotemporal query tools will allow transit professionals to generate different reports based on these performance measures. Performance changes may be shown by day, week, month, quarter, year, or several years. Improved performance may necessitate a study on the possible causes of such improvements with purpose of retaining good service quality and cost-effectiveness. On the other hand, performance deterioration will also alert the agency to investigate the underlying problems and take corrective measures accordingly to reverse the trend. To this end, not only should the performance data be collected and stored, but causes and actions taken should also be stored. This additional information will allow the evaluation of the effectiveness of different decisions and actions under various operating conditions and environments. Therefore, a temporal GIS will serve as a decision tool in addition to being a data management and analysis tool.

Table 5.6 Performance Measures and Indicators

Performance Measure	Performance Indicators
Cost Efficiency	• Cost per mile • Cost per hour • Cost per vehicle • Ridership per expense
Cost Effectiveness	• Cost per passenger trip • Revenue per passenger trip • Ridership per expense
Service Utilization/Efficiency	• Passenger trips per mile • Passenger trips per hour • Passenger trips per capita
Vehicle Utilization/Efficiency	• Mile per vehicle
Quality of Service	• Average speed • Vehicle miles between road calls • Vehicle miles between accidents
Labor Productivity	• Passenger trips per employee • Vehicle miles per employee
Coverage	• Vehicle mile per capita • Vehicle miles per service

Source: Development and Application of Performance Measures for Rural Public Transportation Operators, TRR 1338, 1992.

A temporal GIS database storing information will support analyses at both agency level or down to route or route segment level, individual operator level, and transit stop or catchment area level. Such detailed analyses help to distinguish localized problems from agency-wide problems and allow efforts to improve service to be focused on the solution of specific problems. The availability of historical data also permits a problem that is temporary in nature to be distinguished from persistent problems. The benefit is that real problems will be easier to identify in a timely manner before they result in serious consequences. This same concept may also be applied to service monitoring, including driver performance, vehicle loading levels, schedule adherence, etc. While a specific driver's performance may not be a geographic factor in service monitoring, the information may be needed to explain variances in transit operations along a particular route or route segments. Other spatiotemporal query examples in service evaluation may include:

1. How did the cost per mile, hour, and vehicle change from the CBD to a suburban area in the last two years?

2. Which routes exceeded 25 percent of cost recovery in 1994, 1995, and 1996 and when?

3. How did the average speed for buses on different routes change between the CBD and north Dade in 1990 and 1991? How are the speed changes related to the congestion levels of these roads?

It needs to be reiterated that although such analyses are theoretically possible with the conventional GIS technology, due to the extremely large volume of data and analysis required on them at various levels of detail, the analysis will be economically infeasible and even examining the analysis results will be burdensome. This points to the need for a temporal GIS in scheduling capability and a knowledge-based system for automatically monitoring the system performance and making appropriate recommendations.

6. A PROTOTYPE TEMPORAL GIS

To study the use of a temporal GIS for transportation applications and to explore the possibility of extending the capabilities of commercially available atemporal GIS, we have developed a prototype temporal GIS based on PC ARC/Info. In this section, we will describe the data modeling in the prototype temporal GIS and the basic temporal operations. Its use is demonstrated with examples of transit service evaluation.

6.1 Representation of Time

We have adopted two types of time for our prototype temporal GIS: *valid time* (or world time) and *database time* (or transactional time). A time stamp consists of a specification of the beginning and ending valid time, and beginning and ending database time. The specification is given by four additional attributes added to all database records: *Vd_From, Vd_To, DB_From, DB_To.*

As has been said in **Section 4**, the time granularity, or the smallest time intervals to be represented in a temporal GIS, depends on the need of the particular application. Real-time applications such as Intelligent Transportation System (ITS) applications that may require finer time granularity, even down to minutes or seconds, while long term transportation planning may only need to consider time in months or years. Once the time granularity is determined, appropriate representation of time may be determined. For instance, *19900208* may be used to represent the date February 8, 1990 and *19890912175200* the time and date at 17:52:00 on September 12, 1998. For our prototype, the time granularity is chosen to be the day. Therefore, time is coded as an eight-digit integer in the format of *yyyymmdd* (or year-month-day) such as *19900208*. For simplicity, we represent the database time with the same granularity, which in reality should be much finer to include at least hours, minutes, and/or seconds.

The life span of an event is specified by the user, who gives the beginning and ending of the valid time (Vd_From and Vd_To). If the ending of valid time is not specified, the default time 99991231 (December 31, 9999) is assumed. The ending valid time may be changed anytime by the user with further knowledge of the particular event or by the system automatically when a new event replaces it. The database time (DB_From and DB_To) is automatically recorded at the time when an event is first recorded in the database and whenever it is modified (e.g. to correct a data-entry error) later.

6.2 Representation of Spatiotemporal Information

The versioning technique that we have chosen to use is at the tuple or record level. In other words, if one item in a record is to be changed, a new version of that record in its entirety is generated with the new data replacing the old one within the new record. The old record, in which the valid time and database time are modified, remains in the database to preserve the history.

In ARC/Info, locational information about geographic features is represented by three classes of spatial objects: points, arcs, and polygons. Descriptive information about the geographic features is considered the attributes of spatial objects and is stored in relational databases. To extend ARC/Info by giving temporality to both spatial and attribute information, all spatial objects and attributes are time-stamped. The versioning technique we chose is at the record or tuple level. In other words, in the same record, all attributes have the same time-stamps. Similarly, for spatial objects versions of entire objects are maintained instead of individual arcs or nodes (the database files of which are not accessible through standard database operations). **Figure 6.1** shows the time stamps for point, line, and polygon attribute tables. These tables may be the common database tables such as those with an extension .DBF in ARC/Info, or arc, point, and polygon attribute tables, which, in ARC/Info have the extensions .ATT (arc attribute tables) and .PAT (point and polygon attribute tables), respectively.

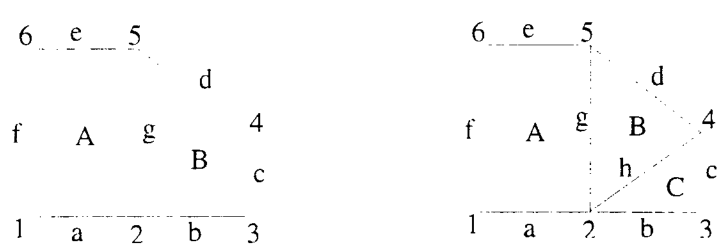
Point_ID	Valid_From	Valid_To	DB_From	DB_To	Attribute1	Attribute2	....

Point_ID	Valid_From	Valid_To	DB_From	DB_To	Attribute1	Attribute2	....

Polygon_ID	Valid_From	Valid_To	DB_From	DB_To	Attribute1	Attribute2	....

Figure 6.1 Time Stamps in Point, Line, and Polygon Attribute Tables

As an example, **Figure 6.2(a)** illustrates a fictitious transportation analysis zone (TAZ) coverage for 1994, which is changed as shown in **Figure 6.2(b)** in 1996. The resulted changes in the TAZ.AAT (the arc attribute table), TAZ.PAT (the polygon attribute table), and TAZ.DBF (TAZ attributes) are shown in **Tables 6.1** through **6.3**. To simplify the problem, the database tables are conceptual instead of actual in terms of table structure.



(a) (b)

Figure 6.2 Polygon Coverages in 1994 and 1996

It should be noted that **Table 6.1** may be much longer if changes are introduced not only by the change of the TAZ boundaries, but also by a new survey on population and employment in the TAZ's. If the new survey data was obtained, for instance, before December 31, 1995, two new records would have been added to **Table 6.3** for each survey conducted, which would give the population and employment figures obtained for the two TAZ's 1, and 2, respectively.

Table 6.1 Polygon Attribute Table for the TAZ Coverage

TAZ_ID	Vd_From	Vd_to	DB_From	DB_To	Area	Perimeter
A	19940101	99991231	19940131	99991231	14.00	15.00
B	19940101	**19951231**	19940131	**19951214**	8.24	12.20
B	**19960101**	**99991231**	**19951215**	**99991231**	**5.53**	**10.90**
C	**19960101**	**99991231**	**19951215**	**99991231**	**2.71**	**8.10**

Table 6.2 Arc Attribute Table for the TAZ Coverage

Arc_ID	Vd_From	Vd_To	DB_From	DB_To	F_Node	T_Node	L_Poly	R_Poly
a	19940101	99991231	19940131	99991231	1	2	A	0
b	**19960101**	**99991231**	**19951215**	**99991231**	**2**	**3**	**C**	**0**
b	19940101	**19951231**	19940131	**19951214**	2	3	B	0
c	**19960101**	**99991231**	**19951215**	**99991231**	**3**	**4**	**C**	**0**
c	19940101	**19951231**	19940131	**19951214**	3	4	B	0
d	19940101	99991231	19940131	99991231	4	5	B	0
e	19940101	99991231	19940131	99991231	5	6	A	0
f	19940101	99991231	19940131	99991231	6	1	A	0
g	19940101	99991231	19940131	99991231	2	5	A	B
h	**19960101**	**99991231**	**19951215**	**99991231**	**2**	**4**	**B**	**C**

While duplication is inevitable when versioning is done at the record level, unless every database table contains only one attribute, it may be minimized by reducing the size of a table. Instead of saving all attribute information about the spatial objects in a coverage in one table, they may be classified, segregated, and stored in a number of smaller tables. If done properly, this will both reduce duplicate data and increase the convenience and efficiency for data processing.

Table 6.3 TAZ Attribute Table

TAZ_ID	Vd_From	Vd_To	DB_From	DB_To	Population	Employment
A	19900401	99991231	19901031	99991231	66,682	14,000
B	19900401	99991231	19901031	**19951214**	47,089	4950
B	**19900401**	**99991231**	**19951215**	**99991231**	31,602	3322
C	**19900401**	**99991231**	**19951215**	**99991231**	15,486	1628

6.3 Temporal Query

A set of temporal query commands have been developed for the prototype temporal GIS. *SNAPCOV* and *SNAPINFO* are used to take a cross-sectional view of the temporal GIS database. *PERCOV* and *PERDINFO* are used to retrieve information from a coverage or a database file for a given period of time. *THISTORY* is used to generate a longitudinal view of the database. *TDOMAIN* and *TVERSION* are used to examine the temporality of the database. These commands are implemented using SML in PC ARC/Info, which are described briefly below.

SNAPCOV is a command used to take a snapshot of the spatial objects contained in the coverage for a given world time. It takes as input a coverage name, a time slice (corresponding to a world time), and, optionally, a version time (or database time), and produces a new coverage for the specified time slice. The result is a new set of points, arcs, or polygons depending on the type of the given coverage. If time slice and version time are not specified, they will be assumed as the current time.

SNAPINFO takes a snapshot of the database for the attributes of the spatial objects contained in a given coverage and for a given time slice. *SNAPINFO* is similar to *SNAPCOV*. The difference is that *SNAPCOV* operates on spatial objects (points, lines, and polygons) while *SNAPINFO* operates on the database tables associated with a given coverage and the result is database file.

PERDCOV creates a new coverage containing the spatial features that existed during a period specified by a beginning time and ending time. All the changes in the specified period of time are captured.

PERDINFO takes a database file and produces a new one that contains records valid between the period of time as defined by beginning time and ending time.

THISTORY generates a complete history for selected features or attributes in a coverage. The result will be a table showing all the changes in the features or attributes from their inception to current time. This complete historical information may then be used for trend analysis.

TDOMAIN reports the time period during which a database file (including .AAT, .PAT, and .DBF files) existed. The time period is given by the earliest valid time, or Vd_From, and the latest valid time (Vd_To).

TVERSION produces a temporal version of a given database file for a given database time. In other words, it performs a similar function to SNAPCOV and SNAPINFO, with the difference that the time of interest is the database time at which the data was modified.

There are many more types of temporal queries that are desirable. For instance, it is conceivable that given a period of time, information about the life span of certain spatial features or of their attributes is of interest. Many similar query tools will add to the effectiveness and efficiency of a temporal GIS database.

7. TEMPORAL GIS FOR TRANSIT PLANNING AND EVALUATION

Transit planning is the process of determining the needs for transit services and facilities. Planning may be divided into long-range planning, short-range planning, and service or operations planning. Simply put, long term planning considers the demand for transit service in a long period of time, such as 20 years, and the necessary improvements of transit facilities to provide adequate services. Short term planning has the same objectives but looks at a shorter period of a few years and determines where services should be provided. Service planning involves the determination of type of service, transit route, service schedule for a given demand in a service area, and the evaluation and modification of existing services.

Traditionally, long term transit planning has been a part of urban transportation planning, with transit being one mode considered in the modal split model. The modeling involves estimating the number of transit trips ending in each analysis zone, distributing transit trips, transit interchange, assigning transit trips to different corridors, and determining transit link volumes. Transit ridership forecasting is an important component of the traditional four-step transportation planning process. Transit ridership forecasts are the product of a sequence of models used to analyze and predict the aggregate travel volume in an urban area, the geographic distribution of trip-making, the level of transit travel in specific corridors, and ultimately, patronage on individual routes or services. Transit ridership estimation is discussed in, e.g., (Azar and Ferreira 1995, Batchelder *et al.* 1983).

Transit ridership in an area is influenced by many factors such as the population density, socio-economic and demographic characteristics of the population, employment density, type and number of activity centers, congestion level of roadways, and transit service quality and quantity. Since these conditions change from locale to locale, travel demand models must be carefully and continually calibrated. Even with careful calibration, one problem with results produced by travel demand models is that they are not accurate. Because of the complexity of the problem, improvements to models are not easily achieved. One of the practices in an attempt to improve travel forecasting models is to collect more accurate data and to adjust the models based on the differences between forecasts and actual data. However, model improvements need to be made continually over a long period of time since short term fluctuations may be caused by special events. For this purpose, a temporal GIS may be useful to store model input, output, and collected data over a long period of time. These data may then be analyzed to identify the causal relationships between various modeling variables and to evaluate the effects of different policies, strategies, planning practices, and operations. This potential use of temporal GIS is demonstrated next with a simple example.

The geographic area in the example is a transit corridor along Southwest 40th Street in Miami. Along the corridor, there are many commercial as well as residential developments, schools, a county library, and a hospital. Bus Route 40 runs in the corridor connecting west Dade County with a commercial area in Coral Gables, a municipality in Dade County, and a Metrorail (heavy rail) station about three miles from downtown area. The bus route has undergone many changes. Using temporal GIS query, changes in both the bus route alignment and the characteristics of the service area along the bus route may be examined. In **Figure 7.1**, changes in bus Route 40 between June 15, 1986, and December 31, 1990, are shown. The map is generated by applying the *PERDCOV* command of the prototype temporal GIS model, which retrieves all the arc segments of the bus route and all the point features representing the bus stops that are effective (or valid) in the given time period. The bus route alignment is created using the present MDTA bus route GIS map, with older alignment segments added based on the route maps published previously. All of the arcs are time-stamped.

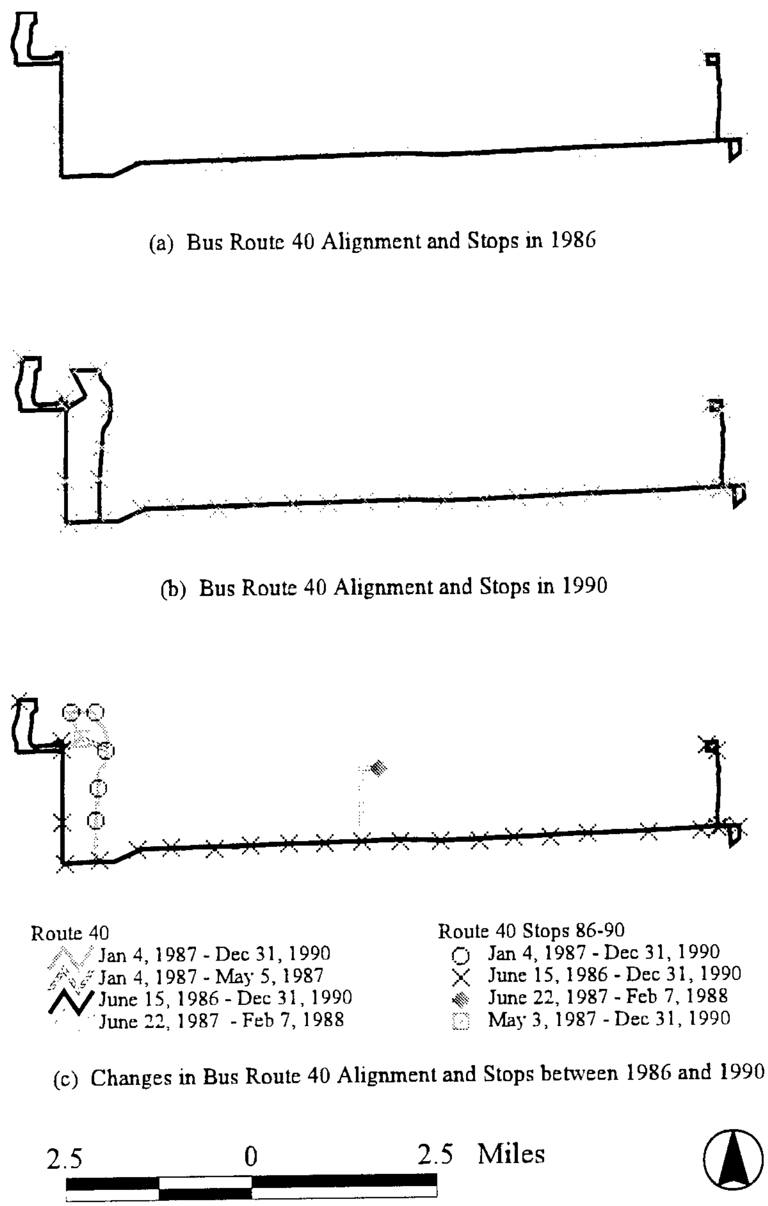
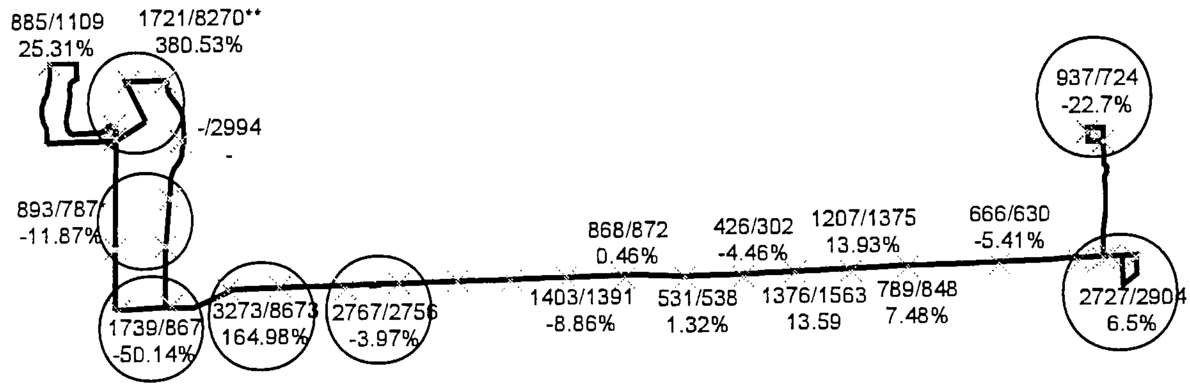


Figure 7.1 Changes in Route 40 Alignment between June 15, 1986 and December 30, 1989

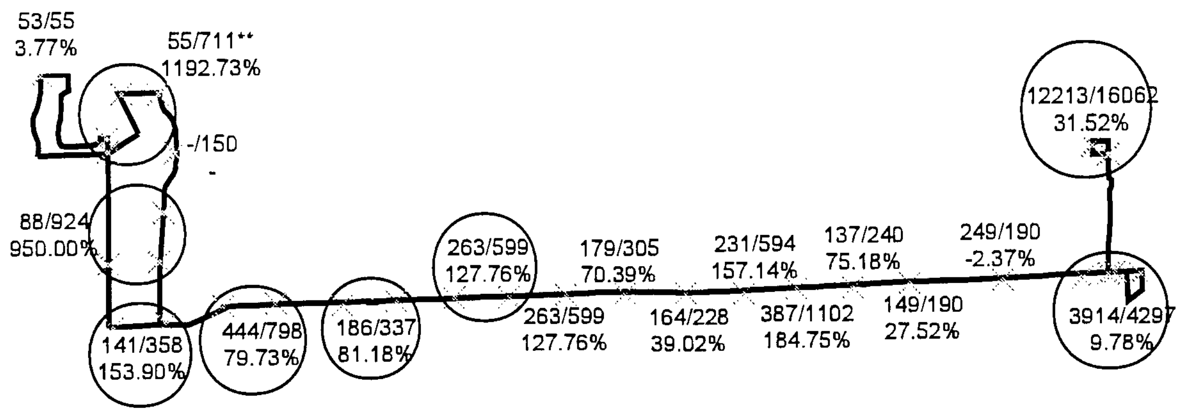
To examine changes in the factors influencing transit ridership, buffer zones of one quarter mile (402 meters) are created around the bus stops along Route 40 alignments of 1986 and 1990, respectively. The buffer zones are then overlaid with the 1986 and 1990 TAZ layers, respectively, which contain statistics of population, employment, and school enrollment. It should be pointed out that, while not shown here, the TAZs have also been modified between 1980 and 1990. The modification involved a small number of TAZs, and the changes were recorded in the database. Map layer overlay is therefore performed using two versions of TAZ coverage produced by *SNAPCOV* and *SNAPINFO*.

In **Figure 7.2**, changes in population density, employment density, and school enrollment in the service coverage area of Route 40 are given in both actual numbers and percentages of increase or decrease. The numbers are given next to the bus stops for which the data has been generated. The first number is the 1986 data, the second the 1990 data, followed by the percentage of change. When bus stops are closely spaced, their buffer zones overlap, and it is difficult to uniquely allocate population, employment and school enrollment to individual bus stops within the cluster. The connected buffer zones are not separated and the data are given for the entire cluster, which appear in or outside the circles in **Figure 7.2**.

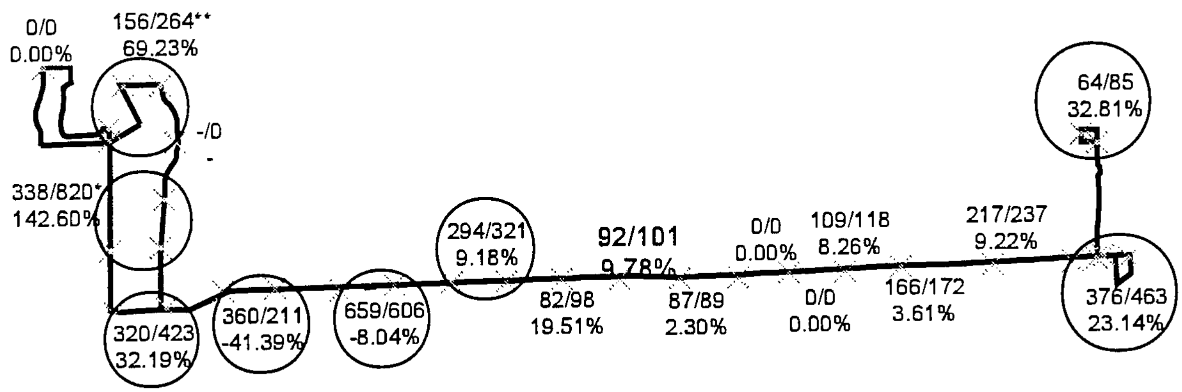
From **Figure 7.2**, it may be observed that, at some locations, there have been significant changes in population and employment. In the majority of the cases, the decrease in population is accompanied by an increase in employment, which has been caused by heavy commercial development such as new shopping centers and strip malls along the bus route. In fact, the total population, employment, and school enrollment in the corridor has increased by 45.52 percent, 43.94 percent, and 20.72 percent, respectively. In contrast, bus ridership has increased only slightly between 1987 and 1990 (see **Figure 7.3**). To understand the relationship between ridership and land use and demographics, a more detailed study is needed to consider many socio-economic and demographic factors. The detailed ridership data collected by traffic checkers that allow the determination of actual transit usage at individual bus stops are also needed. With the information provided by a temporal GIS, the effects of changes in demographic, land use patterns, and transit level of service on transit demand and the potential of a transit market may be analyzed and better understood.



(a) Population Change



(b) Employment Change



(c) School Enrollment Change

Notes: * Only one bus stop served the neighborhood in 1986 and two were added after 1987.
** Two of the bus stops were added after 1987.

Figure 7.2 Changes in Population Density, Employment Density, and School Enrollment between June 15, 1986 and December 30, 1989

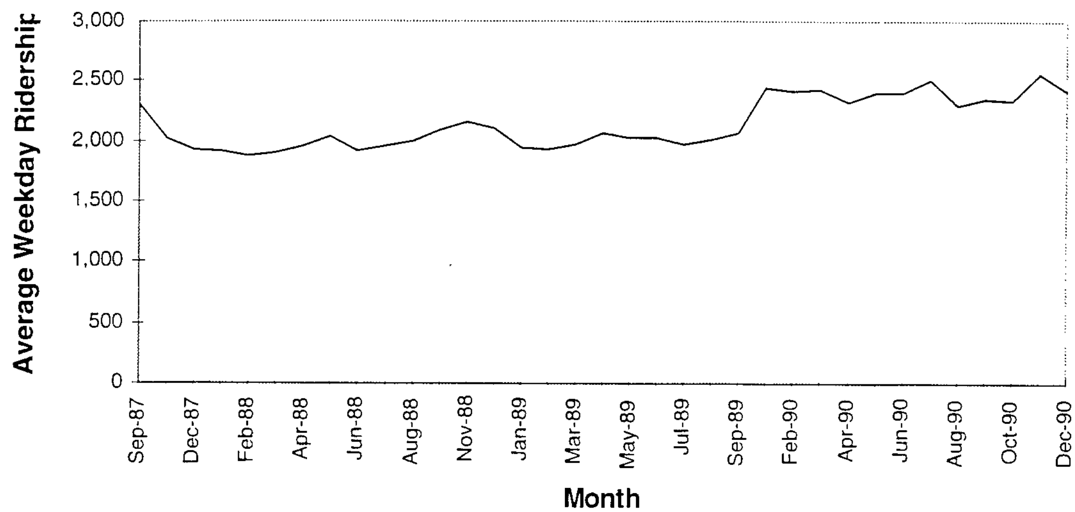


Figure 7.3 Bus Route 40 Ridership between 1987 and 1990

8. CONCLUSIONS

In this report, the current practices in transit GIS and potentials of a temporal GIS for transit applications are discussed. Many transit management tasks may benefit from a temporal GIS. The benefits are derived from the availability of historical data preserved by a temporal GIS, and the utility of these data to allow better transit planning, operations, marketing, customer service, and facility management. A temporal GIS provides the tools that allow the processing and understanding of real-time information, as well as the study and understanding of many complex relationships between various variables that affect transit service effectiveness and efficiency. Especially promising is the scheduling capability supported by a temporal GIS and the integration of GIS with knowledge-based systems. They will allow more advanced analyses to be performed, decision-making to be better supported, and productivity to be increased since less manual processes are needed to track events, monitor changes, analyze complex problems, and develop solutions. With a temporal GIS that provides more accurate information about future transit environments, operating conditions, and political and financial constraints, a transit agency will be able to adjust its practices proactively in anticipation of changes instead of passively reacting to problems and challenges.

To study the design and implementation of a temporal GIS and its application to transit management, a simple prototype temporal GIS built on top of PC ARC/Info is developed that incorporates temporal information and provides some basic support for temporal analysis. An example of transit service evaluation is given to demonstrate the use of the prototype. Work is in progress to further study and improve the data model and expand the temporal functions for data retrieval, processing, analysis, display, generation, and editing. Graphic user interface is also being developed for desk-top GIS software. Other temporal GIS applications for different transportation problems are also being explored.

Many important issues remain to be addressed. For instance, one of the major implementation barriers is the data volume growing inexorably with time since every change of the spatial or attribute information is recorded and no data are deleted. Volume control must be exercised by careful database design to minimize data duplication, by appropriate selection of time resolution (too coarse of a resolution does not serve the purpose while finer than necessary resolution results in waste of storage), and by effective methods and policies for archiving the data. One example concerning the database design is that for a complete set of cross sectional data, such as census data, TAZ data, or data generated periodically from remote sensing for the entirety of a study area, versioning at tuple level is neither efficient nor effective. Instead, such data may best be stored in separate database files. Specially designed database tools should be developed to support the temporal query and analysis, allowing the longitudinal linkage of such cross sectional data sets, while making the details of the linkage mechanism invisible to the user. Such a design will allow data of different time periods to be easily archived and efficiently processed.

Effective presentation of temporal changes is also important and is a challenge. A GIS map generated by a temporal GIS must convey clearly the variation of a phenomenon along the time dimension in addition to that over the space. The degree of difficulty of presenting this third dimension of information increases with the number of time slices for which the spatial information is to be examined, especially when some changes reoccur repeatedly for a group of spatial objects.

Besides the technical issues, there are also many implementation issues that call for special attention. First, it is extremely important to realize the enormous benefits a temporal GIS promises and begin immediate efforts to preserve historical data. Historical data availability is critical for the successful temporal GIS. In the past, because of the lack of ability to store and organize large volumes of data over time. In many cases, the historical data are often discarded after their immediate benefits are exhausted. In other cases when the data are kept, they are either not maintained properly, or not well organized, making the access and use difficult, if not impossible. For temporal GIS to be effectively used, careful analysis needs to be done to determine the short- and long-term objectives to be achieved. Accordingly, realistic data requirements including the types of data and the needed time resolution, strategies for data collection and maintenance, as well as practical and economical means to collect and process the data may be developed to ensure the accomplishment of the goals set for the temporal GIS applications.

Considering the costs associated with data collection and the large variety and volume of data potentially needed for an analysis that involves the determination of past trends and the underlying causes, an enterprise temporal GIS is necessary to ensure that data collection, maintenance, and sharing are coordinated efforts.

Significant research efforts are still needed on temporal GIS and its application to transportation and public transit. The research areas include basic theories, data models, algorithms and analysis, visualization tools, potential applications for transit and transportation, data collection practices, and historical data preservation. Understanding gained through research will also help to develop temporal GIS data standards and define requirements for temporal GIS software for transportation applications.

REFERENCES

Abkowitz, M.D. and Engelstin, I. (1979). Temporal and Spatial Dimension of Running Time in Transit Systems. Transportation Research Record, No. 877, pp. 64-67.

Allen, J.F. (1983). Maintaining Knowledge about Temporal Intervals, *Commun. ACM* 26(11), pp. 832-843.

Allen, J.F. and Hayes, P.J. (1985). A Common-Sense Theory of Time, *Proceedings of the International Joint Conference on Artificial Intelligence*, pp. 528-531, Los Angeles.

Allen, Jr., W.G., Mukundan, S. (1993). "Use of GIS in Transit Alternative Analysis," Presented at the Fourth National Conference on Transportation Planning Methods Applications, May 1993.

Anderson, L.D. (1992). "Applying Geographic Information Systems to Transportation Planning," *Transportation Research Record 1305,* Transportation Research Board, National Research Council, Washington, D.C., pp. 113-117.

Anderson, T.L. (1982). Modeling Time at the Conceptual Level, *Proceedings of the International Conference on Databases: Improving Utility and Responsiveness*, Scheuermann, P. (ed.), Academic Press, Jerusalem, Israel, pp. 273-297. June 1982.

Azar, K.T., and Ferreira, J. (1995). Integrating Geographic Information Systems into Transit Ridership Forecast Models. In *Journal of Advanced Transportation*, Vol. 29, No. 3, pp. 263-279.

Basile, R.E., Teneyck, T. and Pietropola, A.J. (1992). "GIS for the Pennsylvania Department of Transportation," *Transportation Research Record 1305,* Transportation Research Board, National Research Council, Washington, D.C., 1992, pp. 118-122.

Batchelder, J. et al. (1993). "Bus Route Planning Models: Final Report," prepared for the U.S. Department of Transportation, Urban Mass Transportation Administration and Transportation Systems Center by Multiplications, Inc., Contract/Grant No. DOT-TSC-1756, November 1983.

Bennion, Wayne, M. and O'Neill, W.A. (1992). "Building Transportation Analysis Zones Using Geographic Information Systems," *Transportation Research Record 1349,* Transportation Research Board, National Research Council, Washington, D.C., pp. 49-56.

Carter, D.N., and Lomax, T.J. (1992). "Development and Application of Performance Measures for Rural Public Transportation Operators," *Transportation Research Record 1338*, Transportation Research Board, National Research Council, Washington, D.C., pp. 28.

Clifford, J. and Warren, D.S. (1983). Formal Semantics for Time in databases. *ACM Transactions on Database Systems*, **8** (2), pp. 214-254.

Candy, J.T. (1995). *Development of a Prototype Temporal Geographic Information System.* M.S. Thesis, Department of Geography, Simon Fraser University, British Columbia, Canada.

Choi, K., Hanley, P.F., and Kim, T.J. (1995). "GIS-Based Traffic Analysis Zone Design," Presented at the 1995 Geographic Information Systems for Transportation Symposium, Sparks, Nevada.

Chou, Yue-Hong (1995). Automatic "Bus Routing and Passenger Geocoding with a Geographic Information System," *Proceedings of the 6th 1995 Vehicle Navigation and Information Systems Conference Seattle, WA,* IEEE, Piscataway, NJ, pp. 352-359.

Cipolloni, M.J. (1993). "Using GIS to Better Manage Existing Transportation Facilities," *Compendium of Technical Papers*, Institute of Transportation Engineers, 63rd Annual Meeting.

Culp, L. (1994). *Short Range Transit Planning and Marketing Using Desktop Geographic Information Systems.* San Diego Association of Governments, San Diego, California.

CUTR (1996). *Case Studies*, *Proceedings of a Conference of GIS in Transit*, Center for Urban Transportation Research, Tampa, FL.

Dubois, D. and Prade, H. (1989). *Processing Fuzzy Temporal Knowledge*, IEEE Trans. Syst. Man Cybernet, 19 (4), pp. 729-744.

Dueker (1979). Land Information Systems: A Review of Fifteen Years of Experience. *Geo-Processing*, **1**, pp. 105-128.

Eberlein, X.J. and Brown, J.N. (1991). "Combining Land Use and Transit Planning Using GIS," *Proceedings of the 1991 Geographic Information Systems Symposium*, Orlando, FL.

Fielding, G.J. (1987). *Managing Public Transit Strategically: A Comprehensive Approach to Strengthening Service and Monitoring Performance.* Jossey-Bass Publishers, pp. 60.

Freksa, C. (1992). Temporal Reasoning Based-On Semi-Intervals, *Artificial Intelligence*, Vol. 54, pp. 199-227.

Gadia, S.K., and Nair, S.S. (1993). Temporal Databases: A Prelude to Parametric Data. In *Temporal Databases, Theory, Design, and Implementation.* The Benjamin/Cummings Publishing Company, Inc.

Gebhardt, C. (1992). "The GIS and Application In Ohio," *Proceedings of the 1990 Geographic Information Systems (GIS) for Transportation Symposium, San Antonio, Texas.* AASHTO, Washington, DC, pp.231-244.

George, M. (1991). "Transportation GIS Applications," *Second National Specialty Conference in Civil Engineering Applications of Remote Sensing and Geographic Information Systems* , ASCE, New York, NY, pp. 66-70.

Harman, Larry (1995). "National Transit GIS Survey Results," *Proceeding of the GIS In Transit: Using Geographic Information Systems to Enhance Transit Planning, Marketing, and Operation,* Tampa, FL, pp. 35-36.

Hartgen, D.T. and Li, Y. (1993). "Geographic Information Systems Applications to Transportation Corridor Planning," *Transportation Research Record 1429,* Transportation Research Board, National Research Council, Washington, D.C., pp. 57-66.

Hazelton, N.W.J., Leahy, F.J. and Williamson, I.P. (1990). "On the Design of Temporal Referenced 3-D Geographic Information Systems: Development of Four-Dimensional GIS," *Proc. of GIS/LIS '90,* Anaheim, CA, pp.357-372.

Henry, V. And Sirota, S. (1995). "Using GIS to identify Locations with Greatest Potential for Increased Transit Ridership." *Proceedings of GIS '95*, Sparks, Nevada.

Hsiao, S. and Sterling, J. (1992). "Use of Geographic Information System for Transportation Data Analysis,' *Microcomputers In Transportation, ASCE, July, 1992.* ASCE, New York, NY, USA, pp. 94-102.

Hunt, D.T. ,Still, S.E. , Carroll, J.D. and Kruse, A.O. (1986). A Geographic Model for Bus Service Planning and Marketing. In *Transportation Research Record 1051*, TRB, National Research Council, Washington, D.C., pp. 1-12.

Kelmelis, J. (1991). *Time and Space in Geographic Information: Toward a Fourth-Dimensional Spatio-Temporal Data Model*, Unpublished Ph.D. dissertation, Dept. of Geography, Pennsylvania State University.

Langran, G. (1992). *Time in Geographic Information Systems*, Taylor and Francis, London.

Lee, Y.K., Shen, D.L., and Zhao. F. (1995). "Use of FTA's National GIS Transit Database for Guideway Transit Demand Analysis," *Proceedings of a Conference on GIS in Transit*, Tampa, FL, August 13-15, 1995.

Lima, P., Raval, B. and Wright, S. (1992). "The Development of Regional GIS/Transportation Database", *Microcomputers In Transportation*, ASCE, New York, NY, pp. 226-237.

Lycan, R. and Orrell, J.D. (1990). "An Analysis of Bus Ridership Potential to Oregon Health Sciences University Using a Geographic Information System Approach," Technical Paper, Center for Urban Studies and Transportation Northwest.

Matzzie, D. and Roger, R. (1991). "GIS In Transportation Modeling Merging MINUTP with GIS," *Second National Specialty Conference on Civil Engineering, Application of Remote Sensing and Geographic Information Systems,* Washington, DC, USA, ASCE, New York, NY, pp. 39-47.

Meyer, M. and Miller, E. (1984). *Urban Transportation Planning A Decision-Oriented Approach.* McGraw-Hill, Inc., New York, NY.

Movassaghi, K. and B. Parlee (1995). "GIS Application In the development of an Intermodal Transportation Plan," *Transportation Congress, Proceedings*, pp. 1297-1309.

Muehrcke, P.C. 1978. *Map Use.* JP Publications, Madison, Wisconsin.

Osborne, S. and M. Stoogenke (1989). "Integration of a Temporal Element into a Natural Resource Decision Support System," *Proc. of GIS/LIS '89*, Washington, D.C., pp. 221-227.

Oppenheim, N. (1995). *Urban Travel Demand Modeling: From Individual Choices to General Equilibrium.* John Wiley & Sons, New York, NY.

Panchanathan, S. and Faghri, A. (1995). "A Knowledge-Based Geographic Information System for Safety Analysis at Rail/Highway Grade Crossings," Presented at the 74th Annual Meeting of the Transportation Research Board, Paper No. 950717.

Peled, A. and Hakkert, A. (1993). "A PC-Oriented GIS Application for Road Safety Analysis and Management," *Traffic engineering and Control, Vol. 34 , No. 7-8*, pp. 355-361.

Peng, Z., Dueker, K.J., Strathman, J.G., and Hopper, J. (1997). "A Simultaneous Route-Level Transit Patronage Model: Demand, Supply, and Inter-Route Relationship," *Transportation*, Vol. 24, No. 2.

Peng, Z., J. Groff, Jonathan, and K. Dueker (1995). "An Enterprise GIS Data Base Design for Transit Applications," *Proceedings of Geographic Information System for Transportation Symposium (GIS-T),*Sparks, Nevada, AASHTO, Washington, D.C., pp. 147-164

Petzold, R. and D. Freund (1990). "Potential for GIS In transportation planning and Highway Infrastructure Management," *Transportation Research Record 1261,* TRB, National Research

Council, Washington, D.C., pp. 1-9.

Peuquet, D. (1994). "It's About Time: A Conceptual Framework for the Representation of Temporal Dynamics in GIS," *Annals of the Association of American Geographers*, 84, pp. 441-461.

Peuquet, D. and N. Duan (1995). "An Event-Based Spatiotemporal Data Model (ESTDM) for Temporal Analysis of Geographic Data," *Intl. J. of Geographic Information Systems*, 9(1), pp. 7-24.

Prastacos, P. (1992). "Integrating GIS Technology In Urban Transportation Planning and Modeling," *Transportation Research Record 1305,* Transporation Research Board, National Research Council, Washington, D.C., pp. 123-130.

Raj, P.K., Chia, D. And Kulyk, W. (1995). "Application of GIS to Emergency Response in Transit Systems," *Proceedings of GIS-T '95*, Sparks, Nevada.

Raper, J. and Livingstone, D. (1995). Development of a Geomorphological Spatial Model Using Object-Oriented Design, *International Journal of Geographic Information Systems*, 9(4): 359-384.

Sathisan, S., Vodrazka, W. and Lim, S. (1993). "A GIS-Based Rail Infrastructure Management System," *Pacific Rim TransTech Conference proceedings, 3rd international conference on Applications of Advanced Technology In Transportation Engineering, Seattle, WA, USA, 1993.* ASCE, new York, NY, USA, pp. 188-194.

Schweiger, Carol L (1992). "Current Use of Geographic Information Systems In Transit Planning," *Transportation Research Record 1349,* TRB, National Research Council, Washington, D.C., 1992, pp. 93-106.

Segedy, J. (1997). "Development of a Route Level Transit Ridership Forecasting Model Using GIS," paper presented at the *Geographic Information Systems in Transportation 1997 Symposium*, Greenboro, North Carolina.

Segev, A., and Shoshani, A. (1987). Modeling Temporal Semantics. In *Proceedings of the IFIP TC 8/WG 8.1 Working Conference on Temporal Aspects in Information Systems*, Sophia-Antipolis, France, May, 1987.

Shaw, Shin-Lung(1993). "GIS for Urban Demand Analysis: Requirements and Alternatives.," *Computers, Environment and Urban Systems, vol. 17, No. 1, 1993.* pp. 15-29.

Shen, D.L., Huang, J., Lee, Y.K., and Zhao, F. (1996). *Factors Influencing Future Transit Efficiency - Evaluation of the Demographic Impact on Guideway Transit Systems Using GIS and ANN Technologies*, Technical Report NUTI94FIU2.1, U.S. Department of Transportation, Washington, D.C.

Snodgrass, R.T. and Ahn, I. (1986). Temporal Databases, *IEEE Computer* 19, 9, pp. 35-42.

Snodgrass, R.T. (1992). Temporal Database. In *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*, The Proceedings of International Conference GIS from Space to Territory, Frank, A.U., Campari, I. and Formentini, U. (eds.), Pisa, Italy, September 21-23, 1992, Spring-Verlag, Berlin Heidelberg.

Soukeras S., and King, P. (1994). Temporal Database: an Event Oriented Approach. In *Directions in Database, Proceedings of the 12th British National Conference on Databases*, Guildford, United Kingdom, July 6-8, 1994.
1320-1327.

Stokes R. and Marucci, G. (1995). "GIS for Transportation: Current Practices, Problems and Prospects," *ITE Journal*, March 1995, pp. 28-37.

Story, P.A., and Worboys, M.F. (1995). A Design Support Environment for Spatio-Temporal Database Applications. In *Proceedings of International Conference COSIT '95*, Semmering, Austria, September 1995.

TCRP (1994). The Role of Performance-Based Measures In Allocating Funding for Transit Operations, a Synthesis of Transit Practice. In *Transit Cooperative Research Program*, TCRP Synthesis 6, National Academy Press, Washington, D.C.

Van Benthem, J.F.K.A. (1982). *The Logic of Time*, Reidel.

Wensley, J. (1995). "GIS as an Aid to Transit Planning from Vermont to Puerto Rico," *Proceedings of a Conference on GIS in Transit*, pp. 37, Tampa, FL, August 13-16, 1995.

Yang, Xinnong (1995). "The Implementation of Optimization of Dynamic Vehicle Routing with GIS," *Proceedings of GIS-T '95*, Sparks, Nevada.

Yuan, M. (1994a). Representation of Wildfire in Geographic Information Systems. Unpublished Ph.D. dissertation. Department of Geography, State University of New York at Buffalo.

Yuan, M. (1994b). Wildfire Conceptual Modeling for Building GIS Space-Time Models, *Proceedings of GIS/LIS '94*, pp. 860-869.

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