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Temporal gis applications in public transit planning and management

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FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

**TEMPORAL GIS APPLICATIONS IN PUBLIC TRANSIT
PLANNING AND MANAGEMENT**

**A thesis submitted in partial satisfaction of the
requirements of the degree of
MASTER OF SCIENCE
IN
CIVIL ENGINEERING**

by

Hesham R. Elbadrawi

1996

To: GORDON HOPKINS
Engineering and Design

This thesis, written by Hesham R. Elbadrawi, and entitled “Temporal GIS Applications in Public Transit Planning and Management”, having been approved in respect to style and intellectual content, is referred to you for judgement.

We have read this thesis and recommended that it be approved.

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Date of Defense: November 21, 1996

The thesis of Hesham R. Elbadrawi is approved.

Dean Gordon Hopkins
College of Engineering and Design

Dr. Richard Campbell
Dean of Graduate Studies

Florida International University, 1996

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I dedicate this thesis to my wife and my daughter. Without their patience, understanding, support, and most of all love, the completion of this work would not have been possible.

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ABSTRACT OF THE THESIS
TEMPORAL GIS APPLICATIONS IN PUBLIC TRANSIT
PLANNING AND MANAGEMENT

by

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Florida International University, 1996

Miami, Florida

Professor Fang Zhao, Major Professor

Geographic Information Systems (GISs) provide a powerful framework for various tasks of transit management such as planning, performance evaluation, and marketing. GIS may be used to solve complex planning problems, assist in operations planning, and meet other management and operational needs. However, due to the changing nature of transit planning and operational data, transit planners and operators need to analyze the data over time, which requires a temporal GIS that is capable of storing, manipulating, and analyzing changes with respect to both time and space.

Temporal GIS will allow planners and transit operators to analyze data within a certain time frame defined by the user and compare it to those in another time frame or to the current available data. This ability will improve prediction of future transit demand, evaluation of past

operations, and analysis of day-to-day operations and management.

This research entails the study of the applications of temporal GIS in transit planning and management. Transit management tasks are examined to identify those that may potentially benefit from temporal GIS. Their process, data needed, and possible applications are investigated. Examples of temporal GIS applications have been developed.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Due to the declining transit ridership over the last two decades and the diminishing transit federal funds, transit agencies are facing serious challenges to improve the effectiveness and the efficiency of their transit systems to attract more passengers. To meet the challenges, transit agencies have been implementing new technologies and programs for the planning and management of transit services to maximize the ridership and minimize service redundancy.

In addition to automatic vehicle location systems, advanced travelers' information systems, advanced fare collection, and automated passenger counting systems, etc., geographic information systems (GIS) have become the information technology that support a wide variety of transit management functions.

GIS provides a powerful framework for planning and analyzing transit routes and stops. Socioeconomic, demographic, housing, land use, and traffic data may be used in GIS to identify efficient and effective corridors in which transit service may be provided. GIS may also be used to solve complex planning problems, assist in operations design, and meet other management and operational needs.

Socioeconomic data, census tract data, and demographic data are used in transit planning and management. Because of the changing nature of transit planning and operational data, it is often necessary for transit planners and operators to analyze the data over time, which requires a temporal GIS that is capable of storing and maintaining temporal information, and manipulating and analyzing changes with respect to both time and space. A temporal GIS will allow planners and transit operators to analyze data within a certain time frame defined by the user and compare it to those within another time frame or the current available data. This ability may improve many aspects of transit management including planning, operation, and management. Additionally, with the introduction of Intelligent Transportation Systems (ITS), temporal GIS will be a necessary and useful tool in analyzing the large volumes of data collected every minute. An example of temporal GIS applications may be used to analyze historical data to find out the effects of changes in population, number of housing units, car ownership, and economic activities on the transit ridership in a certain traffic analysis zone (TAZ) for a certain period of time depending on data availability. This will help in predicting the future needs for transit services.

The goal of this study is to investigate the potential benefits of a temporal GIS to transit applications. Because there is a lack of understanding regarding temporal GIS, it is hoped that through this research a better understanding will be gained and useful information may be provided to transit agencies regarding how temporal GIS may be used for transit planning and management, and what is required by temporal GIS applications.

This thesis is divided into six chapters. In the remainder of this chapter, the research objectives are stated first and then the methodologies are described. **Chapter 2** provides a review of the literature on transit GIS applications. In **Chapter 3**, the concept of temporal GIS is included. The time dimension in transit management is studied in **Chapter 4**, examining the effect of time on various factors of transit planning process. Examples of potential applications are given in **Chapter 5**. Finally, conclusions are provided in **Chapter 6** alongwith a discussion of future work.

1.2 RESEARCH OBJECTIVES AND METHODOLOGIES

The objectives to be achieved through this study are described as follows:

- Understanding the needs for spatio-temporal analysis in transit planning, operations, and management;
- Studying different types of spatio-temporal analyses that will benefit transit planning and operations and understanding the needs for temporal data; and
- Demonstrating how temporal GIS may be used to analyze changes in transit service over a period of time by developing examples of applying a spatiotemporal analysis.

To achieve the research objectives, the following research tasks have been completed:

1. An extensive literature review has been conducted about the use of GIS in transit planning and management;

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

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. The use of GIS in transit agencies is in areas related to transit operations, such as scheduling and run cutting, marketing, fixed route and paratransit dispatching, and management. MPO GIS uses are mainly for forecasting ridership, service planning, and development of map products.

In this section, various GIS applications in public transit management and some of those in

general transportation are described. GIS applications in public transit are described in Section 2.2 while those related to general transportation are summarized in section 2.3. These applications, reported in publications, represent the current state-of-the-art, but certainly not the limit of the GIS technology.

2.2 CURRENT TRANSIT GIS APPLICATIONS

The use of GIS is rapidly developing because of its database management capabilities for storage and display of spatial data, and its ability to perform spatial analysis of geographical features based on their relationships to each other. GIS technology has been adapted to meet the needs of transportation systems. The GIS for transportation (GIS-T) software combines GIS with systems that contain both analytical and modeling procedures common to transportation planning and operation applications. GIS-T is now leading transportation professionals to a new way of thinking about and dealing with old problems. GIS technology has placed the entire transportation record keeping, analysis and modeling process in a new and exciting light (Simkowitz and Salvin 1995).

Transit GIS applications have included transit planing, service planning, market analysis, ridership forecasting, trip planning, facility management, customer information services, time scheduling, and mapping (Schweiger 1992 and Dueker and Vrana).

2.2.1 Long Term 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 needs for transit service, items such as acquiring new vehicles, changing the general configuration of the network, planning major capital facilities, and introducing new transportation modes. Transit studies such as origin-destination, ridership, and speed and delay studies are necessary for the development of long range plan. The transit planning process is divided into estimating the number of transit trips end by zone, transit trip distribution, transit interchange, transit assignment, and transit link volumes. A detailed description of the transit planning process will be given in **Chapter 4**.

One objective of transit planning is to determine the demand for transit services by estimating the expected number of users in a transit service area. Essential data required for estimating transit ridership may include street segments, intersections, households, shopping centers, commercial buildings, and schools where traffic is generated.

Transit ridership forecasting is 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.

Azar and Ferreira (1995) examined the benefits of using GIS tools for developing transit ridership estimation models capable of forecasting changes in ridership which 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 socio-economic 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 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 is a function of 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 route to motivate persons to take these trips along that route; and
3. A level of service factor related to the quality of service provided along a route.

The PRS model requires computation of several variables which 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. 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 and midday ridership on each modeling segment. Furthermore, the model estimates the total ridership on the whole route for both time periods.

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, it is evident that urban travel demand analysis can benefit from GIS. However, some data (O-D matrix and trip generation rates table) that are required in the urban travel demand models are not currently supported by the topological data model employed in vector GIS.

2.2.2 Service Planning

Service planning is described as short-range planning that needs immediate action plans reflecting the specific needs and operating requirements of transit systems. Service planning refers to the design and analysis of transit service, including route structure, headway, station spacing, and service type. For any existing transit system, service planning would include the design and analysis of modifications to existing services. Thus, it may be defined as the fine tuning of the transit service to balance the demand and the supply for transit services. The main objective of service planning is to determine the number of people within walking distance of transit route or system and to determine the best service configuration for the majority of the people within the service area (TRB 69).

An application of GIS to bus routing is described by Chou (1995), regarding the design and application of 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 handicap 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 2.1**.

Figure 2.1 Conceptual Framework of Bus Routing System

(Source: Chou, 1995)

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 disabilities of each student and the equipment available on each bus assigned to the special education program.

The use of GIS in planning transit services 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 the purpose of estimating passenger demand. The information for building the database was obtained from TIGER/LineTM files, and from a questionnaire survey conducted as part of another study. Data from TIGER/LineTM files include county, state, census tracts, census blocks, blocks groups, 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 into 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 routes 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 will be able to schedule special bus services to link the event location with the fixed route services as well as to make changes on the level of service on the original fixed route services.

2.2.3 Service Monitoring

Transit systems should be closely tuned to ridership requirements from a capacity and a cost standpoint. The challenge is to carry passengers comfortably and expeditiously, at a minimum expense to the agency. If service could be performed in equal hourly amounts throughout the day, the task would be simple. Ridership, however, varies throughout a day, a week, and a year due to changes in economy, school operations, weather conditions, and changes in urban development. These traffic variations with space and time call for constant monitoring and adjustment of services. Ridership on regular routes are monitored on a regular basis in the form of ridership counts as part of a ridership monitoring and service adjustment program (Giannopoulos 1989). In addition to ridership counts, data from customer communications,

staff observation of ridership route operations, and operation reports on passenger loading and recurring problems, are used for service adjustment.

A work was conducted by Papacosta (1995) for 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. Hence, they can be viewed and examined jointly.

2.2.4 Facility and Real Estate Management

Sathisan (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 crossing.

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 U.S. Census Bureau's TIGER/Line file rail alignment in Clark County, Nevada, was used to serve 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.

2.2.5 Customer Information Services

GIS may be used as a powerful tool to provide the transit users with 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 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: 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 emergency situations. 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 users origin and destination will be displayed.

2.2.6 GIS in Transit Agencies

Other opportunities exist for the use of GIS in transit planning, operation, and analysis. Some transportation organizations, however, 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 (GIS in transit, 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 inhouse 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 analyses of alternative GIS implementation strategies. As of today, GIS applications have included:

- 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 analysis.

- 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, 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;

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.

San Diego Associates of Governments (SANDAG)

SANDAG has been using GIS since 1985, and has developed an extensive collection of spatial database. 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 2.1** represents the different GIS application at SANDAG.

Table 2.1 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, L. (1994). Short Range Transit Planning and Marketing Using Desktop Geographic Information Systems. San Diego Association of Governments; San Diego, California.

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 computer-aided dispatch (CAD) and Automatic Vehicle Location (AVL) bus system. 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.
- Schedule adherence information will be available to planners for review of schedule running time.

Table 2.2 summarizes transit agencies using GIS for transit applications.

2.3 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.

2.3.1 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 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 as well as 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.

These information were 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.

2.3.2 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 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 TAZ aggregation model is presented in **Figure 2.2**. 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).

Figure 2.2 Flowchart of TAZ Aggregation Model

(Source: Bennion and O'Neil, 1992)

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 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.

2.3.3 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 problem 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 signage, 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 mileage 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 analysis for the desired information which could be displayed graphically with plots or interactively on screen.

The Kansas Department of Transportation (KODT) 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.

2.3.4 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 Metropolitan Transportation Authority (MTA) in New York City used TransCAD to support data management, modeling, and decision support 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 assignment 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 unique project purpose.

Another application of the use of GIS in transit can be the development of intermodal transportation plan. The Intermodal Surface Transportation Efficiency Act (ISTEA 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. 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. By determining the type, level of detail, and the methodology to perform the analysis, data were collected. 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 are stored in MIS separately. Such data include Ozone and carbon monoxide concentration in air, major imports and exports of various regions,

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 2.3** 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.

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 and 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.

Figure 2.3 RTC Database / GIS Communication Flow Chart

(Source: RTC, 1991)

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.

CHAPTER 3

INTRODUCTION TO TEMPORAL GIS

Current geographic information systems assume a world that exists only at the present. Information contained in a GIS database may be updated over time, but a sense of change or the dynamics of the geographic information through time should be maintained (Peuquet and Wentz 1995). By storing the temporal information, temporal GIS will be able to answer questions such as where and when changes occur, what patterns may be observed about changes, and what may be the underlying causes. The needs and benefits for temporal GIS are obvious. For example, a temporal GIS would allow the relationship between land use patterns and travel demand to be analyzed over a long period of time, or to be monitored and modeled the deteriorations of transportation infrastructure such as railroads and bridges.

Present GIS software lacks the capabilities to support sophisticated spatiotemporal analysis, although the development of such capabilities has recently been receiving more attention (Worboys 1995, Halls, Cowen and Jensen 1995, Barrera and Waechter 1992, Kemp et al. 1993, and Kraak and MacEhren 1995). In this chapter, the basic concept of temporal GIS is introduced and a description of a developed prototype of temporal GIS tool is described.

3.1 Requirements for a Temporal GIS

In spatiotemporal analysis, it is essential to be able to examine changes over time while retrieving spatial objects and attributes on the basis of the temporal relationships of a specific event. Moreover, the examination of the overall patterns of temporal relationships for geographic phenomena is also important. Specific examples of queries that relate geographic changes with respect to specific temporal relationships include:

- What was the alignment for bus route 40 at the beginning of 1989?
- What was the population and activity centers served then?
- How has the population changed within a quarter mile distance along bus route 40 between 1986 and 1990?
- How well has the service responded to changes in population and employment in the service area?
- What are the most recent changes to route 40?

In order to answer such questions, a temporal GIS must process the following capabilities for the investigation of spatiotemporal phenomena (Peuquet and Wentz 1995):

- The ability to represent changes over time efficiently;
- The ability to represent different temporal sequences for the same and different geographic area as well as equivalent temporal intervals;
- The ability to represent temporal distribution at multiple time scales; and

The ability to retrieve, manipulate and analyze spatiotemporal data on the basis of temporal relationships, as well as spatial relationships.

The fundamental functions of temporal GIS may include inventory, display, analysis, updates, quality control, and scheduling. **Table 3.1** summarizes the major temporal GIS functions.

Table 3.1 Major Temporal GIS Functions

FUNCTIONS	DESCRIPTION
Inventory	Store a complete description of the study area, and account for changes in both the physical world and computer storage.
Analysis	Explain, exploit, or forecast the components contained by and the process at work in a region.
Updates	Supersede outdated information with current information.
Quality Control	Evaluate whether new data are logically consistent with previous version and states.
Scheduling	Identify or anticipate threshold database states, which trigger predefined system responses.
Display	Generate a static or dynamic map, or a tabular summary, of temporal processes at work in a region.

Source: Time in Geographic Information Systems, Langran, 1993, pp. 5.

3.2 Temporal Databases

Commonly used databases in a vector GIS are relational databases. Relational databases may be considered as tables where attributes are attached to topological or geographical features. Traditional databases have been designed to store information about a static state of the world,

usually taken to be the “present” or “most recent” state. Databases of this kind are called snapshot databases, since they only model a particular snapshot of the world, and not the history or future of the world (Androutsopoulos 1993).

As an example, a snapshot relational database may contain the following table storing the current salaries of a company’s employees:

Table 3.2 Current Salaries of a Company

Employee_Salary	
Name	Salary
X	30,000
Y	33,000
.....	

When the salary of an employee changes or an employee leaves the company, the corresponding record (a row in the table) is modified or deleted accordingly. Hence, the database “forgets” the past, and will not be able to answer questions such as “What was X’s salary on 1/1/1994?”

In practice, snapshot database systems have been used to store information about non-present states. For example, the previous table may be modified as follows:

Table 3.3 Salary History of a Company

Employee_Salary2			
Name	Salary	From	To
X	24,000	1/1/90	12/31/91
X	30,000	1/1/92	4/4/95
....			
Y	26,000	1/1/90	12/31/91
Y	33,000	1/1/92	12/31/95
.....			

The attributes *from* and *to* above are of type date (a data type supported by most relational database systems). With this modified database, the question of “What was X’s salary on 1/1/1994?” may be answered using the Structural Query Language (SQL) query:

```
SELECT salary
FROM employee_salary2
Where name = 'X ' AND
      from <= 1/1/1994 AND to >= 1/1/1994
```

The SQL selects the tuple (group of data) corresponding to X, which contains his salary during an interval subsuming 1/1/1994. In the example above, attributes “from” and “to” were used to time-stamp the tuples of employee_salary2. However, as far as the database is concerned, there is nothing special about these time-stamp attributes. The database treats them as ordinary

attributes, and it is the responsibility of the user to honor their special time-stamping meaning.

Most of the proposed applications for temporal database models have incorporated at least one and two time dimensions: valid time and transaction time, which have been identified as important factors in modeling temporal information.

Valid Time

Temporality may be viewed as a sequence of states "punctuated by events that transform one state into the next" (Langran 1992). Of course, most phenomena are not static and constantly change. In an information system, however, such phenomena are often modeled in a discrete manner. In other words, we often only capture the world now and then, leaving the states in between unrecorded. It is therefore assumed that, to the best knowledge of the information system, a phenomenon recorded for a given period is "current" until a new observation is made and the record is superseded by the new information about the phenomenon. The time point when update information is obtained becomes the "event" that changes the state of the modeled phenomenon and marks the beginning of the *valid time* for the database records describing the new state of the phenomenon. The valid time is often represented by a pair of attributes: *valid_from* and *valid_to*. **Figure 3.1** illustrates the concept of states, events, and the valid time.

Figure 3.1 Temporality as States of a Phenomenon Separated by Events
(Source: Zhao and Elbadrawi 1997)

Transaction Time

Transaction time refers to the time when the database was informed about an event. For example, it is shown in **Table 3.4** that, on 11/15/89, the database was modified to reflect the fact that X's salary in the period between 1/1/90 and 12/31/91 was \$22,000. However, it was found that this information was incorrect, and a correction was made on 1/4/90, when the database was informed that X's salary in the period from 1/1/90 to 12/31/91 was \$24,000. On 2/1/94, the database received the history for X's salary showing that his salary was \$30,000 in the period from 1/1/92 to 12/31/93 and \$32,000 from 1/1/94 till now.

Table 3.4 Time-Stamped by Both Valid and Transaction Time

Employess_Salary3					
Name	Salary	Valid_From	Valid_To	Trans_From	Trans_To
X	22,000	1/1/90	12/31/91	11/15/89	1/3/90
X	24,000	1/1/90	12/31/91	1/4/90	1/30/91
X	30,000	1/1/92	12/31/93	2/1/91	2/1/94
X	32,000	1/1/94	now	2/2/94	now

Other Time Dimensions

In addition to the above two time dimensions, there may be other time dimensions that are useful for certain applications. For instance, some data are sampled at a "fixed" time point such as census or ground water table measured in a well. Although the sampling time is not an instance, if data is considered relatively stable during the sampling period, the length of the sampling period is unimportant. In contrast, some other data change rapidly. The change, although fluctuating periodically, may exhibit a pattern in a longer time period. To capture the phenomenon in the model without being forced to maintain an "animated" database, which is often unnecessary, data are collected and aggregated for a specified period of time. One example of such data is traffic counts, which are often recorded for time units ranging from 15 minutes to a few hours. In these cases, the length of sampling time becomes important and sample time cannot be considered a fixed time point, although the aggregated data may be considered to represent the current world during the same period of time (in a day, a month, or a year). Hence, while the valid time for

such data may be taken , e.g., as the end of the sample period, the duration of the event (sampling) must also be represented in the temporal model. Event_from and Event_to may be used to mark the beginning and end of the sampling period (Zhao and Elbadrawi 1997).

Another time stamp that may be relevant for some applications is the *measured time*. For instance, when a flood occurs, observations of the flooding may be made a few hours or a few days afterwards. To accurately represent the sample data, i.e., distinguishing the time when a phenomenon is known to take place and when the phenomenon is recorded, measured time may be used. It is possible that there may be other time dimensions that are meaningful and useful for certain types of applications. Such potential time dimensions need to be considered for given applications and appropriate representation needs to be developed.

Temporal Data Type

The user-defined temporal data type is a time representation specially designed to meet the specific needs of the user. For example, the designer of a database used for class scheduling in a school may be based on a “Year:Term:Day:Period” format. For transit operation, the temporal data may be in formats such as “Month:Day:Year” or “Month:Day:Year:Hour:Minute:Second.” Terms belonging to user-defined temporal data type receive the same query language support as terms belonging to built-in temporal data type such as the “DATE” data type.

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). When implemented, a reverse update model saves the most current information as a complete coverage while changes occurred in the past.

The space-time composite model is similar to the update model but stores both past and present data in the same layer and maintains the topology constantly (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 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 as time is being treated 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 have been 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.

3.4 A Prototype Temporal GIS

For this project, a temporal GIS model has been developed in a separate effort. The data model used is some what over-simplistic and, particularly, spatiotemporal topology is not maintained, which results in intensive computation every time a past coverage is retrieved since topology has to be rebuilt. Work is currently underway to construct an update model. Since for this project the emphasis has been on the potential applications of a temporal GIS to transit management, rather than the development of a working temporal GIS program, the weakness of the model did not affect the achievement of the research objectives as established in **Chapter 1** of this thesis.

The prototype temporal GIS including its data model and basic temporal query functions is described in this section. For a more detailed description, refer to (Zhao et al. 1997a, 1997b).

Typical GIS Spatial Model

A feature attribute table is a database file created by PC ARC/INFO and stores information about a feature that may be one of the three feature types: polygons, lines and points. These feature attribute tables hold the thematic data for a map feature or reference thematic data in related database files. For example, thematic data about polygons are stored in a polygon attribute table (PAT), and attributes are tied to each polygon by the User-ID. Thematic data in another table may be associated with the map by any common item, usually the User-ID. Similarly, thematic data about arcs and points are stored in an arc attribute table (AAT) and a point attribute table (PAT), respectively. **Figures 3.2, 3.3, and 3.4** represent the typical structure of feature attribute tables for points, arcs and polygons, respectively (ESRI 1995).

Time Representation

From the previous explanation of temporal databases (**Section 3.2**), there are two types of time needed to be considered, the valid time (world time) and the database time (transaction time). The valid time refers to when the event actually occurred in the real world, and the database time refers when the event is recorded or modified in the database.

Point_ID	Attribute_1	Attribute_2		Attribute_n
.....				
.....				

(a) Point Attribute Table

Point_ID	X_coordinate	Y_coordinate
.....		
.....		

(b) Point Definition - Internal Database File

Figure 3.2 Typical Data Structure Tables for Points

From_Node	To_Node	Left_Poly	Right_Poly	Arc_ID	Attribute_1	...
.....						
.....						

(a) Arc Attribute Table

Arc_ID	Point_List_Address	Number_of_points
.....		
.....		

Arc_Point_List
.....
.....

(b) Arc Definition Table - Internal Database Files

Figure 3.3 Typical Data Structure Tables for Arcs

Area	Perimeter	Poly_ID	Attribute_1	Attribute_2	...
.....					
.....					

(a) Polygon Attribute Table

Poly_ID	Arc_List_Address	Number_of_Arcs
.....		
.....		

Polygon_Arcs_List
.....
.....

(b) Polygon Definition Table - Internal Database Files

Figure 3.4 Typical Data Structure Tables for Polygons

Time representation, in terms of granularity and lifespan, should be determined to the needed applications. For transit management, the life span chosen describes the valid time domain for the related information. For instance, the life span of a bus service schedule begins when it becomes effective and ends when the schedule changes. “Day” has been chosen as the smallest unit of time, considering it is the granularity needed for most transit management tasks. The time in the prototype is defined as a number with a format of “yyyymmdd”. For example, January 1, 1996 and June 30, 1990 may be represented as 19960101 and 19920630, respectively. Other time granularities may be used based on the type of an application. For instance, “yyyymmdd.hhmmss” may be used to represent both date and time, and 19960101.152045 may be used to represent 3:20:45 pm of January 1, 1996.

Spatial-Temporal Approach

Following the same approach for the temporal databases, both valid time and database time are used to describe the temporal information in the world time and database time (transaction time), respectively. Temporal information is divided into spatial and aspatial information. Spatial information describes the spatial elements that may change over time. Aspatial information may change along time and it is related to spatial elements which may also change with time. **Figures 3.5 and 3.6** represent the schemes for spatial and aspatial-temporal information for points, arcs and polygons, respectively. These schemes have the same appearance as the feature attribute tables in **Figure 3.2, 3.3, and 3.4**. The difference is, however, that the attributes serving as the

time stamps receive special treatments in the temporal GIS. As mentioned at the beginning of this section, work is in progress to implement an improved data model, which adds more attributes specially used by temporal GIS that maintains the spatiotemporal topology for any state of the GIS database.

Temporal Query

Temporal query is important in answering questions regarding time in temporal GIS. The main tasks that temporal query should support are the examination of the life span and time slice of features. Temporal query may be divided into four different types:

Simple Temporal Query answers questions about the state of a feature at a given time and seeks a feature version that was current on a specific date.

Temporal Range Query tells what happens to a feature over a given period of time. It searches the feature by either feature key or attribute value match, and locates all versions of the desired feature that may exist during a specific time interval.

Simple Spatial-Temporal Query refers to answering questions about the state of a region at time “*t*”. This requires the current versions of all the objects that intersect in a specific spatial range.

Point_ID	Vd_From	Vd_To	DB_From	DB_To
.....				
.....				

(a) Point Attribute Table

F_Node	T_Node	R_Poly	L_Poly	Arc_ID	Vd_From	Vd_To	DB_From	DB_To
.....								
.....								

(b) Arc Attribute Table

Area	Perimeter	Poly_ID	Vd_From	Vd_To	DB_From	DB_To
.....						
.....						

(c) Polygon Attribute Table

Figure 3.5 The Representation Scheme for Spatio-Temporal Information

Point_ID	Vd_From	Vd_To	DB_From	DB_To	Attribute_1	Attribute_2	
.....							
.....							

(a) Additional Point Attribute Database File

Arc_ID	Vd_From	Vd_To	DB_From	DB_To	Attribute_1	Attribute_2	
.....							
.....							

(b) Additional Arc Attribute Database File

Poly_ID	Vd_From	Vd_To	DB_From	DB_To	Attribute_1	Attribute_2	
.....							
.....							

(c) Additional Polygon Attribute Database File

Figure 3.6 The Scheme for Aspatial-Temporal Information

Spatio-Temporal Range Query deals with questions such as; what happened to a region over time?

Temporal Query in PC ARC/INFO

Since ARC/INFO does not support any temporal operation by itself, several temporal query commands are developed using the Simple Macro Language (SML) and the ARC/INFO commands for the implementation of temporal storage, manipulation, and spatial analysis for spatial and aspatial features. These temporal query commands allow the user to examine a snapshot of the temporal data at a specific time defined by the user, or to examine the history of the attributes of spatial features.

Temporal Query Commands:

@SNAPCOV: Generates a new coverage which is a snapshot of the original coverage at a given time slice from a database version valid at a specified database version time.

@SNAPINFO: Generates a new database file which is a snapshot of the original database file at a given time slice from a database version valid at a specified database version time.

- @PERDCOV:** Creates a new coverage containing the spatial features that existed between the period specified by a beginning time and end 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 end time.
- @THISTORY:** Generates a PAT or AAT in which the selected items at a given time slice will be put together for historical analysis. All data is extracted from a version valid at a specified database version time.
- @TDOMAIN:** Reports the time domain of a database file valid at the specific version time. It can be PAT, AAT, or any database file containing temporal information.
- @TVERSION:** Generates a new temporal database file according to the database time at the given time. This file will include all items from the original file, and those records that are not valid at the given version time will be eliminated.

A more detailed description of the temporal commands is provided in **Appendix A**, which

explains the command usage with the correct syntax.

4. Transit service evaluation.

For each of these areas, the following will be discussed:

1. Definition of each management task;
2. Current practices;
3. Major spatial and temporal information used in each process; and
4. Potential temporal GIS applications for these tasks.

4.2 Transit Planning

There are many transportation planning processes under way in an urban area at any given time, each defined at a different level of complexity and for a unique purpose. For example, while transit planners examine alternative service configuration, traffic engineers might be identifying problems on the highway network. Regional planners might be looking at urban development patterns and the provision of public services. Individual employers might be considering alternative employee transportation programs, and social service agencies might be examining transportation options to improve delivery of their services to the general public. With all these groups involved in transportation planning activities, the primary purpose of each planning effort is to generate information useful to decision makers on the consequences of alternative transportation actions.

One of the most important areas of analysis in the urban transportation planning is the estimation of traveler demand for transportation facilities and services. Urban Transportation Modeling System (UTMS) is a computer software package commonly used to predict the number of trips made within an urban area by type, time of day and zonal origin destination pair, the mode of travel used to make these trips, and the routes taken through the transportation network.

Behavioral travel demand modeling is an alternative method of predicting the number of trips in an urban area (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.

Transit planning is the process of determining the needs for transit service for a specific study area. Transit planning is considered a long range planning that may include, in addition to determining the needs for transit service, items such as acquiring new vehicles, changing the general configuration of the network, planning major capital facilities, and introducing new transportation modes. The needs for transit service in an area is determined as part of the urban transportation plans. The traditional urban transportation models consist of four major steps: trip generation, trip distribution, modal split, and network assignment. These four steps

and their significance to transit planning are described below (Meyer and Miller 1984).

4.2.1 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 4.1**. 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, auto 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.

Figure 4.1 Trip Generation

5. How well did the model worked?

4.2.2 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 4.2**.

Figure 4.2 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 include characteristics of persons, workers, and housing units.

A temporal GIS may be used in a similar way as for trip production. Some spatiotemporal query examples include:

1. Where and how did the activity centers changes along Bird Road between 1980 and 1990?
2. What was the flow pattern of trips from zone 601 to 812 in 1980 and 1990, respectively?
3. How did travel patterns change for zone 701 between 1980 and 1990, respectively?
4. How were trip distributions related to socioeconomic data?
5. How well did the model work?

4.2.3 Modal Split

The function of the modal split (or modal choice) module is to identify the mode, or means

operating cost, parking cost, and other socioeconomic data involved in the modal split module.

Spatiotemporal query examples for modal split may include:

1. How did transit mode split by trip origin and trip destination for Dade County changed between 1980 and 1990?
2. How did the transit trips to zone 778 changed between 1980 and 1990?
3. What may have caused the change in transit trips?

Table 4.2 Attributes Involved in Modal Split Model

	Attributes	Temporal	Non-temporal
Traveler Characteristics	Auto Ownership	X	
	Household Income	X	
	Household Size	X	
	Age	X	
	Occupation	X	
TAZ Characteristics	Population Density	X	
	Distance from CBD	X	

4.2.4 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 4.4**.

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 the 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 comparison of observed traffic counts to model estimated volumes.

Figure 4.4 Trip Assignment

As trip assignment model depends on the transit and highway network configuration, any changes in the network configuration will affect the trip assignment models. Such analyses will be useful to evaluate the effectiveness of network configuration.

A temporal GIS may be used and some spatiotemporal query examples include:

1. How did the travel volume change on Bird Road between 1980 and 1990?
2. How did the level of transit use in Bird Road change between 1980 and 1990?
3. Were the changes in the modal split caused by transit network configuration of level of service?

In summary, examples of a temporal GIS applications in transit planning may include the following:

of public facility such as schools, sewer, water supply, fire station, etc., may be represented by a coverage showing the current and the scheduled facilities for the future. This will allow transit professionals to phase transit service expansions to new areas to minimize the redundancy of transit service.

4.3 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 on tailoring transit services to major activities. Planning factors should include past and current operating data such as service coverage, farebox

- and recreation with the amount and type of service appropriate to each; and
3. To provide and ensure reasonable service for elderly, handicapped, young, and low income people. Usage of paratransit may be analyzed to study the trend and to determine future demand.

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 4.4**. Their adoption will depend on budget changes or other system resources. In some cases, the actions may be a mixture, in which case the system is being 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 scheduling level, actions will affect the waiting times and schedule adherence on an affected route.

Table 4.3 Route Planning Factors and Considerations

Factors	Consideration
Accessibility to route by residents	- 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.
Safety of route	- 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.

Table 4.4 Summary of Generic Actions by Level

Levels	Actions
Area Coverage Level	<ul style="list-style-type: none">- New route- Route extension- Small set of route replacements- Route abandonment- Shortening a route- Route realignment
Route Structure Level	<ul style="list-style-type: none">- Route Splitting- Zonal service- Express/local service- Linking two routes
Scheduling Level	<ul style="list-style-type: none">- 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.

From the previous discussion it may be seen that service planning has to deal with changes in land use, travel pattern, and resources, which have a great effect on transit ridership. Thus, keeping these data in a temporal format is important to help service planners design new service or improve the existing service to meet future transit demand.

Efficient and effective transit service for the community resident and visitors may be better

planned with the support of a temporal GIS. Changes in the population distribution and density may be saved in a temporal format and used for trend analysis to predict the future number of transit trips within the transit service area. Also, historical ridership data may be related to different seasonal activities in the urban areas to determine the expected ridership, thus, improvement may be made to meet the demand. Ridership data during school season may be used to configure the service during school operations. Data needed for this type of analysis are school locations, student concentrations, and transit services within an acceptable walking distance (1/4 mile) from each school.

The Americans with Disabilities Act (ADA) requires state and local transit operators to provide comparable service to elderly and disabled persons within the transit system's service area. Information of the elderly and disabled population may be geocoded into a temporal GIS to track the change in their travel patterns in order to provide efficient and effective service for them. This information may be used to plan for special transportation services (STS) for elderly and disabled persons.

Besides the socioeconomic data and transit network layout, the service planning process needs street network representing all major trips attraction and production. Each street segment should be represented by its capacity, speed limit, number of lanes, and impedance (stops and turning movements). Zoning regulations can be represented for different parcel units to determine future changes on land use and new development, and to reconfigure the

transit service for additional demand . Using an origin and a destination, the optimal transit route for every projected data interval can be determined based on one or more of the following: minimum cost, maximum ridership, and minimum travel time.

Table 4.5 shows different spatial features and attributes that may be used in service planning. Each may be defined in terms of space and time. For example, the percentage of population within 1/4 mile walking distance from each bus stop may be considered as a temporal attribute of a zone, while the distribution of activity centers within the 1/4 mile buffer may be considered as a spatiotemporal phenomenon. Transfer points are considered spatiotemporal objects since any additional transfer point may be added to or deleted from the system. Bus stops and pullout and shelter facilities are considered spatiotemporal objects.

Other temporal GIS applications in service planning may be for one of the following service planning tasks:

1. Gather data on ridership trends and current route ridership to study the changes in ridership patterns with changes in the economic activities of an area over time;
2. Identify the location of other transit modes in an area to study the integration between different public transit services over time and how the ease passengers transfer from one modes of transportation to another changed;
3. Use future road improvement and construction data for an area classified by type to

- determine how to change the configuration of service during road maintenance and construction to minimize transit user inconvenience;
4. Changes in locations of bus stops may be analyzed with ridership and traffic condition to determine the best stop locations to attract more transit riders and reduce traffic congestion; and
 5. Complaints from the public may be analyzed in order to identify the area with inconvenient transit service to the public.

Table 4.5 List of Spatial Information Contributing in Service Planning

Spatial Objects	Temporality in Geometry	Attributes
Bus Stops	Change in location	Location Time point sheltered # of routes
Bus Routes	Change in location	Location Ridership Schedule Headway
TAZ	Change of boundaries	Population Density Employment School Enrolment Average Household Car ownership

Some spatiotemporal query example for 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?
4. How did the schedule and headway respond to the transit demand?
5. When and where the spacing between routes exceeded 1/4 mile?
6. When and where the population exceeded 4,000 persons per square mile?
7. What were TAZs become served by route 40 between 1990 and 1994?
8. How did the activity centers change within 1/4 buffer around route 40 stops between 1986 and 1996?
9. How did the population change within 1/4 mile distance along route 40 between 1986 and 1990?

4.4 Customer Information Services

As presented in **Chapter 2, Section 2.2.5**, that GIS may be used as a powerful tool to provide the information about the transit services, temporal GIS may be used to store data such as delayed trips and schedule adherence. A temporal GIS may also be used to store all the outputs of the automatic trip planning to determine the travel patterns of transit riders.

Receiving public complaints is part of customer information service, rider suggestions and complaints are useful to improve transit service to attract more riders and to meet the community needs of transit service.

By using temporal GIS for customer information services, some spatiotemporal query may include:

1. How did the travel pattern using transit change between 1990 and 1992?
2. How did the network configuration respond to customer complaints?
3. How long will it take to make a transit trip between point *X* and *Y* at a specific future time point?

4.5 Transit Service Monitoring

Transit service monitoring is critical in maintaining the same level of service or improving the quality of the service provided. The main objective of service monitoring is to tune the service to ridership from both a capacity and a cost-effectiveness standpoint. The challenge is to carry passengers comfortably and expeditiously at minimum cost to the agency. Ridership and traffic vary throughout a day, week, and year due to economic conditions, school operations, weather conditions, and changes in urban development. These changes call for constant monitoring and adjustments of service. Operational monitoring is difficult

and, at the same time, is labor intensive. It involves the collection of data regarding:

1. Driver performance;
2. Vehicle schedule adherence;
3. Passenger loads;
4. In-vehicle and off-vehicle security/safety; and
5. Local traffic conditions.

The monitoring program utilizes several methods of data collection:

1. Transit field passenger and time checks are used to determine the number of passengers at each stop and check the schedule adherence of transit buses;
2. Electronic fareboxes automatically calculate the revenue for each bus run categorizing the ridership by different types of fares;
3. Turnstile counts are used in terminal stations to determine the number of passengers using the service for a certain period of time; and
4. Origin destination of transit riders and the type of transit mode use to accomplish their trips are determined by passenger surveys.

Ridership and running time data are most important for service monitoring, which are collected by traffic checkers. On board of a transit vehicle, a traffic checker records information such as actual arrival and departure time along with the number of passengers arriving, alighting, boarding, and leaving on the transit vehicle. Traffic checkers also keep

track of boarding and alighting in between the scheduled stops. Other traffic checkers are assigned at check points for bus routes passing certain locations, in which they record the bus number and route of each bus observed at this location, along with arrival and departure times and the number of passengers arriving to the stop, getting off and on the transit vehicle, and leaving the stops. Data collected are converted into useful information to guide planners and schedule makers. For instance, data analysis is performed to decide whether service or schedule changes are warranted. A full description of Metro-Dade Transit Agency data collecting and analysis is provided in (CUTR 1995).

Using traffic checkers' reports, two important operational monitoring measures may be examined using a temporal GIS:

1. Schedule adherence may be monitored over time for the same route or for different routes for schedule adjustments or evaluating the driver's performance evaluation. **Table 4.6** shows the structure of a database table that may be used for monitoring driver performance and schedule adherence.
2. Passenger loads as well as the change in the load pattern may be monitored over time. Using data from traffic checkers' reports, a database file as shown in **Table 4.7** may be used in temporal GIS.

Maximum load data are important indicators of transit route performance and service quality are widely used in service planning (Banks 1980). Information about maximum load has great impact on decision making regarding scheduling, headway, and the assignment of equipment, especially where buses with different seating capacities are available. Maximum load data also have important implications for long range planning, particularly those related to the mix of bus sizes in the fleet.

With the introduction of new technologies such as automatic vehicle location (AVL) and automatic passengers count (APC), running time and ridership data may be collected at any time and buses will be continuously monitored for schedule adherence and emergency situations. If an agency has implemented Automatic Passenger Counter (APC) it may need to keep data such as the number of seats of a bus and the maximum vehicle capacity of transit vehicles to determine the suitable fleet size for each route. Saving this data in a spatiotemporal database will be useful for evaluating and monitoring transit service at any given period of time by relating it to any recurrent and non-recurrent conditions.

The use of temporal GIS with new intelligent transportation systems (ITS) technologies such as AVL and GPS may provide transit riders with the actual arrival and departure time of transit vehicles. Keeping these data in a temporal format helps to adjust the schedule to minimize the passengers waiting time at stations and transfer points. It is also very important to keep such data in case of a law suit, for which such data will serve as evidence, such as

Table 4.6 Driver Performance and Schedule Adherence Data

Stop_ID	Run_#	Driver's_Name	Route	Direction	Sched_Time	Actual_Time	Comments
1	3129	MS	40	East	0600	0601	Heavy Rain
2	3131	MS	40	West	1230	1232	Accident between Stops 1 & 2
.....							

Table 4.7 Passenger Load Points Database Table

Stop_ID	Run_#	Time	Route_#	Arrv_on	Off	On	Lv_on	Btw_Pt_Off	Btw_Pt_On
1	3129	0602	40 East	1	0	0	1	0	4
2	3129	0608	40 East	5	0	0	5	0	0
3	3129	0610	40 East	5	0	0	5	0	1
.....									...

Note: Arrv_on : Number of passengers arrived on the bus
Off : Number of passengers alighted the bus at a given stop
On : Number of passengers boarded the bus at a given stop
Lv_on : Number of passengers in the bus when leaving the stop
Btw_Pt_Off : Number of passengers alighted the bus between stops
Btw_Pt_On : Number of passengers boarded the bus between stops

confirming a certain transit vehicle being at a certain location at a specific time. It may also answer a questions such as where was driver A at 12:30 pm on 12/02/1995?

Some spatiotemporal query examples may include:

1. How did passenger load points change between 1990 and 1992?
2. How did the performance of driver “X” change in 1991? Is there a consistent pattern? What might have cause the change in the driver’s performance?
3. What was the schedule adherence for route 40 between 12/01/1990 and 01/30/1991?
4. How did the nature of customer complaints change due to a service reconfiguration?
5. How did transit travel time change in Dade County between 1986 and 1990?
6. How did long-term parking cost change between 1980 and 1990?
7. How did the transit travel time to the CBD during the peak period change between 1990 and 1993?

4.6 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 measures how well

resources such as labor, equipment, facilities, and fuel are used to produce output measure such as revenue vehicle hours or revenue vehicle miles. Effectiveness measures transit's consumption of traffic congestion. Overall performance indicators integrate efficiency and effectiveness measures with costs of service inputs 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 applicable to both internal and external purposes. Internally, it can 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. While externally, it 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).

Carter and Lomax (1992) formulated performance measures and indicators to assist in selecting appropriate measures and indicators for assessing and comparing systems shown in **Table 4.8**. A temporal GIS may be helpful to transit professionals in generating different reports based on these performance measures such as day-to-day, daily, weekly, monthly, quarterly performance measures, or long-term performance measures.

Table 4.8 Performance Measures and Indicators

Performance Measure	Performance Indicators
Cost Efficiency	<ul style="list-style-type: none">- Cost per mile- Cost per hour- Cost per vehicle- Ridership per expense
Cost Effectiveness	<ul style="list-style-type: none">- Cost per passenger trip- Revenue per passenger trip- Ridership per expense
Service Utilization/Efficiency	<ul style="list-style-type: none">- Passenger trips per mile- Passenger trips per hour- Passenger trips per capita
Vehicle Utilization/Efficiency	<ul style="list-style-type: none">- Mile per vehicle
Quality of Service	<ul style="list-style-type: none">- Average Speed- Vehicle miles between road calls- Vehicle miles between accidents
Labor Productivity	<ul style="list-style-type: none">- Passenger trips per employee- Vehicle miles per employee
Coverage	<ul style="list-style-type: none">- 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 may also be used to examine and analyze the performance measures and indicators for transit routes shown in **Table 4.8**. Information may be stored by route in temporal database file(s) and linked to GIS route coverage. Moreover, using temporal GIS in transit service evaluation will allow transit professionals to determine progress toward meeting transit service goals and objectives to assist states in evaluating transit performance and to provide a management system to monitor and improve transit service.

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 of 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 segment of the transit system and the reasons for low ridership. Keeping transit data in 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.

By using temporal GIS for service evaluation some spatiotemporal query example may include:

1. How did the cost per mile, hour, and vehicle changed from the CBD to Coral Gables 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 changed between the CBD and north Dade in 1990 and 1991?

4.7 Facility and Real Estate Management

A temporal GIS may be used for facility and real estate management to store maintenance data including repair date, replacement items, cost, type, etc. Transit facilities include park-and-ride lots, transit garages and maintenance work shops, transit stops, rail tracks, etc. To be able to determine facility deterioration rates for each facility type will allow planning for and/or allocation of future funds needed to maintain transit facilities in good conditions. The applications of temporal GIS for facility and real estate management may be expanded to include other facilities such as bridges, roads, and tunnels that are used exclusively by transit.

Some spatiotemporal query example using temporal GIS may include;

1. What types of repair have been done in Douglas Road Station between 1990 and 1996?
2. How did the deterioration rate for buses change in the last ten years?

4.8 Transit Impact on Land Use

Transportation is closely related to land development, both affecting it and affected by it. Given a condition ripe for development, transportation was one of the factors that enable it to happen. The availability of transportation had influenced the growth of port cities and transportation hubs. Streetcar lines and the substantial development of arterials and freeways had shaped the fine detailed of urban land development.

One of the results of using automobiles has been land use patterns that can only be served by cars. Low density suburbs and strip commercial developments were not designed to accommodate public transportation services that require large number of riders to make them work efficiently. Retrofitting traditional bus services into these areas is difficult, under the best circumstances, and may not be very effective. The issue is not to change the land uses that make up the community, but rather influence their mixture and design (Caldwell 1989). Locating apartment buildings on major streets with bus routes and installing sidewalks to bus stops are examples of oriented urban planning for public transportation. Recent statistics show that short trips to stores, day care centers, banks, recreation areas, etc., account for a large portion of all vehicular trip making. Single use land uses are one major reason that so many people have to use their cars for these trips. As new developments are planned, mixed use developments should be given greater emphasis. Daily needed facilities such as banks, restaurants, drug stores and others can enhance a development by reducing the need for

people to use their automobiles to go to these places during the day or after work.

To design public transportation friendly with land uses a variety of criteria have to be defined such as the location and type of land uses which may differ for different types of public transportation. Caldwell (1989) made the following recommendation regarding transit-oriented design:

1. Public transportation works best when land uses are located within an existing urban area or suburban activity center. Generally, the closer the transit service is to activity centers, the greater the number of transit riders.
2. Bus and rail services and rider sharing work better where activities are mixed together and people can walk between activities. For example, in an area where offices are mixed with restaurants and retail stores or small shops within residential area, people can take care of several activities without making auto trips.
3. Land development should be located near bus stops or another public transportation facility or a planned route. A site is not public transportation compatible if service is not currently provided at or planned for that location.
4. Land uses need to be oriented to public transportation facilities. People will not be

motivated to use public transportation services if buildings do not provide convenient, quality access even if the buildings are located close to a bus route or rail line. Building entrances and paved walkways need to lead directly to a bus stop, a park-and-ride facility, or station.

5. The closer both the beginning and the end of a trip are to a transit stop, the greater the likelihood of people using public transportation is. For example, isolated activities do not generate riders if public transportation is difficult to reach.
6. Bus service works effectively where bus facilities, such as bus stops or transfer centers, are designed into buildings, residential developments, roads, and building entrances.
7. Residential, non-residential, and employment land uses are the three main types that have the ability of generating transit riders.

The use of temporal GIS in studying transportation and land use may be to keep track of all zoning ordinances and regulations for certain areas to monitor the urban growth and to ensure sufficient transit service for the community. Each parcel unit may be geocoded into a GIS layer and linked to a database file containing parcel information. Information such as year built, lot size, building area, and activity type, when compared to ridership will provide better

understanding to the relation between public transit and land use. The interaction of land use and transportation including transit may also be studied with the aid of temporal GIS to determine the effect of transit on land use and what type of land uses generate more trips when related to socioeconomic data.

Spatiotemporal query examples for land use may include:

1. How did the land uses change along the route 40 corridor between 1986 and 1996?
2. How did transit service respond to land use changes?
3. How was transit service related to land uses and socioeconomic data?

CHAPTER 5

EXAMPLES OF TEMPORAL GIS APPLICATIONS

In this chapter some temporal GIS application examples are presented to illustrate the use of GIS. In one example, the changes in the number of home-base-work (HBW) trips between 1986 and 1990 are presented based on changes in the socioeconomic data for the selected area of study. The second example concerns how temporal GIS may be used in transit service planning.

5.1 Study Area

The geographic area chosen for these examples is the service area of the Bus Route 40 in Dade County, Florida. The current alignment of Route 40 starts from Coral Gables Terminal at Miracle Mile (SW 24th Street and 41st Avenue). Passing through Ponce De Leon Boulevard, which is considered an office area, connecting with the Metro Rail at Douglas Road Station (SW 40th Street and 37th Avenue), then passing through the residential area of Coral Gables, bus Route 40 penetrates the heart of the commercial area of West Kendall along Bird Road (SW 40th Street). After the intersection of Bird Road and SW 97th Street, the route passes through an area of a mixed residential, light commercial and retail and terminates at the intersection of Bird Road and SW 147th Avenue. The total length of the route is approximately 16.7 miles each way with 30 bus stops. Route 40 started operation

in June of 1986 and modified 9 times. The current alignment has been since October of 1994. With temporal GIS tools, it may be possible to analyze how transit services have been modified based on the changes in the area and evaluate if changes in services effectively respond to the change in the demand.

5.2 The Temporal Information Used in the Example

For transportation planning study purposes, the geographic unit is TAZ for the demographic database. One of the main problems with using TAZ were the changes in TAZ definition (TAZ identification numbers and boundaries). From 1980 to 1990 there were 1,089 internal TAZs in Dade County and after 1990 there were 1,164 internal zones. This means a base map should be selected in order to compare the changes within similar areas. The 1990 TAZ coverage was selected to be the base map. To determine what changes have occurred before and after 1990 regarding the area and boundaries of each TAZ. For example, **Figure 5.1** shows that after 1990, TAZ 623 was divided into TAZ 811 and 812 where TAZ 811 represents 90 percent and 812 represents 10 percent of the original area of TAZ 623, respectively. Additionally, TAZs 635, 636, 637, 640, 641, 642, and 643 were assigned new numbers of 791, 790, 789, 774, 773, 767, and 768, respectively.

The zonal production data (ZDATA1) and zonal attraction data (ZDATA2) for 1986 and 1990 were used to compute the number of generated trips from each TAZ in the area of

Figure 5.1 TAZs Identification Numbers and Boundaries for 1980 and 1990

study. ZDATA1 consist of the number of single family and multi-family dwelling units in each zone, as well as vacancy rate, residential population, and auto ownership characteristics. The data also contains the number of hotel/motel units in each of the zones, their occupancy rates, and number of guests during the peak season. While ZDATA2 consists of the employment and school enrollment within each zone. Employment data are supplied categorically by industrial, commercial, service, and total employment. Other data used in this section are the alignment and stops of Bus Route 40 including all modifications between 1986 and 1996.

5.3 Example 1: Transportation Planning

In this section, an example of applying temporal GIS to transportation planning is presented. This example is a presentation of the trip generation model results for 1986, 1990 and the change in the number of generated trips between the two years. The data used were the 1986 and 1990 zonal trip production data (ZDATA1), which are used by Dade County MPO to determine the number of person trips generated in any specific zone within the Florida State Urban Transportation Modeling Structure (FSUTMS). Upon computing the number of trips for both 1986 and 1990, the output is saved in a temporal database file as shown in **Table 5.1**. **Table 5.1** contains both the total number of generated trips and the number and occupancy for both single and multi-family dwelling units.

SNAPINFO command may be used to determine the number of generated trips for 1986 or

1990. By joining the trip generation output file with TAZ GIS coverage file, shown in **Table 5.2**, a new temporal GIS file is generated, that relates the total number of 1990 generated trips for each TAZ to the geographic entity of the zone (**Table 5.3**). Another way to do this is to extract the ZDATA1 and ZDATA2 information using SNAPINFO command for 1986 and 1990 separately. After computing the generated trips for both periods, the output file is joined with TAZ coverage to get the same result as in **Table 5.3** for 1990. Which way is chosen to follow depends on the size of data, how fast your model performs the calculations, and the size of the area of study.

Figures 5.2 (a and b) represent the number of generated trips from each TAZ in both 1986 and 1990, respectively, and the bus alignment and stops in both 1986 and 1990. **Figure 5.3** shows the TAZs with increased number of trips between the two periods with 1990 alignment and bus stops.

Table 5.1 Temporal Database File for Trip Generation Model

TAZ_ID	VD_FROM	VD_TO	DB_FROM	DB_TO	SF_DU	SF_POP	PS_SF_DU	SF_TRIPS	MF_DU	MF_POP	MF_PS_DU	MF_TRIPS	TOT_TRIPS
701	19860101	19891231	19960724	19960724	472	1230	3	937	633	1705	3	701	1638
702	19860101	19891231	19960724	19960724	508	1345	3	1030	588	1488	3	617	1646
705	19860101	19891231	19960724	19960724	435	1253	3	855	631	1397	2	352	1207
706	19860101	19891231	19960724	19960724	425	760	2	800	451	937	2	326	1126
707	19860101	19891231	19960724	19960724	208	337	2	287	58	88	2	33	320
711	19860101	19891231	19960724	19960724	234	659	3	465	485	1441	3	490	955
712	19860101	19891231	19960724	19960724	3	8	3	7	0	0	0	0	7
713	19860101	19891231	19960724	19960724	0	0	0	0	3	8	3	4	4
714	19860101	19891231	19960724	19960724	139	323	2	216	416	927	2	340	555
715	19860101	19891231	19960724	19960724	337	794	2	547	168	373	2	144	691
716	19860101	19891231	19960724	19960724	155	331	2	244	184	265	2	142	386
717	19860101	19891231	19960724	19960724	2	3	2	4	0	0	0	0	4
718	19860101	19891231	19960724	19960724	0	0	0	0	67	89	1	34	34
719	19860101	19891231	19960724	19960724	0	0	0	0	107	127	1	58	58
.....													
701	19900101	99991231	19960724	99991231	426	1258	3	822	768	2145	3	962	1785
702	19900101	99991231	19960724	99991231	376	1094	3	712	715	2027	3	873	1586
705	19900101	99991231	19960724	99991231	450	1334	3	792	696	1379	2	390	1182
706	19900101	99991231	19960724	99991231	334	869	3	499	453	816	2	225	724
707	19900101	99991231	19960724	99991231	266	452	2	407	0	0	0	0	407
711	19900101	99991231	19960724	99991231	292	733	3	467	309	860	3	230	697
712	19900101	99991231	19960724	99991231	0	0	0	0	90	209	2	87	87
713	19900101	99991231	19960724	99991231	0	0	0	0	0	0	0	0	0
714	19900101	99991231	19960724	99991231	125	352	3	240	368	974	3	454	694
715	19900101	99991231	19960724	99991231	334	722	2	548	193	407	2	191	739
716	19900101	99991231	19960724	99991231	146	328	2	201	170	217	1	88	289
717	19900101	99991231	19960724	99991231	0	0	0	0	2	1	1	0	0
718	19900101	99991231	19960724	99991231	0	0	0	0	32	52	2	20	20
719	19900101	99991231	19960724	99991231	0	0	0	0	13	15	1	5	5
.....													

Table 5.2 TAZ.PAT File

AREA	PERIMETER	TAZ	TAZ_ID
-747594700.000000	209303.300000	1	0
6773918.000000	10389.570000	2	701
7638559.000000	11778.610000	3	702
6431824.000000	10766.370000	4	705
4425555.000000	10583.110000	5	706
3220748.000000	8208.363000	6	707
6359776.000000	10408.170000	7	711
2827696.000000	8070.048000	8	712
1242720.000000	4476.046000	9	713
2698706.000000	7748.200000	10	714
4773234.000000	10737.420000	11	715
4269535.000000	8861.805000	12	716
1173941.000000	4391.321000	13	717
1216875.000000	4487.191000	14	718
1273814.000000	4582.545000	15	719
.....			

Table 5.3 Temporal TAZ.PAT File for Trip Generation Model 1990

AREA	PERIMETER	TAZ90	TAZ90_ID	VD FROM	VD TO	DB FROM	DB TO	SF DU	SF POP	PS SF DU	SF TRIPS	MF DU	MF POP	MF PS DU	MF TRIPS	TOT_TRIPS
-747594700.000000	209303.300000	1	0	19900101	99991231	19960724	19960724	0	0	0	0	0	0	0	0	0
6773918.000000	10389.570000	2	701	19900101	99991231	19960724	19960724	426	1258	3	822	768	2145	3	962	1785
7638559.000000	11778.610000	3	702	19900101	99991231	19960724	19960724	376	1094	3	712	715	2027	3	873	1586
6431824.000000	10766.370000	4	705	19900101	99991231	19960724	19960724	450	1334	3	792	696	1379	2	390	1182
4425555.000000	10583.110000	5	706	19900101	99991231	19960724	19960724	334	869	3	499	453	816	2	225	724
3220748.000000	8208.363000	6	707	19900101	99991231	19960724	19960724	266	452	2	407	0	0	0	0	407
6359776.000000	10408.170000	7	711	19900101	99991231	19960724	19960724	292	733	3	467	309	860	3	230	697
2827696.000000	8070.048000	8	712	19900101	99991231	19960724	19960724	0	0	0	0	90	209	2	87	87
1242720.000000	4476.046000	9	713	19900101	99991231	19960724	19960724	0	0	0	0	0	0	0	0	0
2698706.000000	7748.200000	10	714	19900101	99991231	19960724	19960724	125	352	3	240	368	974	3	454	694
4773234.000000	10737.420000	11	715	19900101	99991231	19960724	19960724	334	722	2	548	193	407	2	191	739
4269535.000000	8861.805000	12	716	19900101	99991231	19960724	19960724	146	328	2	201	170	217	1	88	289
1173941.000000	4391.321000	13	717	19900101	99991231	19960724	19960724	0	0	0	0	0	2	1	0	0
1216875.000000	4487.191000	14	718	19900101	99991231	19960724	19960724	0	0	0	0	32	52	2	20	20
1273814.000000	4582.545000	15	719	19900101	99991231	19960724	19960724	0	0	0	0	13	15	1	5	5

Figure 5.2(a) 1986 HBW Generated Trips from each TAZ

Figure 5.2(b) 1990 HBW Generated Trips from each TAZ

Figure 5.3 TAZ with Increased Trips between 1986 and 1990

is also created to represent the time at which each bus stop was added, changed and/or deleted from the system. Changes in Route 40 alignment and bus stops since the inception of the service are shown in **Figure 5.4**. The command SNAPCOV may be used to find out the route alignment and the bus stops at any given time,. For example, the route alignment for 1986 may be retrieved by using SNAPCOV commands with the time slice beginning 06/15/1986. To find out all the route segments existed between on 01/31/1993 and today, the PERCOV command is used with the beginning time 01/31/1993 and end time present. These previous two examples are shown in **Figures 5.5 and 5.6**, respectively.

Table 5.4 Temporal AAT File for Route 40

FNODE_	TNODE_	LPOLY_	RPOLY_	LENGTH	RT90_	RT90_ID	VD_FROM	VD_TO	DB_FROM	DB_TO
2	3	0	0	1997.597000	1	1	19870104	99991231	19960724	99991231
2	4	0	0	3935.765000	2	2	19870104	99991231	19960724	99991231
3	5	0	0	900.581400	3	3	19870104	99991231	19960724	99991231
4	6	0	0	1650.551000	4	4	19870503	99991231	19960724	99991231
1	6	0	0	7566.796000	5	5	19860615	99991231	19960724	99991231
6	7	0	0	3236.987000	6	6	19860615	99991231	19960724	99991231
1	7	0	0	3742.937000	7	7	19860615	99991231	19960724	99991231
8	8	0	0	2581.426000	8	8	19860615	99991231	19960724	99991231
5	10	0	0	2468.323000	9	9	19870104	99991231	19960724	99991231
10	11	0	0	2825.938000	10	10	19870104	99991231	19960724	99991231
6	12	0	0	5132.725000	11	11	19860615	19931106	19960724	19960724
13	14	0	0	813.277900	12	12	19860615	99991231	19960724	99991231
8	14	0	0	5395.998000	13	13	19860615	99991231	19960724	99991231
14	15	0	0	1143.052000	14	14	19860615	99991231	19960724	99991231
15	16	0	0	3806.353000	15	15	19860615	99991231	19960724	99991231
16	17	0	0	4223.947000	16	16	19860615	99991231	19960724	99991231
17	18	0	0	5408.007000	17	17	19860615	99991231	19960724	99991231
19	21	0	0	4463.047000	18	18	19860615	99991231	19960724	99991231
18	19	0	0	6376.600000	19	19	19860615	99991231	19960724	99991231
22	20	0	0	99.843750	20	20	19870104	99991231	19960724	99991231
20	23	0	0	7864.110000	21	21	19860615	99991231	19960724	99991231
23	25	0	0	2715.866000	22	22	19860615	99991231	19960724	99991231
25	26	0	0	2658.070000	23	23	19860615	99991231	19960724	99991231
26	28	0	0	2547.658000	24	24	19860615	99991231	19960724	99991231
13	13	0	0	3754.652000	25	25	19860615	99991231	19960724	99991231
29	11	0	0	2649.250000	26	26	19870104	19931106	19960724	19960724
29	28	0	0	3423.188000	27	27	19860615	99991231	19960724	99991231
30	29	0	0	2353.476000	28	28	19860615	99991231	19960724	99991231
12	30	0	0	2755.990000	29	29	19860615	99991231	19960724	99991231

Figure 5.4 Route 40 Alignment Changes since 06/15/1986

Figure 5.6 New Route Segments Added in 1993 and Still Effective till Present

Other service planning examples compare the population, employment, and/or school enrolment within a 1/4 mile buffer along the route or around the bus stops for 1986 and 1990.

Figure 5.7 shows the population changes within the 1/4 mile buffer along the effective alignment on 01/01/1990. It may be seen that area “A” experienced a decrease in population density and was still served by bus service. Reduction in population alone, however, does not necessarily result in ridership decline. Employment, school enrolment, and actual transit ridership for the same area should be examined before considering eliminating or reducing the transit service for area “A”.

Ridership Studies

While transit demand influences route structures and service frequency, family income, car ownership, and residential and employment density have an important bearing on line and system promotion. Studying historical and current data will allow for more accurate estimates of future transit riders during the day, which will help in planning more effective and efficient transit service.

It is necessary, therefore, to know the types of riders along any route or group of routes. This means to identify the mix of riders by trip purpose (work, shop, school, other), time of day, and age group. Traffic checkers reports are the main source of passenger counts at any given points along the route. Using historical data, the relationship between the number of passengers alighting and boarding the bus per station and the socioeconomic characteristics of an area around a stop may be better understood. From this, a better forecast of the future types of riders may be made to provide the best possible efficient service. Ridership data may be related to a specific bus stop or to the route. Relating the ridership to bus stops allows a transit analyst to study how changes in the socioeconomic factors in the surrounding area are affecting ridership for that stop. While relating the ridership to special events allows transit professionals to determine the effect of different events on transit ridership. The relationship between route characteristics and ridership may also be studied. **Table 5.5** shows the temporal PAT file for bus stops of route 40, in which the history of bus stop locations is

recorded. **Table 5.6** illustrates the structure of the temporal ridership database file. It may be pointed out that the time representation is slightly different from that in the previous examples to show the exact timing of data collection. This time representation may also be used for monitoring schedule adherence. The data presented in **Table 5.6** are actual data from traffic checkers report for bus route 40. The traffic checker will start recording the actual time when the bus arrives to stop #1 heading east which becomes the time of “*VD_FROM*”, and counting the number of passengers alighting and boarding at stop #1 and between stop 1 and 2 (intermediate bus stops not listed in the ride check forms or at a traffic light when it is red). This information will be valid until the time as indicated in “*VD_TO*”, which is time at which the bus arrives at the same stop in the next round (heading east) with a traffic checker on board.

Temporal query for ridership information may be performed by either selecting a specific time (snap shot) or a period of time (observation period). If a query is made for a period of time, the options may be made available to the user to retain the sum, the maximum, minimum, average, median value, etc. Intrappolation and extrapolation may be necessary if only partial information is available for the specified period of time. When selecting a period of time it might be found that the bus passes a certain station more than one time within this period. In this case there must be a supporting tools (programs) to identify the different arrival times and enable the planners to know the number of passengers alighted or boarded the bus at this station within the specified period. When joining the output file with bus stops GIS coverage

the supporting programs should allow transit planners to overcome the problem of multiple records for the same stop. More studies are needed for temporal ridership studies as the time granularity is small and data change fast. The previous example assumes that only one bus passes this stop until the same bus passes through the same station in the same direction. Thus headway should be considered to get the actual ridership in a day.

Table 5.6 Temporal Structure for Ridership Database Related to Bus Stops

ST40_ID	ROUTE	DIR	ADDRESS	VD FROM	VD TO	DB FROM	DB TO	AP OFF	AP ON	BP OFF	BP ON
1	40	E	SW 42 ST / 127 AVE	199605310619	199605310900	199610311100	199610311100	0	1	0	0
2	40	E	SW 42 ST / 122 AVE	199605310620	199605310901	199610311100	199610311100	0	0	0	0
3	40	E	SW 40 ST / 117 AVE	199605310622	199605310903	199610311100	199610311100	1	1	0	0
4	40	E	SW 40 ST / 112 AVE	199605310624	199605310905	199610311100	199610311100	0	1	0	0
5	40	E	SW 40 ST / 107 AVE	199605310626	199605310907	199610311100	199610311100	0	0	0	0
6	40	E	SW 40 ST / 102 AVE	199605310628	199605310910	199610311100	199610311100	0	1	0	0
7	40	E	SW 40 ST / 97 AVE	199605310629	199605310911	199610311100	199610311100	1	0	1	1
8	40	E	SW 40 ST / 92 AVE	199605310631	199605310913	199610311100	199610311100	0	0	0	0
9	40	E	SW 40 ST / 87 AVE	199605310633	199605310915	199610311100	199610311100	0	2	0	1
.....											
1	40	W	SW 42 ST / 127 AVE	199605310823	999912312359	199610311100	999912312359	0	0	0	0
2	40	W	SW 42 ST / 122 AVE	199605310821	999912312359	199610311100	999912312359	0	0	0	0
3	40	W	SW 40 ST / 117 AVE	199605310819	999912312359	199610311100	999912312359	0	0	2	0
4	40	W	SW 40 ST / 112 AVE	199605310813	999912312359	199610311100	999912312359	3	4	0	0
5	40	W	SW 40 ST / 107 AVE	199605310810	999912312359	199610311100	999912312359	1	0	1	0
6	40	W	SW 40 ST / 102 AVE	199605310807	999912312359	199610311100	999912312359	0	0	1	0
7	40	W	SW 40 ST / 97 AVE	199605310805	999912312359	199610311100	999912312359	0	0	0	0
8	40	W	SW 40 ST / 92 AVE	199605310803	999912312359	199610311100	999912312359	1	0	1	0
9	40	W	SW 40 ST / 87 AVE	199605310801	999912312359	199610311100	999912312359	0	1	1	0
.....											
1	40	E	SW 42 ST / 127 AVE	199605310901	999912312359	199610311100	999912312359	0	0	0	0
2	40	E	SW 42 ST / 122 AVE	199605310902	999912312359	199610311100	999912312359	0	0	0	1
3	40	E	SW 40 ST / 117 AVE	199605310904	999912312359	199610311100	999912312359	0	0	0	0
4	40	E	SW 40 ST / 112 AVE	199605310906	999912312359	199610311100	999912312359	1	5	0	0
5	40	E	SW 40 ST / 107 AVE	199605310908	999912312359	199610311100	999912312359	0	1	0	2
6	40	E	SW 40 ST / 102 AVE	199605310911	999912312359	199610311100	999912312359	0	0	0	0
7	40	E	SW 40 ST / 97 AVE	199605310912	999912312359	199610311100	999912312359	1	0	1	0
8	40	E	SW 40 ST / 92 AVE	199605310914	999912312359	199610311100	999912312359	0	1	2	0
9	40	E	SW 40 ST / 87 AVE	199605310916	999912312359	199610311100	999912312359	0	0	0	0
.....											

CHAPTER 6

CONCLUSION

GIS has been used for several public transportation planning and management applications including transit planning, service planning, service monitoring, facility and real estate management, and customer information services. Current GIS software mainly supports the analysis of spatial information for a fixed time point or a time period for which information is assumed to remain unchanged. Due to the continuous nature of the real world, it is a challenge to design transit GIS databases to maintain past, present, and future information on transit networks, service variations, land uses, economic activities, etc., to study the effect of various factors on transit performance and market. A better understanding of these effects will help to improve decision-making and make transit more competitive.

In this thesis, a study on the potential applications of temporal GIS in public transit planning and management has been described. The current transit planning and management practices are summarized in **Chapter 4** where various factors of transit management are examined to study the time factor in transit planning, service planning, service monitoring, and service evaluation. The potential benefits of a temporal GIS were also discussed and illustrated with several temporal query examples that could not be answered without using temporal data. By using temporal GIS new types of analyses may be made available to transit professionals. An example for transit planning may be to study the basic components of the travel demand

models over a period of time and relate them to the changes in the infrastructure and land use to study their impact on travel patterns. An example for service planning may be to determine the service coverage and network configuration changes over time with the change in the travel patterns and other socioeconomic data. Other examples were also given to show the potential benefit of a temporal GIS for other transit planning and management areas.

Examples of temporal GIS applications are presented in **Chapter 5** to illustrate the use of a temporal GIS. The first example presented the changes in the number of HBW trips between 1986 and 1990 based on the change in the socioeconomic data for the area served by bus route 40. This example shows how temporal data may be used with trip generation model, and how the result of the model may be retrieved using GIS temporal GIS queries. By using temporal information, transit planning models may be updated whenever new developments are constructed in the study area with a defined number of generated trips. Models may also be calibrated by using historical data and by comparing the model results to the actual situation for the same period of time.

The second example presented in **Chapter 5** is concerned with the implementation of temporal GIS in transit service planning. This example illustrated how all route segments and stops may be stored in temporal database files. By using temporal queries, the route alignment at any given period of time may be retrieved and the history of a route alignment changes may be traced. Comparing the population, employment, and school enrollment

There exist several major obstacles for applying temporal GIS to transit planning and management. They are briefly discussed below.

Few Temporal GIS applications - Temporal GIS applications are few and none of them have been used in transit planning and management. As such, there are no prior experiences that may be relied on.

Lack of understanding of temporal GIS - Temporal GIS benefits and needs need be introduced to transit professionals and operators. One of the major problems during the completion of this research was getting feedback from transit professionals and operators on how temporal GIS may be implemented and used. Several interviews and exchanges with transit professionals have taken place during the course of this research, with, however, few insights gained.

Lack of historical data and data limitation - Lack of historical data is a major problem for any attempt of constructing a temporal database and performing temporal GIS analysis. Some transit agencies keep their data only for a short period of time. For example, Metro-Dade Transit Authority (MDTA) collects ridership data for route on regular basis. Traffic checker reports are kept for three years after being logged into the MDTA computer for data analysis. The logged data are, however, difficult to access. Running time summary and average weekday passenger loads are the output of the traffic checker reports. In order to

analyze ridership data with socioeconomic data ridership, data should be kept for more than five years since the socioeconomic data is updated every five years. The analysis of transit ridership changes with the change of socioeconomic data could not, therefore, be performed. For such purpose, transit agencies need temporal GIS tools to record historical data for at least 25 years. Because of the lack of historical data, there may not be significant temporal GIS databases for years to come. However, once temporal GIS is accepted to be useful, plans should be set to start data collection effort to begin the building of temporal GIS databases. During an attempt to get land use data for route 40 corridor to study the relation between public transit and land use, it was found that the method of recording the property tax files is incompatible for GIS use. For example, the property appraisal information for Dade County is divided into three ASCII files, each of 350 MEGA bytes, with each record consisting of 1625 undelimited characters. It was inaccurate and time consuming to extract land use data for the route 40 corridor. Thus, it is important to keep historical data in a GIS compatible format to save time and other resources.

Due to the limited data available, the illustrated examples in **Chapter 5** may not seem to be very powerful to the reader. TAZ data for Dade County are provided by the Dade County MPO. The data are used by MPO for the development and validation of models using Florida Standard Urban Transportation Model Structure (FSUTMS). By Spring of 1997, the Bureau of Transportation Statistics will provide census data in TAZ format. Using such data may allow transit professionals to analyze changes related to other factors in addition to

population, employment and school enrollment.

Lack of GIS software support - Current GIS software does not support spatiotemporal updates. This means that the responsibility of time-stamping the database records is entirely on the user. Not only this is a burden to the user, but it also leaves the database integrity vulnerable.

Although temporal GIS may be implemented for individual applications, its efficiency and effectiveness may only be fully achieved when it becomes a part of the information management system that integrates all kinds of information and support different applications.

Figure 6.1 shows a conceptual framework of such an information management system with temporal GIS serving as the central data manger. Since many analyses involving the time factor are performed individually on distributed data, the user should be able to access the database directly or through application programs or through the temporal information management system (TIMS). TIMS may include both temporal GIS and temporal database management system. The user may also run one or more application programs such as trip generation and trip distribution models. The output may be saved in a database file after being time stamped by the T-DBMS and displayed via GIS.

However, more research is needed to develop the necessary technologies and much experience must be gained through temporal GIS applications before temporal GIS become

widely used.

Figure 6.1 Temporal GIS Conceptual Model

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APPENDIX A

Temporal Query in PC ARC/INFO

@SNAPCOV **[in_cover] [out_cover] {time_slice} {version_time}**

Generates a new coverage which is a snapshot of the original coverage at given time slice from a version valid at specified version time.

arguments **[in_cover]** - the name of the coverage from which the snapshot will be extracted.

[out_cover] - the name of the new coverage to create.

{time_slice} - the time slice at which the snapshot of the coverage will be generated. Default value is the current time.

{version_time} - the time at which a valid version of the coverage will be generated, and the snapshot will be extracted from this version. Default value is the current time.

- notes**
- The PAT and AAT files will be generated in the new coverage.
 - Be sure to specify a different out_cover name from in_cover name, otherwise the original temporal data will be lost.

@SNAPINFO **[cover] [in_file] [out_file] {time_slice} {version_time}**

Generates a new database file which is a snapshot of the original database file at given time slice from a version valid at specified version time.

arguments **[cover]** - the name of the coverage, the original database file is in this coverage, and the generated database file will be created in the same coverage.

[in_file] - the name of the original database file.

[out_file] - the name of the new database file to create.

{time_slice}- the time slice at which the snapshot of the database file will be generated. Default value is the current time.

{version_time}- the time at which a valid version of the database file will be generated, and the snapshot will be extracted from this version. Default value is the current time.

- notes**
- The new database file, which is a snapshot of the original database file, will be created in the same coverage.
 - Be sure to specify a different `out_file` name from `in_file` name, otherwise the original temporal data will be lost.

@Perdcov **[in_cover] [out_cover] [POLY / LINE / POINT] [begin_time] [end_time]**
[version]

Creates a new coverage containing the spatial features that existed between the period as specified by the *begin_time* and *end_time*. All the changes in the specified period of time are captured.

arguments **[in_cover]** - the name of the coverage from which the features will be extracted.

[out_cover] - the name of the new coverage to create.

[POLY / LINE / POINT] - the feature class included in the in_cover.

[begin_time] - the beginning time of the specified period.

[end_time] - the end time of the specified period.

[version] - the time at which a valid version of the coverage will be generated.

notes

- The PAT and AAT files will be generated in the new coverage.
- Be sure to specify a different out_cover name from in_cover name, otherwise the original temporal data will be lost.

@Perdinfo **[in_file] [out_file] [begin_time] [end_time] [version]**

Produces a new one that contains records that are valid between the period of time as defined by *begin_time* and *end_time*.

arguments **[in_file]** - the name of the original database file.

[out_file] - the name of the new database file to create.

[begin_time] - the beginning time of the specified period.

[end_time] - the end time of the specified period.

[version] - the time at which a valid version of the coverage will be generated.

notes

- The new database file, will be created in the same coverage.
- Be sure to specify a different out_file name from in_file name, otherwise the original temporal data will be lost.

@THISTORY **[cover] [PAT/AAT] [in_file] {version_time}**

Generates a PAT or AAT file in which the selected items at given time slices will be put together for historical analysis, all data is extracted from a version valid at specified version time.

arguments **[cover]**- the name of the coverage. A historical table will be generated and

Time slice:

Time slice:

...

Time slice:

User can input all the time slices for the specified item. At each time slice the item's value will be extracted from the in_file and merged into PAT or AAT file. The new item name in PAT OR AAT file is combined by the first 3 characters of the specified item name, "_", and the last 6 digits of the time slice. For example, if the item name is population, for the time slice 19900101, the new item name will be pop_900101.

If user enters blank at the first prompt for time slice, the command will be ended.

- notes**
- For the historical analysis, it is recommended that user make a copy of the coverage first, and make a time version, using TVERSION command, of the responding PAT or AAT file.
 - Several items can be extracted and merged to the PAT or AAT files

using one THISTORY command. All the new items will be inserted after the item VB_TO.

@TDOMAIN **[cover] [file] {version_time}**

Reports the time domain of a database file valid at the specified version time. It can be PAT, AAT, or any database file having temporal information. It is given in terms of the earliest valid time and the latest or furthest valid time.

arguments **[cover]**- the name of the coverage, the object database file is in this coverage.

[file]- the name of the database file, either PAT, AAT or other database files having temporal information.

[version_time]- the time at which a valid version of the database file will be generated, and the time domain will be report about the temporal information. Default value is the current time.

notes ■ The versioning will be done first at the specified version time or current time.

- The reported time domain is given in terms of the earliest valid time and the latest or furthest valid time for all the data records.

@TVERSION **[cover] [in_file] [out_file] {version_time}**

Generates a temporal version according to the database time at the given version time.

The new file will include all the items from the original file, and those records that are not valid at the given version time will be eliminated.

arguments **[cover]**- the name of the coverage, the object database file is in this coverage.

[in_file] - the name of the original database file.

[out_file] - the name of the new database file to create.

{version_time}- the time at which a valid version of the database file will be generated. Default value is the current time.

notes ■ The new database file, which is a temporal version of the original database file, will be created in the same coverage.

- Be sure to specify a different out_file name from in_file name, otherwise the original temporal data will be lost.

- TVERSION can be used to eliminate the not valid records at the given version time. For example, the modified records, deleted features, or changed features, which may be valid at other version time, but not valid at this given version time.