STRATEGIES FOR BUILDING, MANAGING AND IMPLEMENTING GEOGRAPHIC INFORMATION SYSTEMS (GIS) CAPABILITIES IN TRANSIT AGENCIES

by

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ABSTRACT

This thesis is aimed at finding viable pathways for growing GIS capabilities within transit agencies in order to allow transit agencies to become more involved in regional information infrastructures and regional transportation planning efforts. Since transit agencies represent an important sub-sector of regional land use and transportation planning, they provide an interesting context in which to study the extent to which GIS adoption is leading toward a coherent (or fragmented) regional spatial information infrastructure. The research approach is organized around the following five objectives: (1) to identify and categorize the areas of application of GIS in transit agencies; (2) to expose the complexities related to database design of transit applications; (3) to examine the different implementation strategies of GIS in transit agencies; (4) to identify ways of addressing the implementation complexities given the new advances in information technology; and (5) to describe viable developmental pathways that transit agencies can follow for the implementation of GIS.

In order to answer these research questions, we conducted a literature review, a set of interviews with one transit agency's staff, and a survey of the largest 30 US transit operators. We also built three GIS-based prototypes to understand the "what does it take" to build transit applications using GIS technology. Finally, we analyzed the literature, our survey, and the prototypes in order to identify practical developmental pathways for GIS in transit agencies.

The results of this research suggest many useful applications along with a list of complications related to data maintenance, coordination, and technical advances that tend to bog down the implementation of GIS. In this thesis, we describe a schema for growing GIS capabilities at transit agencies that addresses most of these complexities and that allows the building of sustainable and coherent GIS

databases and applications. The key elements of this schema are a "foundation database" containing textual descriptions of routes and stops (without geometry) and a set of automation tools for adding and integrating geometry and related spatial data needed for specific applications. The schema also recommends a "loosely-coupled" organizational structure that retains many of the "top-down" characteristics while allowing some autonomy and "incoherent" GIS development by focusing on standardization and coordination of a limited "core" set of data related to route and stop information.

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Chapter 1

Introduction

1.1. Topic and Overview

Transportation planning is one of the more analytically developed aspects of land use planning that constitutes a logical place to expect early implementations of GIS technologies. Research conducted to date suggests many useful applications of GIS along with a series of complexities that tend to bog down such implementation. These complications are related to data maintenance issues, coordination efforts, technical difficulties, and organizational structure. This thesis is an opportunity to construct a set of guidelines regarding a sensible growth path for GIS technologies in land use / transportation planning area. Toward this end, the thesis focuses on transit-related applications as a specific sub-area in which many generic issues can be discussed and

while making the research manageable, applicable to a set of problems that have not been addressed elsewhere, and well-matched to our interests and experience.

Since the first use of the Urban Transportation Planning models (UTP), around 40 years ago, many improvements to these models have occurred. The improvements involved developing more realistic models for capturing human behavior when choosing routes or modes of travel. The rational for the early use of the UTP models was to identify appropriate locations for new transportation infrastructure investments. At later stages the rational developed into building roads in a smarter way in order to contain congestion without really interfering with land use patterns, travel patterns, or choice of travel modes.

The use of the UTP models faced several problems, however. One of these problems was the limited capacity and speed of the computing environments. Another problem was the lack of needed data. In order to conduct a transportation study at the regional level, major assumptions in variables definition, and model specifications were usually introduced which adversely influenced the prediction capability and the reliability in decision making of these models. In recent years, on the other hand, because of the environmental problems (such as the air pollution and storm water runoff), and due to the fact that these models were not really able to properly capture the relationship between land use and transportation planning, the emphasis shifted from transportation supply enhancement to travel demand management. Nowadays, transportation planners are interested in building tools that can take advantage of detailed data (such as individual's address information and block-level socio-economic information) to better simulate the interaction between land use and transportation needs. This is especially true for transit planners who are constrained by major budgetary cuts and are subjected to major pressures to run more effective and efficient transit services.

Targeting potential transit riders is one example of ways of achieving these goals.

The recent development in computer technologies in general and of GIS tools in particular have created new potentials to address many of the concerns of transit planners. The rapid increase in computing power and speed associated with recent developments in computer technologies and the improved capabilities of GIS tools have made the linking of the transportation process to detailed land use and socio-economic data more feasible. However, the effective integration of GIS technology into transit agency processes is heavily dependent upon complex database design and maintenance strategies. This is especially true, since some key components of the required data, such as the street network files, are likely to be someone else's responsibility (e.g., TIGER files maintained by some combination of Federal, State, and Local authorities).

The complexities of database design of transit applications involve (a) segmentation and representation (e.g., should transit routes be encoded as a collection of TIGER file line segments?), (b) version coordination (e.g., how should changes in routes or street segments be propagated among the various departmental applications), (c) spatial accuracy (e.g., can a TIGER road network be replaced with a more accurate network developed from local base maps without requiring a complete reconstruction of all transit routes?), errors and additions (e.g., how should one encode transit routes, one-way information, and missing street links?).

Development strategies for implementing GIS capabilities in transit agencies vary in terms of their capacity to address these complexities. Variations on three basic strategies are possible: (1) 'top-down' strategies where information technology is coordinated and centrally controlled; (2) 'bottom-up' strategies where every

department/agency builds its own databases and acquires/implements technologies without taking into consideration the other departments' requirements; and (3) 'loosely coupled' strategies where each department is responsible for building most of the tools and databases for its own applications based on key data, tools, and guidelines are developed for general use and in light of some general framework set for the building of databases by a central committee in the agency and/or for the region.

Advances in information technology, on the other hand, can affect the viability of such implementation strategies. The rapidly changing hardware processing power, computing architecture, and database management capabilities are suggesting new approaches for implementing GIS technologies in transit organizations and addressing some of the above complexities. Client-server and distributed systems offer new possibilities for using information in powerful new ways. The technologies that support these architectures have reached a level of maturity where organizations are beginning to adopt client-server model for implementing new systems. Parallel processing, distributed computing architecture, segmentation of applications across multiple nodes, object-oriented principles, and federated databases are some features of these new advances that future GIS implementation plans can utilize.

This thesis investigates the ways of building and managing sustainable GIS capabilities at transit agencies in order to make these agencies capable of joining and benefiting from regional planning efforts. In other words, this thesis is aimed at finding viable pathways for growing GIS capabilities at transit agencies in order to allow transit agencies to become more involved in regional information infrastructures and regional transportation planning efforts.

1.2. Goals of the Research

The research approach is organized around the following four objectives :

1. The first goal of this research is **to identify and categorize the areas of application of GIS in transit agencies**. Transit agencies are facing declining staff and financial resources, coincident with increasing demand for transit services. Improved decision support systems might assist these agencies in managing their resources more efficiently and effectively. GIS technologies provide computerized mapping and spatial analysis tools that can be used to serve this purpose. This research will first identify the departments in a transit agency that are potential users of GIS technologies and then examine the activities which require the use of geo-referenced data, overlaying, and buffering analysis. Such applications usually can benefit from GIS technologies. Nevertheless, the listing of the GIS applications is not intended to be exhaustive since it is beyond the scope of this research to enumerate all possible applications and since the purpose of this task is to identify the type of applications that can benefit from GIS.

2. The second objective is **to expose the complexities related to database design of transit applications**. Transit applications utilize a rich assortment of data including road network, transit routes and stops, ridechecks, pointchecks, passenger surveys, and demographic (census) data. While many of these data are common to many applications in a transit agency, each application has special requirements in terms of data structure, segmentation of routes, scale of representation, level of detail, and encoding scheme. This research will aim at illustrating the complexities associated with building databases for transit applications given the need to share data between different applications, departments, and agencies.

3. The third objective is **to examine the different implementation strategies of GIS in transit agencies**. While many applications share many common data, different departments in a transit agency tend to diverge in adopting a variety of system development strategies. To get a better handle on the data complexities, different implementation strategies need to be addressed. This research will seek to determine viable strategies for enabling different applications to share common data. It will also examine the pros and cons of implementing each strategy and its implications as far as data maintenance and update responsibilities are concerned.

4. The last objective is to **identify ways of addressing the implementation complexities given the new advances in information technology**. Most of the research done to date about the implementation of technology in any organization usually deals with the mistakes committed or the correct steps taken while implementing any new system. Given the complexity of the database structure for transit applications, and given the advances in information technologies such results are quickly obsolete. This research will avoid examining the "what should have been done?" type of questions, but rather focus on the "what should be done?" in the near future to effectively implement tomorrow's GIS in transit agencies. The research will also investigate how the new advances in technology are capable of addressing some of the complexities that are impeding the proper implementation of GIS.

1.3. Research Questions

This dissertation addresses the following set of research questions:

1. What are the areas of integration of GIS in transit agencies?

2. What are the complexities related to database design, system design, and data flow that are affecting the implementation of GIS?

3. How are GIS technologies, regional information infrastructure, and transit planning processes changing and evolving over time?

4. What are the different implementation strategies that can be adopted in a transit agency for the efficient and effective implementation of GIS technologies?

5. What are the viable developmental pathways that transit agencies can follow for the implementation of GIS? How can advances in information technology help in addressing some of the implementation complexities and in shaping the transit planning process in the near future?

1.4. Methodology

In order to answer the above research questions, the following research methodology is adopted:

1. *Literature review:* A literature review is first conducted to set the proper framework for the research. We first review the literature that deals with the use of GIS in transportation and transit applications to check the originality of our research and to know how developed the research in this field is. We then cover the literature on the use of computer technologies and modeling techniques in managing and operating transit agencies. This body of literature helps in understanding the extent of use of models and computer technologies in managing transit agencies which would allow us to assess properly the

impacts of the implementation of GIS technologies. Last, we review the recent technological developments in terms of computer architecture, database management tools, and networking technologies in order to examine their potential in addressing the technical complexities of implementing GIS in transit applications.

2. *Interviews and Survey*: To answer the first research question that deals with the areas of integration of GIS in transit agencies, we first conduct an interview with the staff of the Massachusetts Bay Transit Authority (MBTA) and the Central Transportation Planning Staff (CTPS) in Boston. To check the applicability of the findings on other agencies, we conduct a mail survey of largest 30 transit operators around the US and then summarize and analyze the results in this thesis.

3. *GIS-based Prototypes*: In this thesis, we build three prototypes of applications of GIS in transit planning. These prototypes include a GIS-based passenger information system, a ridership forecast model, and a tool for targeting the employees of large employers. These prototypes serve to understand the complexities attached with each application and to learn about the different data representation and organization and the different encoding schema for each application. A compilation of all these information and a thorough analysis of these findings will help in addressing the second research question of this thesis. The above questionnaire will also check the pervasiveness of these complexities among transit agencies in the US.

4. *Analysis and Synthesis*: We build upon the results of the literature review, the interviews and survey, and the three GIS-based prototypes to identify practical developmental pathways for GIS in transit agencies. We examine which choices do

these agencies have to make about how to get started with GIS applications, what data to use, what other agencies to connect to, and what shortcuts to make along the way that allow the viable implementation of GIS. In our analysis, we also try to understand the scope of what it means to bring GIS into transit agencies in the context of how these agencies fit into the metropolitan infrastructure development.

1.4. Organization of Thesis Chapters

Chapter 2 reviews some of the transit planning literature and investigates state-of-the-art application and use of GIS in transportation, as well as the trends of development of information technology. Chapter 2 provides the means to answer the third research question of this thesis that is concerned with the evolution of GIS technologies, information technology, and transit planning processes over time. Learning about this evolution also helps in addressing the other research questions that involve investigating the impact of recent technological developments on solving the GIS implementation problems.

In Chapter 3, we examine in detail some of the areas of application of GIS in transit agencies. We review the activities of the various departments of a transit agency and discuss the improvements and the benefits that a few typical applications can derive from GIS. In this Chapter, we provide answers to the research question that relates to identifying the areas of application of GIS in transit agencies.

The results of the survey are summarized in Chapter 4. Chapter 4 checks the universality of the findings of Chapter 3 as far as GIS applications are concerned.

It also investigates digital data use and coordination of applications by large US transit operators for the purpose of identifying and studying some of the difficulties in evolving effective GIS capabilities in transit agencies. Chapter 4 serves as the means to answering several parts of the research questions of this thesis. It checks the areas of use of GIS in different departments, the complexities that different agencies are facing, and the implementation strategies of GIS adopted by the largest transit operators in the US.

In Chapter 3, we describe the potential of using GIS without going into the complexities, the meaning, and the "what does it take" to use GIS for each application. In chapter 5, we examine these issues in detail by building three prototypes of GIS applications, namely a GIS-based PIS, a GIS-based ridership forecast model, and a GIS-based tool for targeting major employment centers. These prototypes allow us to understand the meaning and all the complexities associated with using standard data format and standard GIS tools for building GIS transit applications.

In Chapter 6, we classify and categorize the difficulties that are facing the use of GIS for building transit applications. Chapter 6 addresses the second research question of this thesis that is concerned with the complexities that are affecting the viable implementation of GIS in transit agencies. In Chapter 6, we use the GIS-based prototypes that we built in Chapter 5, the interviews that we conducted with the staff of the MBTA and CTPS, and our survey of Chapter 4 to properly illustrate these complexities. We also try to shift the prevailing view that transit agencies must find a one time solution by making the "right choices" to a focus on creating a robust strategy for managing the complexities involved in evolving viable GIS capabilities and that can include multiple geographic representations of

routes and stops across different transit applications.

Chapter 7 discusses the different implementation strategies of GIS in a transit agency. Chapter 7 deals with the fourth and fifth research questions of this thesis. In addition to describing how the various implementation strategies influence building, sharing, and maintaining databases, it also tries to answer the questions related to the choices that transit agencies can make to get started with GIS applications, which data should they use, which other agencies could they connect to, and what kind of shortcuts could they make along the way to get going. Chapter 7 also describes one viable development pathway that transit agencies can follow to implement an effective and sustainable GIS.

Chapter 8 summarizes the findings of the research and describes the impact of GIS technologies on making transit agencies more integrated into regional information infrastructure. Chapter 8 concludes the thesis by making a set of recommendations and discussing future research in this field.

Chapter 2

Review of Related Literature

In this chapter we review some of the transit planning literature and mainly investigate state-of-the-art application and use of GIS in transportation, as well as the trends of development of information technology (IT). We review the following bodies of literature: (1) the use of GIS in transportation applications in general and more specifically in transit applications; (2) the use of computer technologies for transit management and operation; and (3) the recent trends in the development of information technologies. The review first starts by defining GIS. To check the originality of the research, this review then covers the literature that deals with the use of GIS in transportation and transit applications. This helps in knowing how developed the research in this field is and in better shaping the framework within which this research is conducted.

The second body of literature that this chapter covers is related to the use of computer technologies and modeling techniques in managing and operating transit agencies. This is basically a review of applications where computers are used in a

transit agency and a review of the modeling efforts for running different activities in these agencies. The importance of covering these areas relates to the need to understand the extent of modeling and technology implementation in these agencies in order to assess the impacts of the implementation of GIS technologies.

Finally, in this chapter we review the recent technological developments in terms of computer architecture, database management tools, and networking technologies. In order to address the technical complexities of implementing GIS in transit applications, an evaluation of the recent developments in computer and networking technologies as well as of the future trends that these technologies are expected to follow are needed. This sheds some light on the ways future technologies can be utilized to address the complexities of today's GIS.

2.1. What is a GIS?

It is first necessary to define what GIS is. A definition for GIS from the National Center for Geographic Information and Analysis (NCGIA) is:

> "A GIS is best defined as a system which uses a partial database to
> provide answers to queries of a geographic nature... The generic GIS
> can be viewed as a number of specialized spatial routines laid over a
> standard relational database management system." [Goodchild,
> 1985]

On the other hand, in this thesis, by GIS tools or technologies we mean a broad range of techniques and software packages that encode spatial features, associated

attributes, and their topological relationships in more or less standard form that can be created, stored, edited, and retrieved using generic tools for computer graphics, computational algorithms, and interactive queries. Note that "state of the art" technologies are fast changing, as will be discussed later, and tomorrow's GIS will certainly look different from today's GIS, as a result.

2.2. The Use of GIS in Transportation Planning Applications

The literature on the use of GIS technologies in transportation planning can be subdivided into the following three research areas: (1) the integration of GIS into the Urban Transportation Planning models (UTP); (2) the utilization of GIS for management and operation of highway transportation systems; and (3) the use of GIS in transit planning. This part of the literature review is also divided in accordance with these three sub-divisions.

2.2.1. Integration of GIS into the UTP Models

Since the first use of the Urban Transportation Planning models (UTP), around 40 years ago[1], many improvements to these models have occurred. The improvements involved developing more realistic models for capturing human behavior when choosing routes or modes of travel. The rational for the early use of the UTP models was to identify appropriate locations for new transportation infrastructure investments. At later stages the rational developed into building roads in a smarter way in order to contain congestion without really interfering with land use patterns, travel patterns, or

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[1] Most Researchers quote the "Chicago Area Transportation Study" of December 1959 as the first significant effort to develop and calibrate metro scale UTP.

choice of travel modes [Ferguson 1994].

The use of the UTP models faced several problems, however. One of these problems was the limited capacity and speed of the computing environments. Another problem was the lack of needed data. In order to conduct a transportation study at the regional level, major assumptions in variables definition, and model specifications were usually introduced which adversely influenced the prediction capability and the reliability in decision making of these models. In recent years, on the other hand, because of traffic-related environmental problems (such as the air pollution and storm water runoff), and due to the fact that these models were not really able to properly capture the relationship between land use and transportation planning, the emphasis shifted from transportation supply enhancement to travel demand management.

Nowadays, interest has shifted towards building tools that can take advantage of detailed data (such as individual address information and block-level socio-economic information) to better simulate the interaction between land use and transportation needs. The recent development in computer technologies in general and of GIS tools in particular have created new potentials to address many of the above concerns. The rapid increase in computing power and speed associated with recent developments in computer technologies and the improved capabilities of GIS tools have made the linking of the transportation process to detailed land use and socio-economic data more feasible.

The integration of GIS technologies into transportation planning has many potentials but also faces many technical difficulties. As early as the late 1980's, researchers have examined the benefits that can be derived from such integration but no concluding results have been made as to how such integration can be done. In this section of the

literature review we cover articles written by Simkowitz [1989], Dueker [1988], Nuyrges [1988, 1989], Lewis [1990], Cook [1989], O'neil [1991], Eberlein [1992], and Choi [1994]. All of these studies described the benefits and the complexities of using GIS in transportation planning but failed to include ways of addressing these complexities. The benefits of integrating GIS into UTP models included:

1. *Improved Data Capturing Tools:* The most time consuming phase of the transportation planning process is probably data collection. Dividing the study area into homogenous traffic analysis zones, preparing socio-economic conditions related to these TAZs, and generating transportation network which includes the detailed operation of nodes-link data preparation and network encoding are some of the many data preparation activities needed for building a UTP model. Acquiring these data is often very expensive. Even when such data are available from other sources, aggregating these data to required TAZ level or converting existing networks into usable forms have proven to be very complex, costly, and time consuming. In many instance, because of these problems, modelers are forced to make many assumptions which render the accuracy of the results of UTP models questionable. GIS has the potential to address some of these data collection and preparation concerns.

   The overlay and graphical manipulation capabilities of GIS are useful in reducing the data collection and integration efforts required for network generation. The complexity of network generation is related to the need to modify networks and TAZs to test alternative network scenarios or to accommodate changes in land use. TAZ boundaries, which are generally homogenous in terms of socio-economic and land use characteristics, are not stable since land use and demographics are subject to continuous changes. Similarly, transportation networks might be modified by

either changing the geometry and topology of transportation networks or by changing their characteristics such as capacity or speed limit to test different transportation scenarios. Since land use information or socio-economic data that are related to TAZs are usually available from external sources, the need to integrate these information into the UTP models can be more easily met by utilizing the overlay capabilities of GIS. TAZs can be overlaid on top of census tracts or block groups to integrate the census information into the TAZs. The geometry of transportation networks can be more easily edited using a GIS. Links and nodes can be added or removed in a less labor intensive process, and attributes attached to these links or nodes can be as well easily modified.

2. *Improved Graphical Interfaces:* In general, transportation packages are not geared toward displaying information graphically. Tables of data are generated for each step of the four step model. The few software, equipped with graphical interfaces, usually suffer from inadequate, primitive, or over-simplified interfaces. Visualizing, for example, traffic volumes along the different links in a transportation network is one of the major benefits that can be derived from linking GIS tools to transportation models. GIS tools are generally more optimized to perform graphical functions than any other function. The capability to annotate transportation networks with different information saves the modeler a lot of effort browsing through large hard copy tables of data. Furthermore, the capability of a GIS to create bands along different segments of a network with varying width based on changes in data values provides the planner with tools to immediately flag out areas where instant attention is needed.

Productivity is another benefit that can be derived from improved graphical interfaces. Since visual data are faster and easier to understand and since they can

be delivered at much higher information density, work quality of transportation modelers can be improved when databases become more visual-oriented. Interacting with visual spatial objects, such as networks and TAZs, help in uncovering hidden problems, yielding new insights and perspectives, and interpreting causalities more intuitively.

3. *Improved user-interaction:* Transportation packages traditionally consisted of a set of algorithms capable of performing trip generation, trip distribution, modal split, and trip assignment. These packages usually require the modeler to be extremely familiar with every detail associated with each of these models. User unfriendliness that is manifested in complex software design, non-intuitive user interface, and complex data entry processes is one of the major problems that condemned these packages.

Integrating GIS tools into these models had the potential of addressing many of those drawbacks. In comparison to transportation packages and despite their complex or unfriendly user interfaces (especially with their early versions), GIS tools had major potentials for improving transportation package interfaces. This had a lot to do with the fact that GIS tools are capable of reducing the level of abstractions by allowing less spatial aggregation when building the network and traffic analysis zones representations that transportation modelers usually use. For example, a network is usually represented in a forward-star matrix that is utilized to indicate whether a link exists between any pair of nodes or not. The length of these links is attached as an attribute to these links. Transportation analysis zones (TAZ) are also represented by their centroids. Centroid connectors, which do not necessarily represent any existing street link, are contrived for linking centroids to transportation networks. In other words, unlike GIS representations, the

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representation of transportation networks in many instances had little to do with physical and geographical locations of street networks. The capability of GIS to represent space in a more concrete way is one of the ways to render UTP models less abstract and more user-friendly.

4. *Improved Analytical Transportation Methods:* UTP models are usually criticized for their linearity and their lack of feedbacks among and between their various steps. In these models, the decision to make a trip is divided into 4 sequential steps. The process starts by estimating the number of trips generated by, or attracted to, each zone. Next, the distribution of these trips between zones is predicted and an O/D (origin/Destination) matrix is created. The next step in the decision making process is choosing modes of travel. The Whole process finally ends by assigning trips to networks and estimating the traffic volume on each segment of the network. The serial nature of the decision process is questionable and somewhat undermines the reliability of the whole UTP model. It should be possible to feed-back into the trip distribution, mode split, and trip assignment processes the results of the first iteration such as the link travel times to recalculate the new volumes in the network.

In the recent 20 years, researchers have improved many of the deficiencies of the early UTP models. Feedback loops were integrated into the 4-step models and more sophisticated algorithms for route choice and traffic assignment were developed. However, transportation planners came to realize that the focus on providing roads and services is not the answer to the traffic problems. Managing travel demand is increasingly important. More integrated land-use/transportation models were considered useful in supporting travel demand management. Modifying existing land use for the purpose of reducing travel

time and the number of trips became more of the issue. This necessitates the creation and management of large, comprehensive databases that comprise land use information as well as demographic data. The availability of very detailed off-the-shelf socio-economic and network information and the capability of GIS to integrate and manage land use information, demographic data, and detailed address information shifted the focus in recent years to GIS for building these travel demand management tools.

However, integrating traditional transportation models with GIS is a complex process. These complexities are attributed to differences in network representations, in handling intersections and shape points, and in data structures. Following are some of the major differences between transportation models and GIS requirements:

1. *Connectivity:* GIS in general builds topological relationships between spatial objects based on their geometric relationships. The topological relationships that a GIS builds include information related to connectivity, adjacency, closure, and nestedness. Connectivity is probably the most important topological feature that differentiates transportation applications from GIS ones. Most GIS tools work with 2-D representation of space. Hence, they assume connectivity whenever two lines cross and create a node everywhere such two lines cross. In other words, GIS assumes a connectivity relationship between any two crossing lines while in transportation applications this might not always be the case. Overpasses, for example, are represented by two crossing lines and a node at their intersection while in fact no connection may be allowed between these roads.

2. *Difference in Network Representation:* One of the differences between transportation network and GIS network representations is related to the link/arc connectivity. In a transportation model, it is imperative to have one and only one link connecting a pair of nodes. In a GIS, however, it is very common to see more than one arc connecting a pair of nodes. In reality, when more than one street link exist between two intersections, pseudo node are created along these links to ensure that no more than one arc exists between such pair of nodes. Using a GIS network in a transportation package would hence require the splitting of all arcs and the addition of new nodes on all arcs that violate the above rule. On the other hand, when the geographic representation of a network is used for running network algorithms, the shape points or vertexes used by the GIS to represent the geographic location of networks accurately might be problematic. Generalization of GIS networks is required for running these algorithms more efficiently. The issue here is that GIS provides the ease of representing good geographic relationships but lacks the flexibility to transform or otherwise relate to other topological or network representations that facilitate modeling.

3. *Limited ability of one representation to serve all purposes:* Different transportation models and purposes require different network representations, non of which is a simple geographic model. Even when the network is encoded in a GIS to suit the transportation algorithms requirements, the representation used for one transportation model might not be convenient for all other transportation models. In other words, there is no one graphical representation that can serve all purposes and the ability to transform the GIS network representation into the transportation modeling one is quite limited.

2.2.2. GIS for Management and Operation of Highway Transportation Systems

In this part of this chapter we review the literature that deals with the use of GIS in highway transportation management and planning. We cover articles from Fletcher [1987, 1990], Lewis [1992], AASHTO [1990, 1991, 1992, 1993], and Transportation Research Record [1992, 1994]. Since GIS is a "powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world," [Burrough 1986] it is expected that all applications at a transportation agency that require collecting, storing, and manipulating spatial data to benefit from GIS. In other words, all inventory data collection and maintenance activities at a highway transportation agency are prone to utilize GIS.

The applicability of GIS to address transportation problems is related to the many capabilities that GIS are equipped with. The capacity to analyze transportation networks is probably one of the most important capabilities. These capabilities include:

1. *Managing and Manipulating Networks*: A GIS is able to modify, update, and correct spatial and attribute data related to transportation networks. When nodes (street intersections) are moved, for example, the GIS maintains the topological relationships (connectivity) between the arcs (street segments).

2. *Display of Network Attributes*: Displaying data related to roads, such as pavement type, width, and condition, by pointing to intersection and roads on the graphic display is an important feature of a GIS.

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3. *Spatial Analysis:* The capability to create buffers around street links (linear features) and bus stop (point features) in order to, say, count the number of residences or jobs within the buffer region by using a demographic layer of information developed independently from other sources are very useful for transportation planning analyses. Such overlay capability is another feature that many GISs normally have.

4. *Routing Analyses*: In transportation applications, finding the shortest or preferred path between an origin and a destination (optionally with intermediate stops and barrier locations) is a very common operation. Allocating resources from a center to serve an area represented by a linear network is another common operation. GIS is capable of performing both operations.

5. *Georeferencing*: A GIS is equipped with tools for address-matching and geocoding. Textual description of addresses are converted to x,y coordinates data by referencing those addresses to a geocoded street network that has address ranges attached to it. Georeferencing, for example, is a useful tool for generating pin maps of bars and night club locations that are used in drunk-driving or safety analysis types of studies.

6. *Tying Relational Models to Maps*: GISs have the capability of connecting to third party relational database managers (RDBMS). Large database are usually hard to analyze but the link of those databases to maps allows the improvement of their effectiveness.

Fletcher and Lewis [1990] identify a list of applications at transportation agencies

that can benefit from GIS. These applications are related to the fields of highway, traffic engineering, public works, school busing, and others. These applications include:

1. Inventory of roads
2. Bridge management
3. Pavement management
4. Accident analysis
5. Highway safety analysis
6. Traffic signal management
7. Traffic engineering system studies
8. Facility mapping and management
9. Solid waste planning
10. Landfill planning and management
11. Route planning
12. School redistricting
13. School bus routing and scheduling
14. Airport noise abatement
15. Emergency response
16. Hazardous material routing

From the above list, applications that require storing and managing inventory information that relate to transportation objects are usually the ones mostly adopted by transportation organizations. For example, one of the early applications of GIS by transportation DOTs is pavement management systems. These systems traditionally store hundreds of attribute information that relate to thousand of miles that many DOT are responsible for. The capability of GIS to store huge sets of information and to display the results of queries on screen made GIS a good tool for building pavement management systems.

Early GISs, however, were not optimized to handle properly linear spatial objects such as roads and routes. The basic geometric elements that early GISs supported

were restricted to arcs, nodes, and polygons. Transportation applications usually deal with more complex spatial objects, such as routes, that employ a multitude of reference systems. Not until recently, when the "dynamic segmentation" capability that supports these requirements was introduced, have GISs became efficient in dealing with transportation applications. Dynamic segmentation is a method for referencing point or linear attributes along routes based on linear referencing systems that are independent of any road network segmentation. It also allows efficient storage, manipulation and overlay of multiple attributes along routes [Dueker, 92].

One important factor contributing to the recent use of GIS by many transportation organizations is connected to the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. All States and Metropolitan Planning Organizations (MPO) are required by ISTEA to implement seven management systems. The systems are: (1) Pavement management; (2) bridges management; (3) safety management; (4) congestion management; (5) public transportation facilities; (6) intermodal transportation facilities; and (7) traffic monitoring. The primary purpose of these systems is to improve the statewide and metropolitan transportation planning. These systems are also intended to enhance the efficiency of existing and future transportation infrastructure and to protect investments in the nation's transportation systems.

New technologies that help the Nation in moving into the "21st century transportation" are allocated special funds in the ISTEA. Magnetic levitated trains and Intelligent Vehicle Highway Systems (IVHS) are examples of these technologies. GIS is not explicitly recognized in the ISTEA as one of these new technologies. However, it clearly is a supporting technology that is essential in

improving the transportation planning and operation processes. The implementation of these management systems, however, is not a simple process. This is caused by: (1) the lack of specific descriptions of the characteristics of these systems; (2) the absence of guidance for the methodologies involved in the implementation; and (3) the technological complexities related to integrating different systems, models, tools, and data together.

GIS has many capabilities that are instrumental in the implementation of the ISTEA management systems. These systems require the creation of large databases that can be used as a decision support tool for decision makers. The sources of these data are generally very diverse which adds to the complexity of creating and especially maintaining these databases. The capabilities of GIS to manage, manipulate, and query large spatial and attribute databases coupled with its capability to integrate data from different sources make the GIS like technologies a key element in the implementation of the management systems.

In ISTEA, the likely necessity to use information technology at all levels of governments for making decision related to all modes of transportation is well recognized. Since GIS is the best tool for linking transportation and geography, GIS becomes a strong technological foundation for building such decision support systems. The power of GIS in capturing, processing, and analyzing large transportation databases offers the opportunity to adopt GIS as the platform for building the ISTEA management systems.

2.2.3. Use of GIS in Transit Planning

Before discussing GIS in transit planning it would be useful to review the evolution of transportation planning in the US and especially transit planning. Menendez and Cook [1990] provide a good overview of how transportation planning has evolved and how its focus changed over the years. Transportation planners have adopted different transportation planning solutions in different eras. In order to evaluate a transportation system, different approaches were adopted depending on the institutional and political environment and the availability of adequate technologies.

2.2.3.1. Evolution of the Transportation Planning Process

One approach that was mostly used in the early 50's and 60's and then modified in the 70's focused on comprehensive transportation studies for metropolitan areas (such as the Chicago area transportation study). In the 50's and 60's, the highway solution was adopted for increasing accessibility to urban areas and reducing congestion, and in very rare cases the transit or bus solutions were considered in this process. In the 70's, under the effects of the National Environment Policy act and the pressure from groups who mistrusted the government planning capabilities, the highway solution has shifted towards the transit solution within the comprehensive planning process. In the early 80's, transportation planning focused mostly on small area improvements and on enhancing the capacity, safety, and efficiency of existing infrastructure. Later on, this process broadened its scope by including the demand management concept, such as ride-share programs and high occupancy vehicle (HOV) lanes, and the Transportation Systems Management (TSM) approach was introduced. [Menendez and Cook, 90] and [Weiner, 87].

The evolution of the transportation planning process and the several phases that it went

through are related to changes in the institutional context. In the 50's and 60's, the transportation modeling which focused on forecasting demand and providing highway capacity to meet this demand, was carried out on large mainframe computers. Mainframe computers were very expensive and available only in central government offices. As a result the planning process became very centralized.

In the early 70's the centralized process continued but the evaluation criteria of transportation systems started to change. Travel demand included transit and bus demand in addition to highway demand. Efficiency is no longer the only measure utilized in transportation models. "Social, economic, and environmental impacts were explicitly considered and included in decision matrices along with traditional system costs and benefits." [Menendez and Cook, 90]

In the early 80's transportation modeling became less and less centralized. The focus shifted to small area improvements such as analyzing detailed intersection and the effect of local transit. In other words, the process changed from being regional to becoming more localized requiring less coordination by the central government. This was also supported by the availability of Personal Computers (PC) which enabled the use of a host of new tools for transportation planning and project evaluation replacing the regional models with site impact analysis and corridor studies.

In the late 80's, transportation planners came to realize that the local improvements will not solve the larger area transportation problem. Consequently, the very localized focus of studies was dropped and a return to larger metropolitan area focus occurred with a special concern related to larger scale policy issues. Such policies, however, were not very easy to formulate and implement at the regional scale especially when the transportation planning process is still carried out in isolation of land use, zoning,

environmental, or other planning policies.

Ferguson [1994] predicts that in the 90's the "UTP modeling will open up to embrace innovation more widely and more significantly in response both to externalized necessity (federal planning requirements and local and state fiscal austerity) and internalized desire (greater flexibility in investment decisions and more broadly based citizen participation) under ISTEA." Furthermore, the need to address the local and regional transportation problem and to innovate new planning methods that involve the participation of several agencies and the coordination of multi-agency objectives necessitates the creation of transportation planning infrastructure capable of catering for all these needs. "The new modeling tools needed to handle this task are already available. They include database and toolbox structures, GIS database sharing potential, and zoom capabilities adapted to the more powerful microcomputers. It will be up to transportation planners of the 1990s to use these tools to create the open, coordinated transportation planning process of the future." [Menendez and Cook, 90]

2.2.3.2. GIS in Transit Planning

The literature on GIS in transit planning is not as extensive and comprehensive as the one on highway management and operation. The number of researchers investigating the use of GIS in transit planning is limited compared to other transportation fields. To date, little research has focused on GIS applications in transit, compared with other, mainly highway-oriented, contexts. The "Geographic Information Systems (GIS) for Transportation" symposium, sponsored by AASHTO, is probably the most specialized and the largest conference on the applications of GIS in transportation. The proceedings of this symposium and the Transportation Research Records (TRR) of the Transportation Research Board

(TRB) are considered the best two references that show the latest developments in this field. Looking at the proceedings of this symposium and the TRR for the last 5 years, the percentage of GIS transit-related papers to all GIS-related papers in these references varies between 10% and 15%. This shows that little attention is paid to the field by transportation researchers.

In this section we cover a wide range of literature that represents almost every aspect of the research in GIS and transit. We first look at the areas of implementation of GIS in transit agencies covered by Azar and Ferreira [1991, 1992], Dueker [1990, 1991], Antonisse [1991], and Schweiger [1991]. We then look at the use of GIS for studying the relationship between transit and land use planning [Eberlein 1991], analyzing transit service areas [O'Neill 1992], and modeling transit accessibility [Grayson 1993]. Note that these papers are utilized as a representative sample of the research in this field.

The literature describes some of the potential areas of application of GIS in transit. Dueker, Antonisse, and Schweiger include the following in their lists of GIS applications:

1. Mapping products
2. Service planning
3. Ridership forecast
4. Market (demographic) analysis
5. Facilities and real-estate management
6. Scheduling and run-cutting
7. Customer information systems
8. Ridematching (Van or car pool)
9. Transit pass sales
10. Fixed-route transit dispatching
11. Automatic vehicle location (AVL)
12. Paratransit dispatching and scheduling
13. Police operations

Mapping products generally refer to drivers maps showing directions along routes and customer maps showing stops along routes.

Service planning is the process of designing or modifying a bus route structure, its headways, the location of its stops and its service type (local versus express). Ridership forecast refers to the process of predicting and analyzing the level of transit travel in specific corridors and the patronage on individual routes. It is usually part of the 4-step UTP model. Market analysis, on the other hand, is the examination of the socio-economic conditions in relation to the alignment of specific transit routes and the modification of routes characteristics based on these relations.

Keeping track of all inventory information that relates to facilities owned by a transit agency such as stations, lots, stops, and signs is known as facilities and real estate management.

Bus scheduling is the method for assigning buses to routes whereas run-cutting is for assigning drivers to buses and routes.

Customer information systems are also known as trip planning systems. They are telephone-based systems for informing prospective riders about bus or train schedules and stops or stations locations. Ridematching, on the other hand, are programs for informing participants about other participants in their neighborhoods who have similar work destinations and wishing to share rides with them. Optimization software are usually used for finding the most efficient routes for combining riders with common origins and destinations.

Automatic vehicle location applications refer to monitoring locations of buses in real-time. Signpost and odometer technologies are usually used for these applications. They also serve as information feeders to other applications such as the customer information systems in some cases.

Paratransit dispatch applications are those activities where special services with special vehicles are provided for handicap and elderly people. Services are provided for pre-scheduled trips. Assignment programs are used for finding optimal paths between several origins and several destinations with different pick-up and drop-off schedules.

Transit police operations include crime analysis, dispatch of nearest patrols to accident locations, and response to riders complaints.

The application of GIS in all of the above applications is related to the geocoding, overlay, buffering, and the route data structure that GIS can provide transit planners and operators with. These powerful GIS features have the potential to accelerate and automate many of the manual processes required by the above applications. Antonisse [1991] gives several generic examples of such processes:

1. "Determining the total population which resides within a given distance of transit route or station.
2. Producing transit system and route maps which are mutually consistent and accurate with respect to underlying street geography.
3. Determining the most direct transit route, through the use of a network minimum path algorithm, between the origin and destination of an individual customer's trip
4. Reporting the number and location of bus stop facilities in

need of immediate repair and developing a minimum-travel-cost itinerary for a maintenance crew to service them.

5. Performing an analysis of demographic trends across the service area in an effort to discover locations of high ridership potential which deserve introduction of new transit services."

Dueker et al. [1990] point out one major difference between transit applications and highway applications. Transit applications are more dynamic than highway applications. One of the interesting applications identified in their paper is the use of GIS in fleet management. GIS technologies in conjunction with AVL (automatic vehicle location) technologies can be used to manage and monitor transit fleets. However, the requirements of this application place unique demand on GIS technologies. Fleet management is characterized by its dynamism. Buses are always moving and routes followed by these buses are not always static. However, these changes occur at different cycles. Changes in bus location are continuous whereas changes in routes layout are not quite as often. Fleet management requires the integration of data by time and location. In this application, GIS serves as a data integrator and as a tool for visualizing the location of buses in space.

Eberlein et al. [1991] examine the use of GIS for analyzing the relationship between land use and public transport usage. In this study, some land use factors that influence transit usage that are provided by the Institute of Transportation Engineers [ITE, 1989] and Pusharev and Zupan [1977] are tested in Washington DC. According to the ITE, transit use is dependent on residential density and employment density. Transit use is minimal at residential densities between 1 and 7 units per acre. It grows with increase in residential density to the extent of exceeding auto trips at densities above 50 - 60 units per acre. Similarly transit ridership is observed to increase remarkably at employment densities exceeding 50

employees per acre. Pusharev and Zupan identify another factor influencing transit use: "within a walking distance of 6 minutes or 0.3 miles to a rail station, half of commuters or more will prefer transit."

The overlay capabilities of GIS are used in this study to examine the distribution of major residence and employment centers in the National Capital with respect to transit lines. Employment and residential densities are compared to distances from transit rail lines. Recommendations concerning land use policies in Washington DC are then made. Suggestions of where future development needs to take place in order to meet the ITE and Pusharev's minimum density requirements are also made. Although the theoretical bases of this research are not very solid, it shows the type of analysis that can be done using tools such as GIS that are capable of measuring densities and analyzing their spatial distribution with respect to transit lines.

O'Neill et al. [1992] analyze different methods for defining a transit service area using a GIS. A transit service area is defined as the region that is served by a specific transit line. It is usually defined using walking distance (1/4 to 1/2 mile) or walking time. O'Neill compares the usual method of buffering around transit lines or transit stops with more sophisticated GIS procedures for defining transit service areas. She compares the *area ratio* method that is typically used to estimate population in a buffer area around a transit line to the *network ratio* method. In the *area ratio* method a uniform distribution of population within the area of analysis is assumed and the ratio of the area of polygons formed from the intersection between the buffer polygon and the analysis zone polygons to the initial area of analysis zone polygons is used as a weight value for estimating population. In the *network ratio* method it is assumed that the number of houses on

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a street is proportional to the street length and that houses are uniformly distributed along those streets. The population in a service zone, as a result, is proportional to the ratio of the total street miles within the buffer to the total miles of streets in analysis zone polygons.

The network ratio method is shown to be more accurate in residential and modified grid street network area for estimating the number of households in a transit service area. However, in mixed residential zones or zones with retail, industrial, or recreational activities, this model is not very accurate but not less accurate than the area ratio model. The inaccuracy of this model in these zones is attributed to the non-uniform spacing of houses along streets especially in areas of mixed land use. The point of this research is that the simple coverage overlay operation does not necessarily yield accurate and good numbers. Analysts have to use their own judgment to decide which spatial operation is appropriate for which analysis.

Grayson [1993] describes a model for estimating and visualizing transit accessibility, i.e., travel accessibility provided by public transport, in urban areas. In his thesis, Grayson first designs and implements a method for converting textual description of transit routes and networks into digital form suitable for analysis. He uses the address matching and geocoding capabilities of GIS to convert street intersection and landmark text-based information into geographical locations on a digital street network file and then utilizes the path-finding tools of GIS to extract the links between these locations and create the transit network.

The second tool developed by Grayson is the accessibility analysis tool. He implements a prototype accessibility analysis tool with graphical display-and-

query functionality. The methodology he adopts for analyzing accessibility requires the collection and processing of large amounts of data. The model uses a street network base map, a transit network base map (created by the above method), and service quality data, such as headway and speed, for each transit route. Grayson utilizes the relational database management capabilities of GISs to perform his accessibility analysis. The network representation of transit routes is converted into relational representation, the service quality attributes of routes are loaded into the GIS relational database, a path-finding program that utilizes all these relational databases is run to find all the paths between all pairs of origins and destinations in the network, and finally another program computes an accessibility metric based on the paths found in the previous operation. The value of Grayson's research is in showing the advantages of using linked GIS, relational database management tools, and custom programs that access each system for transportation network analysis and transit accessibility and the extent to which complex accessibility issues really matter in capturing rational rider behavior.

2.3. Computer Applications and Modeling in Transit Agencies

In order to properly implement GIS capabilities in transit agencies, it would be useful to first investigate the computer applications and modeling efforts at these agencies. We shall look at the type of computer applications used in transit operation activities, such as scheduling, run-cutting, and ridership estimation, in paratransit planning and operations, and in transportation planning in general. We then look at the different modeling efforts especially in transit ridership forecast.

A couple of reports prepared for the Urban Mass Transportation Administration

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(UMTA) in 1984 and 1985, now known as FTA (Federal Transit Administration), summarize the applications and software used by transit operators in the US [UMTA, 84] and [Wyatt, 95]. One would expect that many more applications or software should have been introduced since, but our experience with several transit agencies, such as the MBTA, shows that the findings of these reports are still valid, although the nature of the tools and the extent of their use might have changed. This is also evidenced by more recent publications in this area [Kravif, 91], [Varanasi, 93], and [Lessard, 93]. We shall use the above reports and publications to describe the most common types of computer applications utilized by transit agencies in the US.

2.3.1. Transit Operation Applications

Transit operations are quite complex and hence require sophisticated programs to do all the operation functions in a transit agency. These applications include scheduling and run-cutting, bus stop and route inventory, time-keeping, cost estimation, and other miscellaneous applications. Transit scheduling and run-cutting are those activities that relate to developing schedules for operating transit vehicles. Run-cutting is the process of organizing all trips into runs. Computer applications are developed to solve many complex algorithms involved in scheduling and run-cutting operations. These algorithms are needed for determining the blocking of vehicles, such as first-in first-out, manipulating headways, and assigning drivers to buses. The earliest software used for these operations was RUCUS, developed by VISTA systems, San Diego. Many add-ons to this software were later developed and are still being used by many transit agencies. HASTUS is another software that is also adopted by several transit

operators. It is marketed by GIRO, Quebec, Canada.

The other operation activity that computerized systems are used for is the bus and route inventory systems. These systems are used to maintain information on bus stops such as location, stop number, route number, boardings, alightings, and amenities at each stop. In small agencies, the computer models used for running this operation consist of spreadsheets, basically. In large agencies, where the facilities to be maintained are quite large and numerous, database management tools are utilized for storing, manipulating and querying all the above inventory data. In the early 80's many of those database management tools were created in house using local programmer. Recently, more sophisticated and powerful generic database management tools are bought to replace or compliment the old legacy inventory systems.

Time-keeping is another application assisted by various tools and models. The level of use of technology in this application also depends on the size of the agency. Small transit operators use spreadsheets to calculate time paid for each piece of work and then the information is transferred manually to payroll. In larger agencies, the system utilizes large DBMS with network connection to payroll databases and tools for automatic calculation of all time paid for each task.

Transit agencies have also developed tools to estimate future revenues and expenses. These tools are used to allocate expenses to different level-of-service variables such as weekday vehicles, revenue vehicle miles, or revenue vehicle hour. These tools are also used to estimate future year units and total costs based on estimates of price changes and expected level-of service. The tools are also used to estimate future revenues based on current revenues and estimates of future

years changes. Elasticity models are usually utilized to estimate passenger fare revenues based on historic passenger count and fare data. Many specialized software are developed for all these tasks and most of the large operators have acquired similar tools for performing these operations.

2.3.2. Paratransit Planning Applications

Transit agencies are interested in developing computerized paratransit planning tools to assess the effectiveness of different alternative transit and paratransit services. These tools are capable of estimating ridership and the associated cost of providing different types of services (such as dial-a-ride, charter, fixed-route, or taxi) to different markets (such as elderly or handicapped) by different trip types (such as work, recreational, or shopping).

Some of these paratransit planning tools are highly sophisticated. They are capable of processing requests for services, scheduling trips, and generating management reports as well as generating drivers manifests. Some of the packages used for performing these operations maintain client files, including travel history, for immediate verification of customer eligibility. Service scheduling algorithms are encoded in these packages to create vehicle tours. These algorithms use information related to locations (origins and destinations), time, and pre-scheduled trips to determine the most effective tour that a vehicle has to follow.

The most comprehensive vehicle scheduling packages are capable of evaluating and designing route allocations and schedules. Their database management tools allow the manipulation of data for transport units, number of available vehicles,

route time and speed, and cost per unit time. They use optimization algorithms or heuristics to determine the least costly schedules. These systems are also capable of generating summary cost and route reports for management.

2.3.3. Ridership Forecast Modeling

Models developed to forecast ridership on transit routes are generally classified under two categories: (1) the Urban Transportation Planning System (UTPS), also known as the 4-step model, and (2) Direct demand or regression models. Most of the transit agencies in the US have implemented one or both models in order to estimate ridership on the their route and to evaluate the performance of their systems, corridors, or individual routes. The UTPS model is generally utilized for long-range, regional transportation planning efforts whereas the regression models are used for short-range, route-specific ridership modeling efforts [Horowitz, 84].

The UTPS model utilizes two sets of networks: a street network, utilized by cars, and a transit network, utilized by transit vehicles. The street network consists of all streets in a study area whereas the transit network is generally a subset of the street network and consists of all transit routes (in addition to rail lines in cases where rail exists). The four-step modeling process, i.e., trip generation, trip distribution, modal choice, and trip assignment, is applied to determine the level of ridership on individual transit routes. A large number of computer packages are used for running the UTPS model and different agencies are using different models.

Regression models are used to estimate ridership on specific routes based on their characteristics and the demographic and economic conditions of areas around

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these routes. These models are also classified under: (1) cross-sectional models or (2) time-series models. Some of the models are a combination of both. Cross-sectional models assume that the relationship between the characteristics of transit service, the socio-economic conditions, and transit ridership, over different bus routes of the same type, are constant. These models are first developed for routes with known characteristics and ridership data and then applied to routes with similar conditions to estimate ridership on these new routes.

The time-series models, on the other hand, are usually used to forecast variation in ridership over time. These models integrate the time factor into the regression analysis by using historic data related to transit ridership and route socio-economic characteristics. The early performance of routes are used to project future performance and ridership information. Many transit agencies have developed their own computerized regression models for conducting market analysis and route ridership forecasts.

2.3.4. Other Areas of Computer Applications

In addition to the above areas, computer technology is utilized in several functions in a transit agency. Computers have been most widely adopted in transit agencies for financial functions. The financial tasks that computers are usually utilized for include budget development, deficit allocation, cash management, fare revenue projection, fixed asset inventory, accounting, and payroll.

The other area of use of computer technologies in transit agencies is the maintenance and inventory applications. These applications include tire inventory,

oil analysis tracking, advertising management, parts inventory control, maintenance management and purchasing. Computers are also used in administration and human service applications. Administration applications include document preparation, personnel records, operator records, pass distribution administration, accident records, claims tracking, labor bargaining, and data transmission. The human service applications include client registration, booking and scheduling, and client billing.

Many of the more technologically advanced transit operators have also developed or adopted what is known as the "executive information system." These systems are computerized packages that allow managers to conduct daily and monthly monitoring of the performance of a transit system. These systems receive information primarily from AVL systems that are mounted on all vehicles and from dispatch and driver scheduling software. These systems are usually based on the concept of "management by exception." Any performance variation is immediately flagged out to the managers in order to take appropriate actions.

Finally, in Varanasi's report [1993], prepared for the American Public Transit Association (APTA), a total of 600 software applications are listed as being used for different applications in various departments of all transit operators in the US. This shows that the level of computerization of transit agencies is quite high and the extent of use of computers for modeling efforts in these agencies is quite large.

2.4. Recent Developments in Information Technology

The last body of literature that this chapter deals with is information technology

(IT) and the recent developments and trends in IT. After reviewing the use of GIS in transportation planning in general and in transit in particular, and the use of computer technologies by transit operators in the US, this section reviews the trends in development of information technology. This body of literature will provide us with necessary information to forecast the impact of these technologies on current GIS and the changes to the problem-solving approach adopted to address the complexities of implementing a GIS in a transit agency. In the previous section we discussed the evolution of the transportation planning process in the US since the 1950's and we talked about the need to create the proper transportation planning infrastructure in the immediate future. In this section we discuss the technological advancement that specifically have an impact on the multi-agency data sharing and collaboration that are needed for supporting such consolidated transportation (and transit) planning environment.

In examining the trends that are significantly influencing the evolution of IT in the 1990s, "The Management in the 1990s Research Project," conducted by the MIT Sloan School of Management and representatives of major corporations [Morton, 90], stated the following theme as one of its major findings:

> "Advances in information technology provide opportunities for dramatically increased connectivity, enabling new forms of interorganizational relationships and enhanced group productivity."

In this section we review some of these advances. The technological developments that occurred in recent years were manifested in several aspects: (1) hardware development; (2) system architecture; and (3) software development. Hardware development is characterized by the introduction of cheaper and faster machines and new hardware architecture such as the 64-bit computing and the massively

parallel processing architecture. The client-server architecture is the recent trend in system architecture. It is also described in the literature as the system architecture of the future also. Object oriented databases and object orientation in general, be it at the programming language level, the database management tools, or at the software structure, are the other important features of recent IT development trends.

The MIS (Management of Information Systems) literature covering this area is quite extensive. Most of the MIS publications in the late 80's and the early 90's dealt with the impact of information technology on the organization and the competitiveness of firms. The most recent and state-of-the art technologies are depicted in these literature and ways of integrating those technologies into old systems are also analyzed. In this section, we review some of the major MIS references to summarize the recent trends in IT development [Morton, 89], [Gunton, 89], [Edesomwan, 89], [Morton, 91], [Harvard Business Review, 91], [Keen, 91], [Weizer, 91], [Banker, 93], [Harry, 94]. We specially rely on the book, "Information Technology in Action" Edited by R. Wang [Wang, 93] to describe some of these trends in this section.

2.4.1. Trends in Hardware Development

Speed and affordability are the major changes that properly characterize the trends in hardware evolution over the last few years. The Arthur D. Little Forecast on Information Technology and Productivity [Weizer, 91] predicted in 1991 that the performance-price ratio of computers will increase nearly tenfold in the 1990s. As a matter of fact, the price of a MIP (Millions of Instructions per Second) on

personal computers (PC) dropped from around $10,000 in 1985 to around $1,000 in 1991. Similarly, "in 1980, IBM's top-of-the-line computers provided 4.5 MIPS for $4.5 million. By 1990, the cost of a MIP on a personal computer had dropped to $1,000, driving the trend toward distributing computing power, instead of relying solely on large central machines" [Keen, 91]. Information technologist are projecting this trend to continue, at least in the coming few years, at the same rate and hence the performance-price ratio is predicted to increase another tenfold between now and the end of the century.

In hardware architecture the recent introduction of the 64-bit computing environment will basically have a great impact on computer speed and price. Previously, the 64-bit architecture were utilized by supercomputers only which were too expensive to the average user. Recently, 64-bit computers are becoming available for under $10,000 [DEC, 95]. The processing capacity of 64-bit computers is so large that future applications will no longer consider the usual 32-bit addressing issue as a limitation.

Another important example of development on the system architecture front is the massively parallel processor (MPP) architecure. The MPP technology is moving from being used by engineering and scientific applications in the 1980s into commercial applications in the 1990s. This development is caused by the maturing of the technology which removed many of the impediments blocking the use of MPP in commercial systems. In the traditional programming models, the hardware usually executes instructions in a serial fashion. In a MPP computer, large number of processors (up to thousands of them), each with its own independent memory, communicate with each other using a network of interconnections to divide the workload over many processors and execute thousands of instructions at the same

time, in a parallel fashion. The traditional problems with implementing machines with thousands of processors are related to communication between processors, transfer of huge data between storage media and processors, and the availability of programs that take advantage of the non-traditional uniprocessing architecture.

Recent developments succeeded in overcoming most of these difficulties. Furthermore, the advent of the client/server database technology enabled the implementation of MPP in commercial applications. In the client/server architecture, specialized applications such as the database management tools reside in a client computer. Commercial database software are very input/output intensive. Supercomputers do not usually excel at these applications. The MPP configuration allows the efficient handling of input/output intensive operations better than supercomputers. Oracle corporation, for example, has adapted their database system to MPP technology and made it economically feasible to utilize.

The factors driving the GIS industry into adopting fast processing computers such as the 64-bit architecture computers or the MPP are related to affordability of fast computers, growth of GIS databases, integration of remote sensing and high resolution imagery into GIS applications, and the complex analysis of large databases. As mentioned earlier, the performance-price ratio is increasingly getting higher and higher. Databases used or generated by GIS usually grow at an unexpected rate. Furthermore, remote sensing and image processing techniques, using high resolution satellite imageries, are routinely used to create basemaps of GIS projects. Processing large databases, such as these high resolution images, requires complex analysis and sophisticated algorithms that can run efficiently on fast machines only.

2.4.2. Developments in Systems Architecture

Distributed computers and networking have made certain forms of distributed computing practical. The most important architecture with respect to transportation is probably the client/server. The client/server model is regarded as the effective combination of mainframe computers and personal computers and workstations. Before the introduction of workstations, users were connected to mainframe computers via dumb terminals which had no processing power of their own. The mainframe handled all data processing and information management. Consequently, when computer use increased, the mainframe capacity became overburdened, and the access time degraded.

In the client/server architecture, the centralized processing power of the mainframe is distributed over several machines (clients). Instead, a host computer (server) provides services and data to client computers. The client computer, unlike in the mainframe architecture, has a lot of processing power and handles many functions, such as front-end computing, organizing data, and manipulating display, in order to reduce the time spent moving data and code to and from the server. The server handles all processes that are not efficiently managed by the client such as database management, security checks, and network coordination. The server also supplies all data and computing power needed by a server to perform a certain task. In other words, each of the servers and clients share the logical handling of a task in an efficient and effective fashion.

Schussel [Wang 93, Chapter 3] summarizes the benefits of the client/server computing. Some of these benefits are:

1. *Cost Savings*: The cost of computer instruction cycles on micro-processor based computers is much cheaper than on mainframes.

2. *Scalability*: Because of the modular nature of client/server architecture, networks can be easily expanded by adding more nodes.

3. *Robustness*: "Client/server approaches are based on SQL relational DBMS servers and offer all of the robustness, security, and data integrity of the mainframe environment."

4. *Interoperability with the desktop*: As Windows becomes a standard on the desktop, client/server applications, such SQL queries, can be coupled with desktop applications using the Windows' clip-board functionality, for example.

Distributed database management DBMS architecture is the other trend in architecture development. Distributed DBMS and client/server architectures are very similar in many aspects. In a typical client/server model, the database resides on a server computer whereas the database management tools run on client computers. In a distributed DBMS architecture, data are not necessarily residing on the same server whereas the DBMS resides on each node in the network allowing transparent access to all databases on the network. In the client/server model, users have to worry about the physical location of each database, whereas in the distributed DBMS users are not required to navigate physically to the data. With a distributed DBMS, remote procedure calls (RPC) are directed to the server and the query optimizer for SQL on that server takes care of the physical database locations.

Locational transparency is not the only requirement/characteristic of distributed DBMS. Schussel [Wang 93, Chapter 3] lists other characteristics of distributed DBMS. They include: performance transparency, copy transparency, transaction

transparency, fragmentation transparency, schema change transparency, and local DBMS transparency. We shall not discuss all these "transparencies" in this section but suffice to say that they are to ensure that the distribution of databases over several nodes on the network does not affect the performance of database managers nor the integrity of databases.

2.4.3. Trends in Software Development

The most important advances in software development are probably related to object orientation and the creation of software applicable to parallel processing platforms. Parallel processing is not really a new concept. It was first developed in the 1970s. The Illiac IV was one of the first parallel processing systems. One of the major obstacles to using these systems was the lack of software that is applicable to these platforms [Faust et al., 1991]. The algorithms for parallel architecture are different than those for sequential machines. The adaptation of parallel architecture algorithms to sequential machines is possible while the converse is not always true. The typical sequential algorithm must be redesigned to take full advantage of the parallel architecture. The basic concept of parallel processing is to decompose a problem into units that may be solved in parallel by several processors while the sequential algorithm solves a problem sequentially, one unit after the other. There are several ways of decomposing problems, and different decompositions lead to different implementation of parallel architecture. The point is that for GIS technology to take advantage of the parallel processing development in hardware technology, the sequential algorithms must be redesigned. Recently, the research in GIS technology has started exploring this area. Future GISs will certainly benefit from these software developments

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[Hodgson et al., 1995].

The other important trend in software development is object orientation. Object-oriented technology has become one of the major forces driving the IT industry in the past several years. Object orientation is manifested at two levels: (1) object-oriented programming systems (OOPS) and (2) object-oriented databases. OOPS are developed to address the issues of improving the quality of software and the efficiency of software development. In an OOPS, programs are developed using a building block approach. Each block is called an object. Each object can run on its own without necessarily being dependent on other objects. Objects can be changed without really affecting others, as a result. Objects are reusable in different programs and entire systems can be built using existing objects.

In a program, objects pass information between one another. For example, one object that performs one function can link to another object that uses the results of the first object to perform another function. The first object does not need, for instance, to know how the second object performs its functions. Each object contains information about itself and this is known as "encapsulation." It also contains information about other objects that it can link to. This is known as "inheritance".

Object oriented techniques are impacting the operating system, the programming language, the applications, and the database management tools. Many GIS vendors have started taking advantage of this development by converting their codes into object-oriented code and by implementing object-oriented programming languages that facilitate the handling of complex data structures that are typical of GIS applications and more importantly, help allow multiple representation of spatial

features to be used in the particular applications that best suit them.

The other important aspect of object-orientation development in recent years is the object-oriented databases. Some IT specialists are speculating on the replacement of relational databases by object-oriented databases, the same way relational data model replaced the network model. These speculations are based on the fact that although relational DBMS have increased the speed and ease of user access to data, they do not provide proper support to handle complex entities such as the ones used by graphical engineering software including GIS. Object-oriented DBMS are based on an approach that accommodates the storing of complex entities and operations.

In an object-oriented database, the objects are data structures that meet the encapsulation and inheritance characteristics. They contain descriptions of entities as well as the operations that can be performed on these entities. These complex database capabilities are usually demanded by programs that frequently access and modify complex objects, such as CAD and GIS software. According to Weizer [1991], traditional databases are not effective at performing these operations because "they were designed to support typical business applications that require simple objects and a limited number of operations, such as insert, modify, and delete. Object-oriented database systems place operations alongside their related data within the database so applications can get to these operations without reimplementing them. Localizing complex operations within the database improves software maintenance by confining updates to one location. Both data and the operations allowable on them are immediately visible, making it easier for end-users and application programmers to work with the database."

In summary, the advances in information technology can improve the quality of the transportation planning process by providing the adequate information infrastructure for it. Since joint coordinated efforts between several agencies need to access a variety of geographically distributed databases, the ideal environment and infrastructure for transit planners to tap into these different databases can be characterized as follows:

- Heavy reliance on fast computing machines such as UNIX workstations.
- Sharing of data and basemaps among all GIS users in a transit agency
- Sharing of data and basemaps with outside agencies
- Easy access to outside data available on line such as off-the-shelf databases
- Easy access to high-speed processing power.

In the next Chapter we examine some of the areas of application of GIS in transit agencies. We review the activities of the different departments of a transit agency and discuss the benefits of using GIS in a few typical transit applications. Chapter 4 checks the universality of the findings of Chapter 3. It investigates GIS and digital data use and coordination of application by the largest US transit operators in order to identify and study some of the difficulties in evolving effective GIS capabilities in transit agencies.

Chapter 3

Areas of Application of GIS

in Transit Agencies

In Chapter 2 we reviewed the literature on GIS in transit applications. In that review we included a list of the potential areas of application of GIS technology in transit agencies. In this chapter we examine in detail some of these areas and discuss the improvements that GIS can provide. Then chapter 4 summarizes the results of a survey that examined the different aspects of use of GIS by the largest 30 transit operators in the US, including the areas where GIS is currently used. In this chapter, we limit our discussion to those areas where GIS might have a great impact. We intend by no means, in this chapter, to generate a comprehensive list of all applications of GIS in a transit agency, rather we use a few applications as examples of the type of applications that can benefit from GIS technologies. These applications will also serve to identify and classify the complexities encountered while implementing a GIS. Chapter 6 will utilize these applications, in addition to the three GIS prototypes described in Chapter 5 to illustrate the complexities

associated with using a GIS.

3.1. Introduction

This chapter is based on a proceeding paper that we published in 1991[2]. The paper was part of an MIT research project aimed at improving the ability of transit agencies to use spatially referenced data and computer graphics effectively. The research tried to identify and evaluate areas of applications of spatial decision support systems within transit agencies, and to identify and compare alternative data structures and systems design that meet transit agencies applications requirements.

As part of our research on the above issues, we have worked closely with the Massachusetts Bay Transportation Authority (MBTA) and the Central Transportation Planning Staff (CTPS) in Boston. Key officials in the different departments of the MBTA and CTPS were interviewed on several occasions in order to make a GIS user need assessment and to get an idea about the current practice in each department. We have identified particular applications of GIS and developed a matrix relating these applications to the data requirements, mapping and geo-referencing need, and observed system development strategies. The built matrix enabled us to examine commonalties in data structures between the different applications and to better understand the complexities related to data sharing and maintenance issues. These complexities were further accentuated when a second matrix relating the applications in each department to the hardware used was developed. Examining this matrix helped us also in identifying strategies for development of coordinated systems. Matrix 3.1

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[2] Azar K.T. and J. Ferreira Jr., "Standardizing Transit Applications of GIS Technology: A Corridor Study Example," Proceedings of the Urban and Regional Information Systems Association (URISA), Volume I, San Francisco, 1991.

shows a summary of both matrices. These issues are developed further in later chapters of this thesis. The survey that we summarize in chapter 4 used these findings and examined, among many other things, whether they apply to all transit agencies in the US or whether they are peculiar to the MBTA.

Matrix 3.1. Portion of Matrix Relating Transit Departments, GIS applications, Data Requirements and System Development Strategies										
(Selected Applications Within the MBTA and CTPS - 1991)										
		Required Data				Mapping & Geo-Referencing				
Depar-tment	GIS Application	Road Network	Route & Stop	Rider Count	Demog raphics	Address Match	Routing	Editing Bufferig	Overlay	Mapping and GIS Development Pathway
Planning (via CTPS)	UMTA reports & corridor Studies	Street Map (digitized locally)	Route Map digitized locally	Survey Data	Census Data	Not Yet	By Hand	By Hand & Computer	Visual Only	AutoCAD Street Maps & Routes; Spreadsheets & Flat Files; Macintosh Document Production; Arc/Info on SUN
Scheduling	Locate Garages; Link Routes	Street Map (Paper Only)	Generated Locally (Paper Only)			Not Yet	Main-frame computer	Not Yet	Not Yet	Turnkey, text-only package on mainframe for schedule analysis; No Mapping and GIS activities.
Marketing	Passenger Information System	Customized DIME file	Other Departments			main-frame computer	main-frame computer	Not Yet	Not Yet	Turnkey DIME-based main-frame package for address match & routing; proprietary & text only; MapInfo on PCs
Engineerig Real Estate	Facilities Inventory and Management	Engineering Maps (paper only)				Not Yet		Not Yet	Not Yet	Automated mapping and CAD; McDonell Douglas software on VAXstation 3100

In this chapter, we shall discuss some of the findings of the research, particularly the areas of use of GIS in transit agencies. A full description of the matrices is included in chapter 6 where complexities and generalities of GIS-based applications are discussed in detail. We also include in this chapter a description of the benefits that can be derived in using GIS in each of the identified applications.

3.2. Potential Benefits of GIS Use

As defined in Chapter 2, a GIS is a collection of computer-based tools that facilitate the storage, display, manipulation, and analysis of spatially (or geographically) referenced information. A GIS links the capability of generating maps on a computer or a paper with the querying functionality of a database. It integrates three aspects of computer technology: database management, routines for displaying and manipulating graphical data, and algorithms that facilitate spatial analysis [Antenucci, 1991]. One of the most important spatial analyses that GIS can perform is the overlay of several geographical layers of information and establishment of spatial relationships, such as proximity, intersection, and adjacency, between the geographical objects of these different layers. However, in order to perform such an operation, the geographic data should be reduced to the same coordinate system with the same spatial projection. Generally, GISs have the necessary tools for doing these geographic transformation of data layers.

The implementation of GIS in transit applications is perceived to be beneficial on several levels and in several aspects:

1. *Visualization:* The capability to see geographic objects on screen and to understand the spatial relationships between different spatial objects is one of the advantages of GIS. As we shall illustrate later in this chapter, many transit applications can benefit from the visualization tools that GIS have. The update process of the street centerline database that the passenger information system in the marketing department utilizes can become more efficient when network data are displayed on screen and overlayed on top of aerial photos or land use maps, for example. Visualizing transit routes with respect to the demographic and socio-economic

distribution of people in the city to assess the adequacy of existing services, is another example of GIS potential benefits.

2. *Automation:* GIS has the capability of automating many of the manual work conducted in transit agency. The benefits of automation can materialize when manual tasks can be reproduced on a computer in a more efficient and accurate way. For example, the manual process of creating a buffer around a transit route and intersecting it with a layer of demographic information to estimate ridership along that route can be automated in a GIS environment. Such automation would yield more accurate results and saves a lot of manual work.

3. *Improved Analytical Techniques:* Automation, in general, yields narrow efficiencies. The advantage of using GIS is more related to redefining or organizing basic works in ways that are not possible without automation. The real benefits of GIS can be derived when the GIS is used to re-engineer the old analytical processes in order to render them more efficient and effective. In other words, the benefits of automation are not as important as the benefits of creating new tools that take advantage of the spatial analysis tools of GIS that make certain tasks more effective. For example, in the corridor analysis, a GIS can be used to display information on the screen, perform spatial overlays, and calculate the areas of parts of polygons falling within a buffer. (We describe this application in detail later in this chapter and in Chapter 5). However, the GIS can be used in a more useful way and take the old process one step further. It can be used to build ridership forecast tools that can estimate ridership on routes based on different socio-economic factors. This will be also illustrated later in this chapter.

4. *Link to Outside Data:* The other potential benefit that GIS has, is the capability to

link to external databases. Changing the old analytical processes might require the use of additional information that are available from outside sources, such as standardized off-the-shelf databases or databases maintained by other public agencies. The fact that external databases are becoming spatially referenced, i.e. related to objects in space, the GIS would allow the integration of these databases with existing databases in the agency. Environmental, land use, traffic information, are some examples of these external databases that a planner at a transit agency can tap into to include in his analysis of the environmental impact (such as noise pollution) of constructing a new transit line, for example.

Finally, note that the use of GIS technologies does not imply "buying a package." For example, one can use the TIGER data in a relational database manager (RDBMS) to conduct many of the analyses or build many transit applications. However, given current state-of-the-art technologies, GIS use implies more or less the use of specific purchased mapping systems.

In the next section we shall describe the general tasks of each department of a transit agency and identify some of the applications that can benefit from implementing a GIS. We shall also describe how would GIS make a difference in terms of turning those applications into more effective ones.

3.3. Areas of Application of GIS in Transit Agencies

As mentioned above, the MBTA and CTPS were the two organizations used for the initial investigation of the areas of application of GIS in a transit agency. The following departments were identified as potential users of GIS technology:

1. Service Planning Department
2. Marketing and Ridership Department
3. Scheduling Department
4. Real Estate Management Department
5. Engineering and Maintenance Department
6. Police Department

Detailed interviews with the staff of each of the above departments were conducted in order to understand the activities of each department and to determine which can be enhanced by the use of GIS. The activities which required geo-referenced data, overlaying, and buffering analysis were usually the ones that can really take advantage of GIS technology. Note that in our analysis, when referring to GIS, we are not focusing on GIS per se, rather the data preparation and certain kinds of systematic attention to geo-referencing that allows easier handling of geographic data and the computation and performance of data overlay.

3.3.1. Service Planning Department

The goal of planning departments in general is to improve the efficiency and effectiveness of transit services. The planning department develops proposal to improve transit service, reviews externally generated proposals for service changes, works with affected community representatives, holds public meetings, and assists marketing departments in planning publicity efforts needed for implementing service changes. Service planning departments are also involved in conducting ridership counts and surveys, publishing data and statistics (including

FTA annual required reporting, such as Section 15 service input, output, and consumption), creating schedule maps and timetables, coordinating with other departments, and several other miscellaneous activities.

Proposing and evaluating service changes are probably the most important activities that GIS can help in. Corridor study and route analysis are the two analytical procedures for evaluating of modifying services. Corridor studies are aimed at examining existing bus service on different routes in a corridor to determine whether available resources are being used as effectively as they should be, whereas route analyses are aimed at determining whether new routes are needed to serve an area or whether special requests (by large employers, for example) for additional bus routes are cost effective or not. The two types of activities are somewhat similar or related to each other. Practically the same analysis is done in both cases except for a few exceptions.

In a corridor study, bus routes are examined from the perspective of how well each route performs and of how effective each route within the overall system is. This process involves a number of steps such as data collection (field checks, ridechecks, pointchecks, on-board passenger surveys, demographic data, cost information, etc...) and market analysis and assessment of existing service. General socio-economic and travel characteristics of all residents in a corridor area are matched with similar characteristics of bus riders of that corridor. This analysis provides information useful for identifying which segments of the overall corridor market are served by the existing routes and major trip attractors or generators that are not served. The study process involves some subsequent steps such as identification and evaluation of alternatives for improved service and finally the development of a set of recommendations and conclusions. Note that the step of

identifying alternatives for improved services is apparently done informally in most agencies, especially since the process could get quite complex and involve the creation of sophisticated ridership forecast and sensitivity models that are far too complicated for the average transit planner.

The bulk of the work (almost 70% of the time) in a corridor study is spent on collecting data. Market analysis and assessment of existing services are the second most time consuming. In determining the number of trips directly served by a particular route, current practice assumes that the percentage of trips between census tracts served by the route would correspond to the percentages of the tracts areas that were within one quarter of a mile of the route. The process of determining these trips is quite complicated as it involves drawing by hand the routes on a map of census tracts, drawing to scale a buffer (1/4 mile wide) on the sides of the routes, and measuring (sometimes using a planimeter), or visually approximating, the area of census tracts which fall within the buffer.

Similar kind of analysis is also conducted for proposed new routes, except that demographic data and journey-to-work data are used instead. Basically, both kinds of studies involve the overlay of two or more different layers of data and the analysis of one or more variables across the layers. Some of the data layers are common for both analyses and some are slightly different. In any case, the analysis across the layers is currently done by hand and is time consuming. A GIS has the tools for conducting such analyses.

The other activity in planning department that can benefit from GIS is the production of schedule maps. Schedule maps that planning departments usually produce, are not generally based on any real world coordinates. Typically, they

consist of dots showing a subset of stop locations and names, and of arrows showing the directions of bus movements between stops. Better quality maps which are based on geographical references can be produced by a GIS. GIS-based maps can include land marks and other useful information that prospective riders can use to know more about the service and the location of bus stops with respect to well known reference points or land marks. Sometime these maps are distorted on purpose in order to make the whole route fit on one paper. This is however done at the expense of also distorting the scale and giving wrong information about distances and proximity.

Some of the other activities that the planning department is involved in are the collection of "Section 15" data[3] and conducting stopchecks and ridechecks. Street and route maps, needed for these activities, are generally digitized and length of routes information (needed for "Section 15") are sometimes computed manually.

3.3.1.1. Applying GIS to Corridor Studies

As mentioned earlier, we select one application, the corridor study, to show the benefits of implementing a GIS and of the geo-referencing of data. The manual analysis in corridor studies can be done in a GIS. The GIS has the capability of overlaying many layers of data and analyzing across the layers. It also has the capability of drawing buffers around the route and automatically calculating the areas of census tracts which fall within the buffer. In the determination of number of trips served by a particular route, a better assumption would be to consider a

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[3] The Urban Mass Transportation Act was amended in 1974 to include Section 15, which requires a uniform system of accounts and records as well as a uniform system for reporting by all transit operators in the US. UMTA issued, in 1977, regulations that require annual submission of reports by all transit agencies desiring federal operating assistance. Section 15 includes statistics such as service input, service output, and service consumption.

quarter of a mile walking distance from a bus stop instead of a quarter mile buffer on the sides of a route. Logically, the people served by a certain route are the ones within walking distance from the stop, not just the route. With a GIS, drawing a buffer around the bus stops is feasible and the determination of trip number would be more accurate.

GIS can be used not just to display or visualize specific routes under consideration, but also to analyze the location of new routes or defining transit corridors. It might also be used to analyze the environmental impacts, such as pollution and sound levels, around certain routes. The GIS capability to create 3-D models of terrain can be utilized to develop such applications. GIS can also be utilized to perform siting analysis, such as siting alternative stations within a certain corridor based on factors related to expected ridership, and potential for joint development. In Chapter 5 we discuss a GIS-based prototype-model that can be used by planning departments to forecast ridership along specific routes. The model uses socio-economic characteristics and employment opportunity factors of the area within walking distance from a route, in addition to some level of service factors, to estimate the different levels of ridership along different segments of that route.

3.3.2. Marketing and Ridership Department

Marketing departments are usually in charge of implementing a plan that is consistent with the overall agency goals and services, to market public transit. The typical activities that a marketing department usually conducts include market research, service development, promoting transit, and customer service.

Market research consists of market segmentation studies to determine who the regular users of the system are, how to make the service commensurate with their needs, and how they react to new services or changes of service. Customer service activities include pricing of transit and sales of passes. Transit fares are usually set to reflect the value of the trip to the rider as well as the cost of providing the service whereas passes (monthly or weekly) are utilized as a marketing device to make transit more attractive.

Promotion is another important function of the marketing department. It is used to communicate service characteristics to potential riders. Promotion of ridership is usually conducted via advertising and public relations. Customer services is the other area where marketing departments are also involved. Customer services include the provision of user information in the form of system maps, timetables, signs, and telephone information assistance services. The passenger information system can probably benefit the most from GIS tools and geocoding of data of all the customer services.

The Passenger Information System (PIS) is the main identified area for potential application of GIS in a marketing department. A PIS is a 'turnkey' computerized system used to provide prospective customers with information needed for trip planning such as, how to get from one address to another, the trip duration, and the trip cost. Basically, it is a system where the computer assists the telephone operator in finding transit routes between two addresses. In general, PIS systems are very powerful at calculating routes, except that they have three major defects:

1. They lack a graphical on-screen display of routes.
2. They are not flexible to update and maintain data.
3. Their development and implementation cost are very high.

These defects can be dealt with by either adding GIS functionality to the PIS or by using a standard GIS to replicate the capabilities of the PIS. The PIS, utilized by the MBTA, uses standard street network files (DIME files) to match addresses and to calculate walking time between addresses and origins/destinations. It is a custom-designed system which runs on a mainframe, services between 2,000 and 3,000 calls per day, and was developed at a cost in excess of $1.5 million.

3.3.2.1. Applying GIS to Passenger Information Systems

In Chapter 5, we describe at length a GIS-based PIS prototype. We describe all the components of this prototype, the benefits and complexities of using GIS for building a PIS, and the technical problems and data requirements of the prototype. In this section, we briefly discuss the potential of using GIS to build a PIS while in Chapter 5 we actually build a GIS-based PIS model and discuss its pros and cons.

As mentioned above, a PIS takes for input an origin and a destination address, uses the routes network configuration to process the query, and outputs the most efficient path between the origin and the destination. In this query, three basic operations are performed by the PIS:

1. *Address matching:* the Origin and destination addresses are converted from text form into x,y coordinates. GISs are capable of utilizing a street network file that contains address information to do this operation.

2. *Assignment of a location to a stop:* Once the origin and destination are located on a map, the next step is to find the nearest stop to each of them. GISs can

perform an "allocation" operation whereby resources are allocated from point centers to adjacent streets. This functionality can be used to allocate streets to transit stops and hence to determine origin and destination stops from origin and destination addresses.

3. *Path Finding:* Once the origin and destination stops are identified, a PIS utilizes a set of complex algorithms to determine the most efficient route between these two points. These algorithms can be replicated in a GIS using the routing capabilities of GIS plus the scripting language of GIS to incorporate the needed sophistication into these algorithms.

These three operations basically focus on replicating, more cheaply, existing applications in a GIS environment in order to address the third limitation of current PISs (mentioned above). The other advantage of using GIS to replicate the PIS model is related to the on-screen display of the origin and destination addresses, nearest stops, and the path to follow. This would first help the operator to check the accuracy of the query results and second assist in answering some other questions that non-graphical PIS can't answer, such as: "does the recommended bus pass by a certain location?"

The GIS also provides the tools for update and maintenance of network data utilized by the PIS. For example, the MBTA had a team of 2 persons involved for almost a year in the correction of 7,800 inaccurate records in their database. They had to conduct many site visits to ascertain whether a segment in the network exists or not and whether it is located correctly. A GIS-based PIS can assist in reducing the time needed to update the network database. Once the network is geocoded to the right coordinates, aerial photos can be used as a backdrop on the

screen to check the locational accuracy and update the network.

3.3.3 - Scheduling Department

Scheduling departments usually have a goal of providing the highest quality of service with the least amount of resources. The operations that the scheduling department deals with vary from changing headways according to demand, to maintaining a schedule with the least amount of labor-hours or vehicle-miles. "Runcutting" and "blocking" are two operations that large transit operators conduct in their scheduling departments. Runcutting is the process of cutting scheduled service into blocks and runs. Runcutting is the process of assigning drivers to vehicles whereas blocking is the process of assigning vehicles to routes. Scheduling departments establish schedules and build vehicle trips. Trip building is a very tedious arithmetic operations since the trips are later grouped into blocks that have to account for layovers between trips and travel time (when a block contains trips on more than one route).

Specialized software are used to do these operations for scheduling departments. Many large transit operators in the US and Canada utilize these software. Some of these packages are quite sophisticated and are developed using linear programming algorithms to find the optimal solutions to the above problems. These Software include RUCUS, a package developed by UMTA, and HASTUS, a package developed by GIRO, Inc. Montreal, Canada.

The MBTA scheduling department is not heavily involved in activities which might easily capitalize on the use of geo-referenced data or buffering capabilities,

except for some minor activities such as location of garages and drivers relief points. Vehicle scheduling, manpower and service planning, and operators assignment activities are calculated by sophisticated 'turnkey' software, such as the ones mentioned above. These software do not usually require any geographical data but rather a tabulation of the routes characteristics and the nature of the service such as traveling time between bus stops, number of buses operating on a route, headway between buses, etc. Transit routes and road network paper maps are used in order to calculate some of the required data such as distance between stops, the locations of routes links, and the position of bus garages and drivers relief points. Some vendors of these software have developed graphical add-ons that provide some GIS capability. A route link is usually created between the ends of two routes in case a route is not heavily ridden and buses have to wait for some time between trips. The purpose of creating these links is to minimize idle time between trips. A relief point, on the other hand, is a position where drivers change shifts. It is usually a bus stop within walking distance of a garage. Clearly, GIS capabilities can be used to save much of the efforts to do these calculations. Buffering quarter of a mile around a garage, for instance, can help locate all possible relief points. However, current practice indicates that such use would have to be built into the complex scheduling software that scheduling departments buy in order to be coordinated with other scheduling activities.

3.3.4. Real Estate Management / Engineering and Maintenance Departments

The real estate management and the engineering and maintenance departments are usually involved in many similar activities which require geo-referencing and spatial data. These activities include:

1. Properties and Facilities Management
2. Storing and Maintaining Inventory Data
3. Map Production.

In general, the properties of transit operators are quite extensive and the volume of inventory data related to these properties is very large. In many cases, the real estate department has a large number of old paper maps related to the different agency facilities and offices. Many of these maps which are decades old, are worn out and in need of updating or redrawing. The general usage of these maps is for clearly defining the boundaries of the transit agency's property boundaries and rights of way. The importance of accurately defining the boundaries lies in the current and potential revenue generation by these properties, and in the need for resolving boundary disputes or encroachment on the agency's properties.

Similarly, the engineering and maintenance department has a large number of engineering drawings which are changed and updated very frequently. Draftsmen are usually busy redrawing maps, as a result. Automating the updating process of engineering maps is the main concern of many engineering departments. Many transit operators in the US are using CAD systems for these functions. However, many of the old engineering drawings are still in paper format and any modification to these maps requires a lot of manual work. Maintaining and storing all inventory and engineering data related to transit facilities is another activity that engineering departments are concerned with. Engineering facilities include transit rails and tracks, power cables, power supply systems, manholes, and the like.

3.3.4.1. Applying GIS to Engineering and Real Estate Activities

The usefulness of GIS in these two departments is quite obvious. Digitizing the paper maps into a GIS would help in resolving the updating and storing problems. Moreover, many utilities have their infrastructure running under the transit operator's tracks, or within its rights of way and hence the digital maps that the engineering and the real estate are creating in a GIS (or CAD) can be shared with, or borrowed from, the other utility companies. For example, efforts in Boston are being made to share data between the public agencies, including the MBTA, and the utility companies.

Another area of application of GIS in these 2 departments is related to extension of lines or building of new lines. When building or realigning lines, transit operators need to known who are the people affected by these lines, how much property is to be compensated for or acquired, and the environmental impacts of any such construction. The overlay capability of GIS can be used to superimpose the property lines and ownership information that can be accessed from the assessor's office on top of a buffer around the new line with a width equal to the right-of-way reservation. A similar overlay can also be done on a land use map. The GIS can compute the amount of property required, list the names and addresses of affected people, generate a map of affected parcels. It can also check the type of land use affected and assess any environmental impact such as, endangered species, flood plane zones, hazardous waste sites, and the like.

GIS can also be used to track and schedule maintenance and engineering activities. It can be used to build an inventory system that can assist in these activities. These inventory databases can, for example, include information that is referenced to mileposts along rail lines such as, the dates each segment of a line was built, laid,

and realigned, the maintenance schedule, and the required maintenance equipment. Much of these needs are properly handled by good database management tools. The value of GIS, however, comes from attention to spatial aspects of inventory and maintenance data whereby the spatial relationship between location of repairs and other geographical factor might be important. The GIS, for example, can be used to display the location of line repair overlaid on top of a soil-type map in order to understand any relationship between the two and to schedule preventive maintenance.

3.3.5. Police Department

The two major areas of application of GIS in a Police department are safety and security analysis, and emergency vehicle routing. When the police receive a call about an accident involving a transit bus or an attack on any of the agency vehicles, they need to locate that incident in order to decide which is the closest patrol to that location and which is the shortest path between the incident and the nearest patrol car. Crime analysis (such as, attacks on passengers, graffiti, and vandalism of transit facilities) is usually conducted using historical data about location of incidents, type of incidents, number and type of injuries (if any), neighborhood where incident occurred, and some other socio-economic, demographic, and spatial data. Manual pin maps are usually created using these data to examine patterns or spatial agglomeration of accidents or crimes and patrol cars are usually assigned to the city neighborhoods accordingly.

Many police departments, nationwide, have started using GIS in their patrol dispatch and crime analysis activities. When the address of an incident is reported,

the GIS address matching capability is used to locate that incident on a map. The GIS is then used to find the nearest police station or patrol car to the incident. The "buffering" and "allocation" tools of GIS are utilized for that purpose. The path finding tools of GIS are then used to find the shortest path between the location of the patrol car and the place where the incident occurred. Similarly, if a fire breaks out somewhere in the system or if a rider gets ill, the GIS can identify the nearest fire station or hospital.

The manual pin maps that are used for conducting crime analyses can be generated using a GIS. The address matching and graphical capabilities of GIS can be utilized to create pin maps of different themes, such as location of vandalism of wayside facilities incidents and map of drunk-driving accidents. The GIS can also be used to understand, interpret and hence avoid the re-occurrence of these accidents by overlaying these pin point maps on top of the socio-economic conditions of neighborhoods.

Obviously, the limitations of GIS are related to their deficiency in effectively replicating the dispatching and assignment algorithms built in customized dispatching system. However, gradually, as is the case with scheduling, run cutting, and PIS software, vendors of systems will start incorporating GIS features into their packages.

3.4. Summary / Conclusion

In this chapter, we examined some of the important areas of application of GIS in the different departments of a transit agency. We described the potential of using

GIS without going into the complexities, the meaning, and the "what does it take" to use a GIS for each application. In chapter 5 we examine these issues in detail. There we build three prototypes of GIS applications, namely a GIS-based PIS, a GIS-based ridership forecast model, and a GIS-based tool for targeting major employment centers, to understand the meaning and all the complexities associated with using a GIS, and to explain what is really needed and how can applications be built on standard data format, such as TIGER files, and on standard GIS tools. In Chapter 6 we examine the technical as well as the institutional and organizational complexities facing the implementation of GIS.

In conclusion, it can be seen from the above-listed applications that there is a common need for many data in the different departments of a transit agency. Road network files, schedules, bus stops, and standardized coordinate system are some of these common data. Moreover, the activities in the various departments require some common analysis capabilities, such as geo-referencing, address-matching, and buffering. However, as we will show in chapter 6, despite these facts, the pathway adopted for system development, in general, tends to diverge across the different departments of the agency.

Finally, most of the departments of a transit agency are interested in the mapping capabilities of GIS but for different applications and purposes. These applications, however, are in need of common data such as road network and transit routes and stops. The lack of a common approach to encode these data across the departments may result in situations where duplication of work becomes very often and the capacity to share information impossible. Moreover, as we shall discuss in Chapter 6, the acquisition of different platforms and the implementation of inflexible customized packages for the different applications in the agency is a very common practice. This

shows the lack of an overall information and technology implementation strategy suitable for the sharing of databases and the integration of GIS.

Chapter 4

Survey of Use and Implementation

of GIS by Large Transit Operators

In the previous chapter we examined some of the important areas of application of GIS in a transit agency. We have used the results of our interviews with the staff of the MBTA and CTPS in Boston to determine these areas. However, to check the universality of our findings, we surveyed the largest transit operators in the US. In this chapter, we summarize and analyze the results of this survey.

4.1. Introduction

In Chapter 2 we discussed the research on the use of Geographic Information Systems (GIS) in transportation planning and the integration of GIS technologies in transit applications. Most of the GIS-Transit research has focused on the type of applications that can benefit from GIS technologies [Azar / Ferreira, 91], [Dueker et. al., 91], [Antonisse 91], [O'Neill et. al, 1992], on prototyping GIS-Transit

applications [Azar, 91], [Azar/Ferreira, 1992], [Azar et. al, 1994], or on discussing the deficiencies/capabilities of GIS tools in addressing transit applications needs [Dueker et al., 90], [Grayson, 1993]. Other studies and surveys have also been conducted to develop a comprehensive picture of the fraction of agencies in the US that are using GIS, in which departments, and for which applications. A survey conducted by EG&G Dynatrend, Inc.[4] for the Office of Grants Management of the Urban Mass Transportation Administration[5] in August 1991 is probably the most extensive of all such surveys [Schweiger, 91].

The Dynatrend survey was aimed at identifying "current penetration of GIS technology into transit planning practice", sources of spatial data, and specific GIS software products used by transit agencies. This chapter, however, focuses in more detail on how the big transit operators in the US are encoding digital data and coordinating applications in order to identify and study some of the difficulties in making GIS use evolve effectively in transit agencies. To answer this question we conducted a follow up survey to the 1991 EG&G Dynatrend survey and targeted the largest transit operators in the US. Our survey borrowed some of the Dynatrend questions and created some other questions relating to data sharing, digital data encoding schemes, and GIS development strategies in transit agencies.

4.1.1. Survey Design

The EG&G Dynatrend survey was a telephone-based survey whereas our survey is based on written replies to a questionnaire mailed out to different transit operators (often with phone follow-ups). This survey is conducted in several steps:

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[4]EG&G Dynatrend, Inc., 21 Cabot Road, Woburn, Massachusetts 01801
[5]Office of Grants Management, Urban Mass Transportation Administration, Washington, D.C. 20590

1. Telephone calls were first made to transit operators in order to ascertain that the questionnaires are mailed out to the right persons at the right departments, to set the proper tone for the survey, and to check the validity of mailing addresses.

2. A questionnaire, with a cover sheet explaining the purpose of the survey plus the benefits that can be derived from participating in the research (see Appendix 1), was mailed out to the largest transit operators in the US.

3. Two weeks later, follow-up telephone calls were made to remind late respondents of the questionnaire.

4. Later, telephone interviews were conducted with agencies reporting "interesting" results.

4.1.2. Surveyed Agencies

The survey was mailed out to a total of 28 transit operators across 16 states. The survey targeted transit operators only and did not include MPOs or oversight agencies. Initially a list of all transit agencies operating in large metropolitan areas and with transit vehicle fleets exceeding 100 vehicles were selected. However, in the course of making the first set of phone calls, several operators did not show any interest in participating in the survey and were hence eliminated. Most of those agencies who declined to participate in the survey, did not have any GIS in place and felt that their contribution will add no value to our survey. The

Massachusetts Bay Transit Authority (MBTA) in Boston was also excluded from the survey since we have worked very closely with the MBTA and are very much aware of their GIS efforts. The final count of agencies to whom we mailed the questionnaire was 28 (see Appendix 2 for a list of participating agencies plus their contact persons, addresses, and phone numbers).

Out of the 28 finalists, 23 agencies sent their replies back in time to be included in this analysis. While conducting the second set of telephone calls to remind late respondents of the survey, we sensed that some of those agencies probably found the questionnaire either hard to complete or time consuming. Statements ranging from "have no time" to "not sure where the questionnaire is" to even "the reply must have been lost in the mail" were clear signs of a lack of interest to participate in the survey.

4.1.3. Overall Quality of Responses

A interesting relationship was observed between the quality of the responses and the return time of the questionnaires. Responses that were received within the first week and the ones received after the second reminding phone calls were usually of lower quality than the ones received the second week. Early respondents were organizations that either did not have a lot to report, or agencies who wanted to get done with the survey as soon as possible, caring less about the accuracy of their answers.

Responses that were received the second week after the survey was mailed out, were of the best quality. They showed that the respondents have put some time and

effort in answering the survey. In few cases, a cover letter, with additional information, was attached to the response.

Responses that were received after the second phone call was made, were of lower quality than those received the second week. Some of these responses were good, but the majority were not. It might be that many of those respondents were embarrassed after the second set of phone calls and felt that answering the survey with the least effort would be better than not answering at all.

The blame can not be put on the respondents only. In all fairness, it must be confessed that the questionnaire was quite hard to answer. Respondents had to be aware of all the GIS, information technology, data sharing, and data propagation activities in their agencies. Such a knowledge obviously can not be easily found in one individual.

This being said, the responses were generally acceptable and served the purpose of the survey. They showed what is really happening in all these agencies, confirmed many of the theories that we were investigating, and flagged out agencies that have interesting issues/matters to follow up on.

4.2. Survey Results

Of the 23 responding transit agencies, 17 agencies claim to use GIS in some fashion or another. One of the 6 agencies not using GIS expressed the will to acquire a GIS in the near future. As expected, planning departments of transit agencies are the number one users of GIS (reported by 16 out of the 17 agencies),

followed by scheduling departments (6 out of 17), and followed by marketing departments (4 out of 17).

4.2.1. Areas of Application of GIS

To determine the areas of use of GIS in a transit agency, a list of potential applications was included in the survey for the respondents to choose from. (For the full list of applications, refer to Appendix 1, Question I.2). It was found that GIS is primarily used for planning applications, cartographic or map production applications, facilities management, and IVHS-related applications.

GIS is mostly used for applications involving transit ridership analyses. Sixteen (16) of the seventeen (17) transit agencies that have acquired a GIS, reported the use of GIS in transit ridership forecasting, service planning, or market analysis applications. The difference between market analysis and transit ridership forecast is that the former looks at the demographics and socio-economic conditions in relation to current route configurations and their level of service, while the later is more of a long range planning study whereby transit use along certain corridors is estimated and ridership on specific routes is predicted.

Map production and facilities management were equally reported as the second areas of use of GIS. Nine (9) transit agencies are using GIS to produce transit maps or to keep information on their facilities. Map production applications refer to the use of GIS technologies to create and produce maps of the transit system, print route schedule maps, or generate operator maps (that show route path and turn movements for bus drivers).

Table 4.1: GIS Use and Applications

ORGAN_ID	CITY-STATE	GIS_USE	RIDERSHIP	SCHEDULING	MAP_PRODCT	PIS	RIDEMATCH	PASS_SALES	DISPATCH	AVL	PARATRANS	REAL_ESTAT	POLICE	OTHER
ACTD	Oakland, CA	Y	Y	-	Y	-	-	-	-	-	-	Y	-	
BART	Oakland, CA	Y	Y	-	-	-	-	-	-	-	-	Y	-	
BSDA	St. Louis, MO	Y	Y	-	-	-	-	-	-	-	-	-	-	
COTA	Colombus, OH	-	-	-	-	-	-	-	-	-	-	-	-	
CTA	Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-	
DART	Dallas, TX	Y	Y	Y	Y	Y	Y	-	-	Y	Y	Y	-	
DDOT	Detroit, MI	-	-	-	-	-	-	-	-	-	-	-	-	
KCATA	Kansas City, MO	Y	-	-	-	-	-	-	-	-	-	-	-	Sect 15 Pass mi
LACMTA	Los Angeles, CA	Y	Y	-	Y	-	-	-	Y	Y	-	-	Y	
MCTS	Milwaukee, WI	Y	-	-	-	-	-	-	-	Y	-	-	-	
METRA	Chicago, IL	Y	Y	-	-	-	-	-	-	-	-	-	-	
MMTA	Baltimore, MD	Y	Y	-	-	-	Y	-	-	Y	Y	-	-	
MTAHC	Houston, TX	Y	Y	-	Y	-	-	-	-	-	-	-	-	
NJT	Newark, NJ	Y	Y	-	Y	Y	-	-	-	-	Y	-	-	
NYCTA	Brooklyn, NY	Y	Y	-	Y	Y	-	Y	-	-	-	Y	Y	Accident Analys
RT	Sacramento, CA	-	-	-	-	-	-	-	-	-	-	-	-	
RTA	Chicago, IL	Y	Y	-	-	-	-	-	-	-	-	-	-	
RTD	Denver, CO	Y	Y	-	Y	-	-	-	-	-	-	Y	-	
SEPTA	Phildelphia, PA	-	-	-	-	-	-	-	-	-	-	-	-	
SMART	Detroit, MI	Y	Y	Y	-	-	-	-	-	-	Y	Y	-	
SORTA	Cincinati, OH	Y	Y	-	-	-	-	-	-	-	-	-	-	
TRIMET	Portland, OR	Y	Y	Y	Y	Y	Y	-	Y	Y	Y	Y	-	
WMATA	Washington, DC	fu	Y	Y	Y	Y	-	Y	-	-	Y	Y	Y	Future GIS Apps
Yes		17	16	4	9	5	3	2	2	5	6	8	3	
No		6	7	19	14	18	20	21	#	18	17	15	20	
% Yes		74	70	17	39	22	13	9	9	22	26	35	13	

The fixed facilities and real-estate management applications are basically inventory databases to keep track of the condition of the facilities of an agency. These facilities include rail lines, bus stops, transit signs, parking lots, etc. In 8 agencies, GIS is used to build systems that are capable of creating, managing, and querying inventory databases of transit agencies effectively.

The other areas where GIS is used significantly are related to Automated Vehicle Location (AVL) systems, Passenger Information Systems (PIS), and paratransit management. In 6 agencies, paratransit scheduling and dispatch applications use the routing capability of GIS to determine the optimal path between several origins and destinations of disabled people. Similar routines are used in PISs to indicate to prospective riders the optimal route between one origin and one destination. Five (5) agencies reported that GIS is used in PIS and AVL applications. In AVL applications, GIS is used as the database to store real time information related to bus locations and to display these information on screen in real time as well. For the list of applications of GIS in transit agencies, please refer to Table 4.1: *GIS Use and Applications*.

4.2.2. GIS and CAD Software

In this survey, questions about GIS and CAD software use were also included. The purpose of these questions is to examine the compatibility between GIS and other mapping software used by different departments or different applications in a transit agency. Table 4.2: *GIS and CAD Software Use by Departments* shows all the graphical and mapping software used in each agency. It can be noted that GIS is mostly used in planning departments, whereas CAD software is mainly used in Engineering departments. This is related to the fact that CAD systems are geared toward, and optimized for, 2D and 3D drafting and engineering design applications whereas GIS products are more adapted for spatial analysis type of applications.

In planning departments, the GIS list of products include Arc/Info, MapInfo, Transcad, GDS, Atlas*GIS, MGE, and other customized products. In planning

departments, Transcad is used in 5 agencies, MapInfo, and Atlas*GIS are equally used in 3 agencies, Arc/Info is used in 2 agencies whereas GDS and MGE (Intergraph) are equally used in one agency. As for the CAD software in engineering departments, Autocad is the leading software (7 agencies) followed by Intergraph (5 agencies).

It is important to note that most of the GIS applications used in planning departments are desktop applications. This can be attributed to the following:

1. *Price Difference Between PC-based and Workstation GIS applications*: Desktop GIS packages are less expensive than the workstation ones. They might have less capabilities but have enough functionality to meet the initial requirements of early users.

2. *User-Friendliness of Desktop PC-based GIS:* The fact that desktop GIS software have comparatively limited capabilities make them easier to use. Furthermore, desktop GISs are windows-based, menu-driven applications which make them look more familiar and user friendly than workstation GIS systems with unfamiliar and complex windowing setups or even command-driven interfaces.

3. *Comparable Computational Power of Desktop PCs and Workstations:* PCs are the mass market computing platforms that reach every desk. Users are banking on their becoming cheaper and more capable and the fact that workstation versions of GISs are being ported to windows NT which might provide them with the additional functionality that their desktop GIS lacks.

4. *The Use of GIS for Pilot Projects in Transit Agencies:* Most of the GIS use in the surveyed agencies show that GIS initiatives are always started for specific and limited pilot projects. Pilot projects usually have limited budgets and requirements which make desktop GIS more appropriate for such projects.

Table 4.2: GIS and CAD Software Use by Deparments

ORGAN_ID	GIS_PLANNG	GIS_SCHEDL	GIS_MARKET	GIS_ENGING	GIS_OTHER
ACTD	MAP INFO	TRAPEZE			
BART	ATLAS/GIS				
BSDA	ARC/INFO				
COTA					
CTA					
DART	GDS ORACLE	GDS GSCHED	GDS ORACLE		
DDOT					
KCATA	MAP INFO				
LACMTA	ARC/INFO				
MCTS		TRAPEZE			
METRA	ATLAS GIS				
MMTA	TRANSCAD				
MTAHC	ATLAS/GIS				
NJT	MGE,TransCAD				
NYCTA	TRANSCAD				MAP INFO
RT					
RTA	TransCAD				
RTD	MAPINFO		MAPINFO		
SEPTA					
SMART	CUSTOM GIS	CUSTOM GIS			
SORTA	TRAPEZE				
TRIMET		ARC/INFO	MAPINFO		TERRAVIEW
WMATA	TRANSCAD	TRANSCAD	TRANSCAD		

ORGAN_ID	CAD_PLANNG	CAD_SCHEDL	CAD_MARKET	CAD_ENGING	CAD_OTHER
ACTD					
BART					
BSDA					
COTA					
CTA					
DART	GDS	GDS	GDS	INTERGRAPH	
DDOT					
KCATA					
LACMTA				INTERGRAPH	
MCTS		SMART TRACK			
METRA				INTERGRAPH	
MMTA				AUTOCAD	
MTAHC				AUTOCAD	
NJT	MICROSTATION			AUTOCAD, MICROST	
NYCTA				INTERGRAPH	
RT				AUTOCAD	
RTA					
RTD				AUTOCAD	
SEPTA					
SMART					
SORTA					
TRIMET				AUTOCAD	
WMATA				AUTOCAD	

Some agencies, like TRIMET in Oregon, are using several GIS software for different applications and in different departments. For example, Arc/Info is used

in the Scheduling department, MapInfo in the Marketing department, Terraview/Multimap in the Dispatch, and AutoCAD in the Engineering Department. Arc/Info is used for transit ridership forecast and analysis applications, MapInfo is used for Carpool and Paratransit application, whereas Terraview is used for fixed route dispatch applications. In answering the question about the problems of GIS at their agency, TRIMET, as expected, stated the data sharing and exchange between their different systems as one of their biggest challenges. The same problem was also reported by New Jersey Transit, NJT, which uses Transcad and MGE (Intergraph) in the planning department, and Microstation (Intergraph) and AutoCAD in the planning and engineering departments. This is not a peculiar, unusual or atypical problem. Table 4.2 shows many other agencies, using combinations of GIS software, that are or will be facing similar problems. Of course, data sharing is much more than exchanging disks in these cases. Data interchange is becoming more supported by various packages. The deeper issue is the extent to which the digital data encoded for an application can serve the continuing needs of another application.

4.2.3. Platforms Running GIS

Table 4.3: *Hardware-Use in Each Department* shows the number, the type, and the network configuration of machines running GIS in each department. The most common architecture used for running GIS apparently is the Networked PC. This is probably due to the fact that, in most cases, before implementing or acquiring a GIS, the networked PC architecture is adopted to run other applications and processes, such as word processing, local electronic mail, printing, and other engineering applications. Around 60 networked PCs, for instance, are used in the

engineering department of NJT.

Dedicated PCs are also used for running specific GIS applications, especially in planning departments. This is somewhat related to the fact that many of the responding agencies are using desktop GIS for limited applications only or for testing what can GIS deliver to them.

Table 4.3: Hardware Use by Each Depatment

ORGAN_ID	PC_PLANNG	PC_SCHEDL	PC_MARKET	PC_ENGING	PC_OTHER	NETPC_PLAN	NETPC_SCHD	NETPC_MRKT	NETPC_ENGG	NETPC_OTHE	WKST_PLAN	WKST_SCHD	WKST_MRKT	WKST_ENGG	WKST_OTHER	NTWKST_PLN	NTWKST_SCH	NTWKST_MRK	NTWKST_ENG	NTWKST_OTH	MNFRM_PLAN	MNFRM_SCHD	MNFRM_MRKT	MNFRM_ENGG	MNFRM_OTHE
ACTD	3						8																		
BART						1																			
BSDA	1								1																
COTA																									
CTA																									
DART						3	1	1	2	37									1	5					
DDOT																									
KCATA																									
LACMTA														1		1									
MCTS							1										5								
METRA	1					4															3				
MMTA						1				25															
MTAHC																									
NJT	2					4				60															
NYCTA	2		1	1		5																		1	
RT																									
RTA	2																								
RTD	3		3																						
SEPTA																									
SMART	2	4																							
SORTA						3																			
TRIMET		1							1										1		3				1
WMATA						1	1	1	1																

The Dallas Area Rapid Transit authority (DART) and the TRIMET are two examples of organizations where GIS is widely used in the organization. The network architecture in both organizations includes both PC and workstations.

DART is using GDS as their main and only GIS software supported with Oracle RDBMS. On their network a large number of PCs are connected and serve for running different applications in different departments. The bulk of those networked PCs, 32, are used in the customer service department. However, on the same network, 5 Alpha VMS workstations are also accessible.

TRIMET is using a Network of Sun Sparc10 and Sparc2, DEC Alpha, IBM AIX RS 6000, and PCs in their operations. Dedicated non-networked PCs are also used for running Carpool applications. TRIMET , like the MBTA in Boston, is an example of organizations that had many uncoordinated GIS startups that resulted in a diversity of GIS platforms running a multitude of GIS software that, after the fact, are being driven to become more coherent.

In many cases, we noted that the number of machines running GIS is insufficient for doing all the tasks listed in the other sections of the survey. This apparent discrepancy is caused by the fact that, in many instances, the agencies are reporting the legal number of PC licenses they have acquired while in fact they have the GIS running on more PCs than are licensed. This was also confirmed in a telephone conversation with one respondent.

4.2.4. Use of Digital Network Data in GIS Applications

Most of the GIS applications in a transit agency are network-dependent. The representation method, source, and building schema of the network basemap is very important in determining how viable a GIS application is and how sharable the data becomes. In this survey, one section was dedicated to investigate the

source of the basemaps used for building applications. In another section the encoding methods to create transit routes and stops were also investigated.

Table 4.4: Digital Networks and Other Digital Data

ORGAN_ID	DIME	TIGER	ETAK	USGS_DLG	STATE_DOT	LOCAL_MPO	DIGITIZED	OTHER_NET	RAIL_ROUTE	BUS_ROUTE	ROW	STOP_STATN	BUS_TIMEPT	AVL_SIGNPS	ACCIDENTS	PARK_RIDE	MAINT_FACL	CENSUS_TRC	POLTCL_BND	TAZ	OTHER_DATA
ACTD	-	Y	Y	-	-	-	-		Y	Y	-	Y	-	-	-	-	-	Y	Y	-	
BART	-	Y	-	-	-	-	-		Y	Y	-	Y	-	-	-	Y	-	Y	Y	Y	
BSDA	Y	-	-	-	-	-	-		Y	Y	-	-	-	-	-	-	-	Y	-	-	
COTA	-	Y	-	-	-	-	-		-	-	-	Y	Y	-	-	-	-	-	-	-	
CTA	-	-	-	-	-	-	-		-	-	-	Y	Y	Y	-	-	-	-	-	-	
DART	-	Y	-	-	-	-	-	Reworked TIGER	Y	Y	Y	Y	Y	-	Y	Y	Y	Y	Y	Y	Parcel, Bldg ft
DDOT	-	Y	-	-	-	Y	-		-	Y	-	Y	Y	-	Y	-	-	-	-	-	
KCATA	-	Y	-	-	-	-	-		Y	-	-	-	-	-	-	-	-	-	-	-	
LACMTA	Y	-	-	-	-	-	-	Thomas Brothers	Y	Y	Y	-	-	-	-	Y	Y	Y	Y	Y	
MCTS	-	Y	-	-	-	-	-		-	Y	-	Y	Y	-	-	Y	-	-	-	-	
METRA	-	Y	-	-	-	-	-		Y	-	-	-	-	-	-	-	-	-	Y	Y	
MMTA	-	Y	-	-	-	-	-		Y	Y	-	Y	-	-	-	Y	Y	Y	Y	Y	Survey Geocodes
MTAHC	-	Y	-	-	-	-	-		-	Y	-	-	-	-	-	-	Y	-	Y	Y	Y
NJT	-	Y	-	-	Y	-	-		Y	Y	-	Y	-	-	-	-	Y	Y	Y	Y	
NYCTA	Y	-	-	-	-	-	-	NYC DIME Based	Y	Y	Y	Y	-	-	Y	-	Y	Y	Y	Y	Exits, Signals
RT	-	-	-	-	-	-	-		-	-	-	Y	Y	-	-	-	-	-	-	-	
RTA	-	Y	-	-	-	-	-		Y	-	Y	Y	-	-	-	-	-	Y	Y	Y	
RTD	-	-	Y	-	-	-	-		-	-	-	-	-	-	-	Y	-	Y	Y	Y	
SEPTA	-	Y	-	-	-	-	-		Y	-	-	-	-	-	-	-	-	-	-	-	Commuter Rail
SMART	-	Y	-	-	-	-	-		-	Y	-	Y	-	-	Y	-	-	Y	-	-	
SORTA	-	Y	-	-	-	-	-		-	Y	-	-	Y	-	-	-	-	Y	-	-	
TRIMET	-	Y	-	-	-	Y	-		Y	Y	-	Y	Y	-	-	-	-	Y	Y	Y	
WMATA	-	Y	-	-	-	Y	-		Y	Y	-	Y	Y	-	-	Y	Y	Y	Y	Y	Surveys, Plans
Yes	3	17	2	0	1	3	0		14	15	4	15	9	1	4	8	6	15	13	12	
No	20	6	21	23	22	20	23		9	8	19	8	14	22	19	15	17	8	10	11	
% Yes	13	74	9	0	4	13	0		61	65	17	65	39	4	17	35	26	65	57	52	

Table 4.4: *Digital Networks and Other Digital Data* shows the sources of the basemaps used by transit agencies. TIGER files are basically the most widely used files for building road network basemaps. It was interesting to note that no transit agency has digitized its own basemap in-house. Three (3) agencies reported using the local MPO's basemap but these basemaps in the 3 cases are derived from TIGER. Enhancing TIGER files is usually conducted by outside parties. One of

the few examples where TIGER files are updated at the agency is the case of DART. 32 man-months were spent on updating the TIGER files for 5 counties in the Dallas area. Three (3) agencies reported the use of DIME files as their basemap. ETAK and Thomas Brothers files are also reported as the source of digital basemaps in 2 agencies. Note that TIGER files are used because they have a network model in place that is consistent for whole metropolitan areas. Note also that TIGER files are used even in places like TRIMET that have other more accurate local basemaps in place in other local agencies.

Table 4.5: *Data Use by Departments*, shows which department uses which road network data, route and stop data, ridership and demographic data. It also shows which encoding method of bus route data is adopted and by which department. In most of the cases, the planning department is usually in charge of encoding transit routes. Scheduling and marketing departments in few cases either build their own routes or had a consultant build the routes for them.

Table 4.5 shows that routes are in most cases built using TIGER or other off-the-shelf road network data files. Unlike the case with road network basemaps, a large proportion of transit operators have reported the in-house digitization of bus routes. Nine (9) agencies have reported digitizing their transit routes in-house, whereas eight (8) agencies reported the use of consultants for encoding their routes. Note that five (5) agencies have both digitized and used consultants for creating their transit routes.

In general, such cases occur when one department digitizes the routes while another hires a consultant or in some cases the consultant is hired by the same department to do part of the work. The questionnaire included sections on data

update and data sharing processes to examine how data sharing and update in such cases are handled. However, the agencies that reported using several sources for creating their routes indicated that no sharing or update have been conducted so far. This is related to the fact that these agencies are new adopters of GIS technologies.

Table 4.5: Data Use By Departments

ORGAN_ID	ROAD_NET	ROUTE_STOP	RIDERSHIP	DEMOGRAPH	OTHER_AVL	RT_DIGITIZ	RT_TIGER	RT_CONSULT	RT_OTHER
ACTD	P	P				P		P	
BART	P	P	P	P		P	P	P	
BSDA	P			P				P	
COTA		P,S	P	P	P			P	
CTA		P,S	P	P	P,S				
DART	P,S,M,O	P,S,M,O	P,M,O	P,M,E,O	P,S,M,O	E,O	P,O		
KCATA									
LACMTA	P,M,E	S,M,E	P,S	P			M	P,E	
MCTS	S	S					S		
METRA	P	P	P	P			P		P
MMTA	P	P	P	P			P		P,S
MTAHC	P	P	P	P		P	P		
NJT	P,E	P,S	P	P,M			P	P,E	P
NYCTA	P,E,O	P,M,E,O	P,O	P		P,O	P,O	M	
RT									
RTA	P	P	P	P			P		
RTD	P,M			P,M		P,M			
SEPTA									
SMART	P,S	P,S	P	P			P,S		
SORTA	P	P		P		P	P	P	
TRIMET	S,M	S,M	P,S	P	P,S	S			
WMATA	P,S,M	P,S,M	P,S,M	P,M	P	P,S,M	P,S,M		
Planning [P]	15	15	14	17	5	7	12	8	3
Scheduling [S]	5	10	4	0	3	2	3	0	1
Marketing [M]	5	5	2	4	1	2	2	1	0
Engineering [E]	6	2	0	1	0	1	0	2	0
Other [O]	2	2	2	1	1	2	2	0	0
% Planning	65	65	61	74	22	30	52	35	13
% Scheduling	22	43	17	0	13	9	13	0	4
% Marketing	22	22	9	17	4	9	9	4	0
% Engineering	26	9	0	4	0	4	0	9	0
% Other	9	9	9	4	4	9	9	0	0

4.2.5. Other Digital Data

The survey also investigated the existence of other digital data at transit agencies.

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All but two agencies reported the use of other digital data. These data included rail/bus transit routes, stops, and boundary files. Fifteen (15) agencies reported having their bus route system in digital form. On the average more than 50% of the respondents have their rail system, bus routes, bus stops and train stations, census tracts, political boundaries, and their traffic analysis zones (TAZ) on a computer. This is somewhat related to their use of the GIS for conducting ridership and market analysis studies. These applications require information about the layout of transit routes and stops and the socio-economic data of their operation areas. Given also that TIGER files are the most widely used for generating basemaps and transit routes at these agencies, it is expected that the census tract boundaries are also used in conjunction with the census data for conducting these applications.

4.2.6. Data Sharing

One of the main objectives of this survey is to examine the areas of data sharing that exist between different departments, the efforts that are made to share data, and the problems deterring such efforts. The survey contained several questions that relate to these issues. It included a matrix to be filled out with data that are shared between departments, a set of data items to be checked by each department using them, and a direct question about the data sharing problems (refer to questions 7,8,and 9 of Appendix 1).

Table 4.5 also summarizes the data that are used by multiple departments. These data include road network, route and stop locations, ridership, and demographic data. All of these data items are shared between several departments. For example, the route and stop location data are used by 65% of the planning departments, 43% of the scheduling departments, 22% of the marketing departments, and 9% of the

engineering departments of all agencies.

Table 4.6: *Data Shared Between Department*, shows which data are shared between departments. It helps to understand whether common data are shared or duplicated. For example in Table 4.5, six agencies reported the use of the route and stop locations data in both of their Planning and Scheduling departments. However, Table 4.6 shows that only 4 of these agencies are sharing these data. This means that two of these six agencies are duplicating their route and stop location data between their planning and scheduling departments.

Table 4.6: Data Shared Between Departments

ORGAN_ID	PLAN_SCHDL	PLAN_MRKT	PLAN_ENGG	PLAN_OTHER	SCHD_MRKT	SCHD_ENGG	SCHD_OTHER	MRKT_ENGG	MRKT_OTHER	ENGG_OTHER
ACTD										
BART										
BSDA										
COTA										
CTA	bus stops									
DART	all	all	all	all	all	all	all	all	all	all
DDOT										
KCATA										
LACMTA	ridership headways, route									
MCTS	unknown									
METRA										
MMTA										
MTAHC		Socio-economic								
NJT		Demog. Rider. Census. TAZ	Transit + Road Network							
NYCTA		routes, demographic	capital assets							
RT										
RTA										
RTD		road net, demograph, TAZ								
SEPTA										
SMART		employment								
SORTA										
TRIMET	Routes	Stops, Shelters			Routes, Stops					
WMATA										

Table 4.6 also serves as a means for learning about which departments share more information than others. It shows that the planning department usually share GIS-related data with all other departments more than these other departments share among themselves. Routes and stop locations, ridership, route characteristics (such as headway and bus schedules) are the most shared information between planning

and scheduling departments. Demographic data, socio-economic data, road network files, Routes and stops locations, and boundary files (such as TAZ) are the most commonly shared data between planning and marketing departments.

As for the data sharing problems, each agency pointed out some of the many aspects of these problems. The reported problems relate to compatibility between software data structures, difference in graphical database scales, and difference in segmentation of data (refer to Table 4.7: *Data Sharing Problems*). New York City Transit Authority, NJT, and TRIMET have all reported the problem of transferring data from one software to the other, especially when these software have different ways of structuring data. TRIMET mentioned the problem of moving data between Arc/Info, MapInfo and Terraview, whereas NJT and New York City Transit mentioned problems related to transfer of data in and out of Transcad.

Table 4.7: Data Sharing Problems

ORGAN_ID	IMPLT_STRA	DATA SHARING PROBLEMS
ACTD	BU	
BART	BU	
BSDA	BU	
COTA	NA	
CTA	BU	
DART	TD	Problems are procedural: impact on individual dept with update responsibility. All data is online
DDOT	LC	No data sharing yet. Currently working toward city-wide GIS. Needs assessment just beginning.
KCATA	BU	
LACMTA	LC	
MCTS	BU	Not Yet -- Still implementing
METRA	BU	No sharing of mapping data is happening now
MMTA	BU	
MTAHC	none	GIS not yet widely used. So far no sharing problems
NJT	BU	Moving data between Intergraph and Transcad: DXF retains only graphics & no attributes
NYCTA	LC	Transfering schedule data into TRANSCAD is diffiult due to structural differences in software
RT	LC	
RTA	No Answer	
RTD	BU	No problems yet
SEPTA	BU	
SMART	TD	
SORTA	LC	No sharing is presently happening. It is being discussed
TRIMET	LC	Segmentation of data (MPO vs TRIMET). Moving data b/w packages (ArcInfo, Mapinfo, Terraview)
WMATA	BU	Sharing problems with Engineering: They require larger scales than is available for planning purpose

TRIMET touched upon one of the most fundamental problems that are complicating data sharing efforts, namely the difference in segmentation or

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representation of network files. Network files created by the local MPO have different segmentation than the ones created at TRIMET. This usually results in one-to-many or many-to-many correspondence problems between the two networks which renders data sharing efforts extremely tedious. Segmentation problems arise from different representations of linear objects and their associated data. A segment is usually delimited by two nodes (extremities). It represents a part of a network that has constant attributes. The usual segmentation of road networks is based on street intersections whereas the usual segmentation of transit routes is based on bus stop locations. One-to-many problems occur when a road segment corresponds to several transit route segments. Many-to-many problems occur when several road segments correspond to several transit route segments. The complexity of these issues relate to conflating data from one network to another that do not necessarily have a one-to-one geometric correspondence.

The Washington Metro Area Transit Authority (WMATA) identified another essential problem that usually obstructs data sharing attempts. They identified a common problem that happens between engineering and planning departments, namely the difference in scale requirements. The scale required for engineering applications is higher than the one needed for planning applications. The level of detail of transit networks required for engineering applications are usually higher than the ones required for typical planning applications. Merging information between two networks that are of different scale is a main problem to interdepartmental data sharing.

As a general observation about data sharing between departments of transit agencies or with other transportation agency, we note that data sharing is not occurring very often. In addition to the above technical problems, the other

explanations to this fact include:

1. *GIS is still new*: Many transit operator have found that not many other agencies in their area have used GIS. For instance, according to the Bay Area Rapid Transit District (BART) in Oakland California, they are the first agency in the area to apply GIS for multi-purpose applications. As such, there was not enough momentum to work at inter-agency or even inter-departmental coordination. However, most of these agencies are hoping for future data sharing opportunities.

2. *GIS is used for pilot projects so far*: In many of the surveyed agencies, the use of GIS is generally limited to one specific application only. For example, The Kansas City Area Transportation Authority bought a few years ago a desktop GIS to automate the Section 15 measurements that were done on paper maps using map-wheels. GIS has been used for this application only so far and hence there was no need to share data with any other group or application.

It is reasonable to conclude that the problems identified in the agencies where sharing has already started will be replicated in the other agencies as their use of GIS intensifies and as the maintenance issues for mature systems becomes an issue.

4.2.7. Basemap Update Processes and Responsibilities

Once network data sharing occurs between different departments or different agencies, the questions of who is in charge of the basemap updates and how such

updates are carried out, is certain to become an important and complex issue. The survey investigated these questions in order to understand how transit agencies are dealing with this issue. However, as discussed above, data sharing is not really very frequent between the departments of the surveyed agencies. Nonetheless, several processes for dealing with this issue were reported by those agencies currently sharing data. These processes varied from the "provider of data is responsible for updates" to "cooperative update efforts between departments are being made for this purpose" and to "no real formal maintenance process" is in place. The later is the case where GIS is still in its infancy stage or where the resources allocated to GIS are quite limited. The Maryland Mass Transit Administration is one example of such cases.

Table 4.8: Data Updating Processes

ORGAN_ID	IMPLT_STRA	WHO DOES THE DATA UPDATE
ACTD	BU	Updating is handled by Planning department
BART	BU	Planning Dept. maintains Basemaps
BSDA	BU	
COTA	NA	Cooperative efforts between scheduling and planning
CTA	BU	
DART	TD	IS/GIS does maintenance with established procedures for other dept to report discrepancies
DDOT	LC	Responsibilities will be set in the future
KCATA	BU	No one
LACMTA	LC	Planning maintains street-base derivatives, parcels around rail stations.
MCTS	BU	Transportation/Dispatch Dept. maintains base maps & routes
METRA	BU	The system planner is the only GIS user and is responsible for updates that are adhoc.
MMTA	BU	No real formal maintenance system, limited resources, adhoc maintenance
MTAHC	none	No one
NJT	BU	No one. No protocol for developm't, maintenance & dissemination adopted yet. Part of Strategic Plan
NYCTA	LC	MTA family of agencies has a GIS user's group to coordinate basemap sharing.
RT	LC	MPO for Sacramento Region is implementing a GIS & is responsible for Basemap updates
RTA	No Answer	
RTD	BU	Planning Dept -- as needed
SEPTA	BU	
SMART	TD	Planning dept updates base maps (TIGER), route maps, and stops
SORTA	LC	No one. TIGER files are supplied by consultant who has made some corrections at our request
TRIMET	LC	MPO maintains regional Basemap. Updates can be done by users but must report to MPO
WMATA	BU	Builders of data sets are responsible for maintenance and updates.

Table 4.8: *Data Updating Processes*, shows a summary of the responses to the question of who updates data at each agency. In the case where the street basemap is created by the planning department, most of the time the planning department is in charge of maintaining this basemap. Such cases were reported by Los Angeles

County Metropolitan Transportation Authority, the Suburban Mobility Authority for Regional Transportation in Michigan, the Regional Transportation District (RTD) in Denver, and the Bay Area Rapid Transit District (BART) in Oakland.

In many areas where inter-organizational cooperative efforts are being made for sharing data and coordinating data building and propagation strategies, the responsibility of basemap data update is in many instances in the hands of organizations outside the transit agency, such as the local MPO or some other transportation agency in the region. New York city (New York), Baltimore (Maryland), Sacramento (California), and Portland (Oregon) are few such examples.

In New York City Transit, the MTA family of agencies has a GIS user's group to coordinate basemap sharing efforts. The responsibilities of data update are hence divided between different users. The New York City department of city planning, for instance, is in charge of maintaining and updating the basemap that several users in the city use, while the New York City Transit is in charge of maintaining and updating the subway network. Databases that are developed by individual users using either basemap, such as bus stop files, are generally updated by each developer. A joint effort with New York City DOT is also underway to develop a master bus stop file that could be used for bus stop management applications.

In Portland, Oregon, the local MPO, METRO, maintains the regional basemap covering 3 counties. The MPO's system has partitioned the basemap in such a manner that users must recombine it to use it as their own basemaps. TRIMET uses the partitioned basemap to build their own map and to create their transit routes network. Geometrical and topological errors in the basemap are usually

reported to METRO to include in their updated version of the basemap.

At the Dallas Area Rapid Transit (DART), a top-down GIS implementation rule is imposed to force the ease of data maintenance and of progation of updates. The IS department, for instance is allowed to make changes to the basemap and departmental users can only make requests for updates using procedures for reporting discrepancies that are also set by the IS department.

In Baltimore, The Maryland State Government Geographic Information Coordination Committee (MSGIC) is working with several state agencies, as well as the utility companies (such as, Bell Atlantic) to develop a highly accurate digital basemap called MD landbase. This basemap will be available to all state agencies to use including the MTA. This basemap is created by conflating TIGER information onto the Maryland State Highway Administration's (MDSHA) street grid files. MSGIC is basically setting the procedures for updates and maintenance of the MD landbase that will be used by the Maryland Mass Transit Administration.

4.2.8. GIS Implementation Strategy

In order to learn about the implementation strategy of GIS at different agencies, we included in the survey a 2 page description of 3 prototypical development strategies. Respondents were asked to read these descriptions and decide which one is the closest to what is happening at their agencies. The alternative strategies comprised a "bottom-up" strategy, a "top-down" strategy, and a "loosely-coupled" strategy. A description of each of these strategies is included in Appendix 1.

Of the 23 surveyed agencies, 12 agencies reported a bottom-up strategy, 2 reported a top-down strategy, 6 reported a loosely-coupled strategy, and 3 didn't have any. However, out of these 23 agencies 6 have no GIS but yet they answered this question. If these agencies are excluded, the number of bottom-up agencies becomes 9, the top-down remains 2, the loosely-coupled becomes 4, and the "no-strategy" becomes 2. Refer to Table 4.9: *Implementation Strategies of GIS*.

Table 4.9: Implementation Strategies of GIS

ORGAN_ID	GIS_USE	NET_DIGITL	IMPLT_STRA	OTHER COMMENTS
ACTD	Y	Y	BU	
BART	Y	Y	BU	1st transit agency in the area to use GIS. No interagency coordination. Future data sharing possible
BSDA	Y	Y	BU	
COTA	N	Y	NA	
CTA	N	N	BU	
DART	Y	Y	TD	IS refuses to support modified datasets. All dept use centralized datasets.
DDOT	N	Y	LC	Each depart. will maintain databases in accordance with criteria established by GIS users Group
KCATA	Y	Y	BU	
LACMTA	Y	Y	LC	It has become loosely coupled after having been a bottom-up strategy
MCTS	Y	Y	BU	As agency GIS knowledge matures we expect to be involved with loosely coupled strategy
METRA	Y	Y	BU	
MMTA	Y	Y	BU	Plan to hire Consultant to help in GIS implementation
MTAHC	Y	Y	none	
NJT	Y	Y	BU	Top-Down desired but not probable; Loosely-coupled is probable in the future
NYCTA	Y	Y	LC	NYC Dept of City Planning maintains streets basemap; NYC Transit maintains subway net
RT	N	N	LC	SACOG is setting standards and developing base mapping. RT has not yet become involved in GIS.
RTA	Y	Y	No Answer	
RTD	Y	Y	BU	RTD has begun to develop agency-wide GIS. It will be a loosely coupled strategy (wkst Arc/Info)
SEPTA	N	Y	BU	TRANSCAD appears to be the most useful GIS for our works
SMART	Y	Y	TD	
SORTA	Y	Y	LC	Probably move to Top-Down strategy
TRIMET	Y	Y	LC	While coding transit routes, topological errors were discovered.
WMATA	Y	Y	BU	Some databases will reside on mainframe with logical interfaces for periodic downloading into GIS

Bottom-Up (BU)	12
Top-Down (TD)	2
Loosely-Coupled (LC)	6
None / No answer	3

% Bottom-Up	52%
% Top-Down	9%
% Loosely-Coupled	26%
% None / No answer	13%

As a general note on the quality of the implementation strategy reply, chances are that respondents were not well-informed about what is happening at their agency as a whole. Answering this question usually requires the knowledge of all the activities in the whole agency as far as information technology and computer use are concerned. In other words, the accuracy of these answers might be quite questionable. This does not mean, however, that these answers should be totally disregarded as one can make his own judgment by carefully observing the rest of

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the answers in the survey sheet. For example, when an agency describes its implementation strategy as a loosely-coupled one, while only one department or even one single application is reported in answering the question about departments' use of GIS, one can conclude that probably the respondent referred to the future strategy that will be adopted when GIS use becomes an agency-wide activity. As a matter of fact, this is the case with the Southwest Ohio Regional Transit Authority.

Table 4.9 shows which agencies are using GIS, which agencies have digital networks, the GIS implementation strategies, and final comments on the survey. Most of these comments are somewhat related to the implementation strategy since the comments question followed the question on implementation strategy immediately. The majority of the transit agencies are adopting the bottom up strategy. This can be interpreted as follows:

1. *Few agencies have agency-wide GIS.* Since the majority of the surveyed agencies have limited use of GIS, it is expected that the GIS initiative in these agencies was initially driven by a need to meet a limited number of specific application requirements in one or several departments. Since the need for GIS is not realized at the agency level but at the application level, the development of GIS is expected to take the form of several individual efforts that will flourish in isolation of each other. This automatically results in a bottom-up strategy.

2. *Limited GIS budgets and short development time frames.* Many transit agencies did not have enough momentum or resources to work at inter-agency or inter-departmental GIS development. As a result, decisions were made to go for

quick start-up, quick return programs, using as many existing databases and map sources as possible on user-friendly and affordable platforms. The lack of coordination between departments resulted in many different start-ups which finally got translated into a bottom-up implementation strategy.

3. *Less risky implementation.* As the benefits of GIS are not really and immediately conceived by top-level decision makers, it is always safer to risk little resources and capital on scope-limited GIS pilot projects. This will serve as a test of the benefits of GIS without the need for taking major risks. Such a policy, in many instances, might end up with several test/pilot projects which can create a top-level-supported bottom-up strategy.

Two agencies reported a top-down implementation strategy of GIS. DART is probably a good example of a top-down agency. The MIS department at DART is in charge of all GIS activities in the agency. All naming conventions are adopted by the IS/GIS based upon standards used by the department which has maintenance responsibility on that data set. All the geographic files in the agency have the same projection and scale. All the data are on line and "read-only". No discrete data are allowed. IS refuses to support "extracted" and modified datasets developed by individual users. All departments use a centralized dataset.

As for the DART's data update propagation between departments and the way such updates flow, it is all based on procedures formerly set by the IS department. At the early stages of GIS implementation at DART, the IS department established departmental reporting structures that are used for reporting data updates and discrepancies. Data maintenance is generally conducted by the IS/GIS group based on reports of discrepancies received from other departments. For example, when

the planning department proposes a change to a route alignment, the changes have to go first to the engineering department to make the necessary changes in their mapping databases, then the IS makes the necessary applications environment changes before forwarding the updates to the scheduling department which in its turn sends it to the marketing/graphics department before it ends with the operations department.

The top-down strategy has the advantage of ensuring compatibility between databases used in different departments. However, as is the case in DART, the reporting procedure and data propagation pipeline is so structured that it creates a very rigid system that might not address all the users requirements in sufficiently tight time-frame. The survey was filled by the IS department which explains why the system is portrayed as the most efficient system. In a telephone conversation with two GIS users at DART, one user did not feel that the structured system is causing any delay or problem and spoke highly of the IS role while the other mentioned that he would have prefered to have his own GIS unit to "test a few things" on it in-house.

The loosely-coupled strategy was reported by 3 agencies: The Los Angeles County Metropolitan Transportation Authority, the New York City Transit Authority, and the TRI-County Metropolitan District of Oregon (TRIMET). Out of these 3 agencies, it is not clear whether any of them is really adopting a loosely-coupled strategy or not. The responses do not contain enough information that indicate whether the implementation strategy is conceived as a loosely-coupled one or whether it really is. Many organizations that are adopting a bottom-up approach but have GIS coordination committees, feel that their strategy is a loosely-coupled one. GIS coordination committees are necessary but not sufficient conditions for

making the strategy a loosely-coupled one.

4.3. Summary / Conclusion

The following observations/conclusions pertaining to the state of GIS implementation and data encoding and sharing in big transit operators in the US were derived from the analysis of the survey responses:

1. *Widespread use of GIS at the pilot or task specific, desktop level*: In most of the surveyed agencies GIS is still at the stage of experimentation. Many agencies are still testing what can GIS deliver to them. As a result, most of the GIS use is for pilot projects or limited test tasks. Desktop GIS packages are commonly used because of price affordability and because they can run on PCs, already in place.

2. *GIS is not mature enough at most agencies for the maintenance processes/problems to be settled*: The complex issues of data maintenance are not yet realized at most transit agencies. This is due to fact that GIS is not yet mature enough for these complex issues to start surfacing out. Moreover, almost no agency is preparing itself by setting up maintenance processes to avert these problems in the future.

3. *Limited development of in-house capacity to generate, manage, and manipulate digital spatial data*: Except for few exceptions, almost all big transit operators in the US have limited GIS capabilities developed in-house. The development, management, and maintenance of digital spatial can not yet

be performed using local expertise and does not yet have the proper infrastructure to make it easily sustainable.

4. *Widespread similarity in types of applications and techniques used with no hint of abandoning GIS*: The types of applications where GIS is used are very similar between agencies. Ridership forecast and analysis are the most common GIS applications. No agency has hinted in anyway at abandoning its GIS. Conversely, some of those agencies who have no GIS at the moment expressed their intentions to acquire one in the future.

5. *Signs of major difficulties in data integration and coordination*: Lots of signs were observed which indicated that coordination will be hard and surprisingly tough both to integrate GIS use, agency-wide, or to utilize externally generated GIS basemaps that are incidentally improving and expanding. The unawareness of the importance of several key issues related to database design is a clear signal that agency-wide GIS will soon be facing major implementation and coordination difficulties.

6. *GIS is used as a visualization tool rather than analytical one*: The way GIS is applied shows that it is more about maps displayed as part of constructed applications rather than a change in the agency's capacity to do spatial analysis. GIS is not used to its full capability yet in transit agencies. Applications are not yet benefiting from the spatial analysis that GIS can perform. Old processes are in most cases automated within the GIS environment but no innovative methods are contrived to change these processes and make them more effective.

Finally, in comparing the results of our survey to the one conducted in 1991 by Dynatrend for the same transit operators only (excluding MPOs and oversight agencies), we observed that the GIS use by transit operators has increased over the years at a moderate rate. In 1991 around 50% of the operators were using GIS compared to 75% by the end of 1994. However, many of the 1991 users did not progress much in their use of GIS. The number and scope of applications did not change considerably over the years.

In the next chapter we shall examine in depth three prototypes of GIS applications to understand the technical complexities associated with using GIS. We shall examine the data structure needed by each application in order to better design sustainable and sharable GIS transit applications. Chapter 6 is a digestion of all previous chapters. It encapsulates all the difficulties and complexities discussed in the previous chapters and classifies them into several categories. This helps in designing strategies for addressing these complexities.

Chapter 5

Prototypes of GIS-Based

Transit Applications

In this chapter we describe three GIS-based prototypes that we built to demonstrate the use of GIS in transit applications and to grasp the technical complexities related to using GIS for building transit applications and to designing the required databases. When applications are built with the intention of making their data structure usable by other applications, the process can become very complex. In this chapter we will first explore the "what does it take" to utilize GIS for each of three prototypes, discuss the general deficiencies and strength of GIS for meeting the requirements of each application, and expose some of the complexities relating to building maintainable and sharable GIS databases. The long term viability of building GIS-based applications depends to a large extent on whether each of the various applications can be built upon a standard set of databases, base maps, and tools. In the next chapters we address all these complexities at

length and suggest some procedures or a framework for dealing with them.

The three GIS-based prototypes that we describe in this chapter are the following:

1. A GIS-based passenger information system (PIS).
2. A GIS-based ridership forecast model.
3. A GIS-based tool for targeting major employment centers.

We developed these three prototypes over the last few years and the results of the research were published in the proceedings of conferences or in transportation journals. Major parts of this chapter are hence extracted from the following publications:

1. Azar K.T. and J. Ferreira Jr., "GIS for Transit Passenger Information Systems," Proceedings of GIS for Transportation Symposium, March 1991, Orlando, Florida.
2. Azar K.T., "Integrating Geographic Information Systems Into Transit Passenger Information Systems," Masters Thesis in City Planning, Massachusetts Institute of Technology, May 1991.
3. Azar K.T. and J. Ferreira Jr., "Visualizing Transit Demand for Current and Proposed Transit Routes," Proceedings of GIS for Transportation Symposium, March 1992, Portland, Oregon.
4. Azar K.T., L.L. Wiggins, and J. Ferreira Jr., "Using GIS Tools to Improve Transit Ridership on Routes Serving Large Employment Centers: The Boston South End Medical Area Case Study," Computers, Environment and Urban Systems, Volume 18, Number 3, ISSN 0198-9715, May/June 1994.

Note that all the above prototypes were developed using UNIX Arc/Info[6] software. However, in our discussion of GIS, its capabilities, and its deficiencies we shall be

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[6] ARC/INFO, Environmental Systems Research Institute, 380 New York Street, Redlands, California 92373

talking in generic form as much as possible and not referring specifically to Arc/Info unless explicitly stated.

5.1. GIS-Based Passenger Information System Prototype

In this prototype we examine the feasibility of using GIS technologies to build so-called Passenger Information Systems (PIS) used by marketing departments to assist in trip planning. First, we describe a typical PIS and describe various options for adding certain mapping capabilities to a PIS or building PIS capabilities within a standard GIS environment. Then we build a prototype PIS using a commercially available GIS package and compare it to that of custom-built PIS systems. Finally, we develop conclusions regarding the practicality of integrating PIS and GIS functions, the technological improvements that will benefit such efforts, and the system design strategies and database development efforts that can help transit agencies make effective use of GIS technologies.

5.1.1. The Components of a PIS

A PIS is a 'turnkey' system used by transit agencies to do trip planning. That is, an analysis package that helps customers determine how to use transit to plan a trip from an origin address to a destination address. The customers usually call the agency and ask about how to get from point A to point B at a particular time of day. The customer service operator who answers the phone types the origin and destination addresses and the desired arrival time into a computer terminal and the PIS package then does all the calculations (usually on a mainframe) that are needed to plan the trip. The results are provided in textual form -- that is, written instructions about the nearest bus (or train)

stop, the bus to take, any transfers that are required, where to get off, and how long the trip will take.

The three main defects of existing PIS systems are: (1) the inability of the transit operator to generate a map showing the proposed route, (2) the difficulty in updating and maintaining data, and (3) the comparatively high cost of these tools[7]. The first problem is potentially solved by using GIS technology to draw a map (either on the computer screen or on a printout) showing the origin and destination, the selected transit routes, transfers, and bus stops, and the surrounding streets and landmarks. The second problem (maintenance) could be helped by the same mapping tools if they allowed street segments, routes, and bus stops to be edited graphically (by pointing to the appropriate spatial feature on the screen). The third problem (cost) might be helped by building a PIS using standardized encoding of street networks and transit routes and generic mapping tools (instead of a customized, turnkey system).

To be functional and maintainable, a PIS with a mapping component must address the following capabilities:

1. *Encoding the road network* so it can be drawn to scale, used to locate street addresses, and efficiently maintained;

2. *Encoding the transit routes* so they can be drawn to scale, linked to bus stops and schedules, and efficiently maintained;

3. *Encoding connectivity, transfers and time* restrictions for the transit routes so that

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[7] The total development and implementation cost of the PIS's used by the Washington Metropolitan Area Transit Authority (WMATA) and the Massachusetts Bay Transportation Authority (MBTA) are $1,635,000 and $1,500,000, respectively.

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trips that combine routes can be constructed;

4. *Matching addresses* for the origin and destination to the appropriate street segment (and, hence, to the nearest bus stop);

5. *Pre-assigning street segments to bus stops* so it takes less time to find the bus stop that is closest to the origin and destination addresses;

6. *Finding the shortest path* along the transit routes from the origin stop to the destination stop;

7. *Packaging* the steps into a friendly application with appropriate graphics, functionality, interaction, and speed.

The mapping and spatial analysis capabilities can be incorporated either by adding GIS functionality to a PIS or by adding PIS capabilities to a standard GIS package. Since it uses standard GIS tools, one might expect the latter strategy to be a less expensive way of combining graphic and PIS tools. In any event, the cost of constructing and maintaining the required databases could be reduced (or at least spread across more transit and highway applications) if they were encoded in a standard format. In order to test these assumptions, we undertook to build a prototype PIS system using, as much as possible, standard datasets that are accessible to any transit agency, and standard network algorithms and GIS capabilities.

In general, the following data are required:

1. *Road network* -- a digital representation of the road network in a form that encodes sufficient positional accuracy, network connectivity, and address information to support meaningful visual display, address matching and shortest path computations. (The TIGER and DIME formats are standardized and well-suited for this purpose.)

2. *Routes* -- a digital representation of the bus and transit routes which is consistent with the road network files (in terms of positional accuracy and network connectivity), but which must have additional information and attributes such as bus-only or rail-only segments (that aren't included in the road network), connectivity restrictions (such as routes that cross without making transfers possible), and the location of stops (which need not occur only at road intersections).

3. *Schedules* -- the scheduled times, for each route, of arrival/departure of vehicles at each stop. In general, these schedules differ by day and by time of day.

5.1.3. Building a Prototype PIS Using GIS Tools

While building a PIS using GIS tools is conceptually straight forward, few GIS packages come with enough tools to enable the PIS application to be built with only the "off the shelf" packages. Many software packages can display road networks (or routes) graphically but most cannot handle all the spatial analysis features listed above. Computer-aided drafting (CAD) packages, for example, could display the graphics, but generally do not represent the road segments and associated attributes in a form that is well-suited to handle address matching and routing models. Most packages that advertise GIS features are able to read (and display) road networks encoded in a TIGER format and can use these data to provide address matching capabilities. However, most such software do not include the required 'shortest path' capabilities, many packages lack the spatial editing and display that would be useful, and almost none of the packages provide sufficient 'macro languages' and other model building tools for the packaging of a PIS application to be a practical application development task.

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The basic idea of the prototype is to pre-process the road network and route information so that PIS capabilities a, b, c, and d (listed above) are represented at the outset as maps ('coverages') and associated data attribute tables in Arc/Info. A prototypical PIS inquiry is then handled by supplying the Arc/Info application with 'origin' and 'destination' addresses and then waiting for the application to do the necessary computations and then draw (on-screen) a map that shows two addresses, the connecting streets, and the recommended stops, routes, and path to get from the origin to the destination. Each step of the entire process is described below:

5.1.3.1. First Step: Encoding the road network

In this step, TIGER files are used to represent the road network geometry and topology in order to create the network map. Each row in the TIGER file contains location and attribute information for a single street segment (i.e., the longitude and latitude of the intersection at each end of the street segment, and the street name and address ranges that identify addresses along each side of that street segment). This scheme for representing the road network is useful for matching origin and destination addresses and geographically locating these addresses on the map.

5.1.3.2. Second Step: Encoding the Bus and Transit Routes

Bus and rail routes were also constructed using data from the TIGER files. They are extracted into a "routes file" from the road network file created in step 1. The routes file is a subset of the larger road network and hence has fewer links and nodes. Nevertheless, the extracted links have the same geometry, links and node numbering as the network file links in order to ensure certain desired consistency between the two map coverages and to facilitate the transfer of attributes from one to the other.

5.1.3.3. Third Step: Encoding connectivity, transfers and time

When a GIS is used to represent streets as (center) lines, the intersection of two links generally implies connectivity. (This is because GIS tools tend to focus on 2-dimensional 'planar' geometry that doesn't explicitly account for the geometry of 'overpasses'.) However, in the case of transit, connectivity does not necessarily exist at any intersection of two routes. For instance, a rail line might be crossed by a bus route where no transfer is possible at that intersection. To accommodate this possibility (and other turn restrictions that might complicate the path that one can take through an intersection), one must have some additional capacity to store information (e.g., in tables) that are linked to specific nodes (intersections) in the map and data files that contain the routes and the road network.

5.1.3.4. Fourth Step: Pre-assigning streets to bus stops

For simplicity, we assume that people always begin their transit trip at the nearest bus stop to their origin and then get off at the nearest stop to their destination. (Other more complex options are discussed later.) In order to speed up the PIS process, every street segment is pre-assigned a 'closest' stop. This allocation operation is run beforehand and its results are added to the attributes of the roads network file. As a result, every address can be associated with the nearest stop to it much more rapidly than if we had to recompute which stop is closest every time we ran the PIS application.

5.1.3.5. Fifth step: Address Matching

The road network file is used to locate the origin and destination addresses. GIS tools, in general, are provided with the capability of matching an address to the TIGER street segment containing the address. In order to integrate this capability into the PIS

application, however, the results of the address match must be supplied in a form that can be used in the next step i.e., finding the *id* of the nearest stop to that street segment. Just because a package can highlight on-screen the street segment containing the matched address, it may not be able to pass the *id* of that link along to another command needed to accomplish the next step.

5.1.3.6. Sixth Step: Finding Shortest Path

After identifying the nearest stops to the origin and destination addresses, the shortest path between these two stops is calculated. The shortest path is determined based on some measure of time (or cost) for each possible path from origin to destination. Variations of standard "shortest path" algorithms can be used to find the "best" path.

5.1.3.7. Seventh Step: Packaging

A scripting or 'macro' capability is needed in order to link the above six steps and to use the output of one operation as the input for another. The basic strategy we adopted is to run steps one to four in advance, and then to package steps five and six into a macro. The macro is used to match the origin and destination addresses to the address coverage, identify the internal number of the links where addresses matched, find the nearest stops attached to these links from the TIGER coverage, and use these nearest stops to determine the shortest path between them. Finally, a series of display commands are used to draw the required features, labels and routes on-screen.

5.1.4. Limitations of Using GIS to Build the Model

The model is built on many assumptions, and the updating of routes in it is quite a sophisticated process. The defects of the model can be attributed to either the

limitations of GIS tools in general or to Arc/Info's specific capabilities. The following is a list of assumptions that were convenient but questionable and a discussion of several other limitations of the model:

5.1.4.1. Assigning Links to Nearest Stops

It is assumed that every address has only one stop close to it and this stop can be used for travel in any direction or any distance. In fact, more than one stop might be close to an address and different stops might be good for different travel purposes or different directions. For example, it might be that one address is located between two bus stops or is close to a train station and a bus stop. The train station is usually the one useful for long trips while the bus stop for short ones. Moreover, the closest stop to an address might not always be the best for all kinds and directions of travel. In this model, however, every address is assigned only one stop regardless of the direction of travel, and the direction and the type of travel are not taken into consideration while allocating stops to links.

One way of reducing the simplisity of this assumption, would be the assignment of two types of stops to every link: "local stops" and "express stops". Local stops can be the nearest bus stops and light rail stops, while the express stops can be the nearest heavy rail and train stations. The allocate command can be run twice to allocate to every link a local stop and an express one. The shortest path between each of the two origin near stops and each of the two destination near stops can be calculated, and the shortest one of the four possible combinations would be considered the best.

5.1.4.2. Absence of Time Factor

The model does not take into consideration any time-of-day factor. It also assumes that

in-vehicle travel time or travel distance are the only factors which determine the shortest path. Waiting time is not given any consideration. In reality, bus schedules vary across the time of a day and a morning path between two addresses might be different than the evening one for the same addresses. Moreover, the standard shortest path algorithms used by GIS software, such as Dijkstra algorithm, are not the appropriate ones in networks with travel times that are both random and time-dependent. More adequate algorithms, such as the "time-adaptive route choice"[8], should be used instead.

Also, the assumption that distance of a stop from an address is the only criterion for selecting a stop is not correct. The level of service of different lines is an important factor that needs to be considered too. That is, the headway between buses at a stop which is within 5 minutes walking distance from an address might be much larger than the one at another stop which might be 7 minutes walking distance from that address, for example.

Incorporating time factor into the model would render the task of coding it very complicated. A simplified way of incorporating time would be to include waiting time and delays in the turntable. The expected waiting time at every stop (which can be approximated to half the headway,) can be added to the delay time for every stop in the turntable. To accommodate for the variation of the schedules, three delay times can be created for every stop: morning peak, evening peak, and off-peak delays.

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[8]-Randolph W. Hall, "The Fastest Path Through a Network With Random Time-Dependent Travel Times," Transportation Science, Vol.20, No.3, August 1986.

5.1.4.3. Adding Nodes to TIGER

In a GIS, path-finding algorithms require that origins and destinations should be located at nodes. Nodes in TIGER files, however, represent street intersections only. Bus stops are not always located at streets intersections but sometimes along a street between two intersections. If bus stops are to be inserted by splitting the arcs, the default behavior of GIS implementation would be to assign all the attributes of those links to both parts of the split arcs. For example, the same address range would be assigned to both arcs while in reality it should be rearranged proportionally to the length of split arcs or more accurately based on parcel/lot sizes. As a result, when matching addresses, more than one location would match a certain address which would disturb the running of the program. Furthermore, the splitting of arcs would create new link internal id-numbers and new node numbering which would cause the loss of cross-referencing IDs between the TIGER coverage and the old routes coverage, unless the route coverage is explicitly rebuilt on top of the updated TIGER file. However, the problem of rearranging address ranges would remain unsolved, unless manual changes of addresses are done. In other words, handling the representation of stops along TIGER segments by splitting the segments where needed is a problematic approach.

On the other hand, current GISs, in general, lack the capacity to store data related to nodes. Nodes in a GIS can only be identified by referring to the links connected to them. If nodes are deleted or added to a coverage, and the topology of that coverage is then rebuilt, then these node numbers will be reshuffled and matching the old node numbers to the new one is very complex, if not impossible

5.1.4.4. Shared Arcs Between Multiple Routes

A GIS does not handle every route as an entity by itself, but rather as a set of links and

nodes. In other words, routing programs in a GIS are built on link and nodes concepts. A shortest path program, for example, would check every link connected to a node while calculating a route. Some of the links connected to a node might not be a part of a route. A "look-up" table of turn attributes for each intersection (that is called a "turntable") is used to set a negative impedance for these links to inform the program to exclude them while calculating shortest paths. The turntables, however, do not function properly in the case of shared links between multiple routes. This idea is better clarified in the following example:
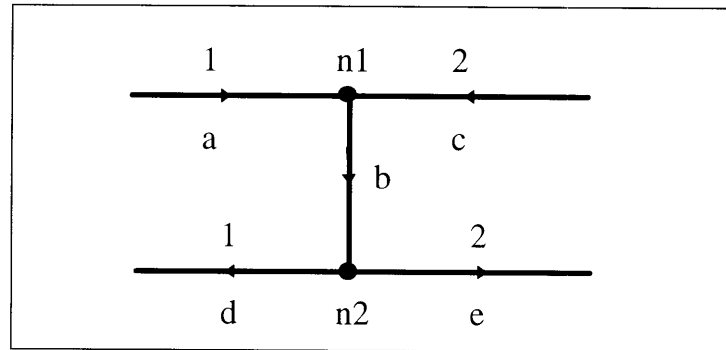
Links 'a', 'b' & 'd' belong to route 1, while links 'c', 'b' & 'e' belong to route 2. Link 'b' is common for both routes. the turntable can be used to set negative impedances at node n_1 for flows coming from link 'a' to link 'c' and vice versa in order to refrain the flow from going in the wrong direction. The flow on the 'b' link can be either the one coming from route 1 or route 2. The turntable at node n_2, however, can not be used to inform the program that only the flow coming from link 'a' can turn to link 'd' and only the flow coming from 'c' can turn to link 'e'. At n_2, the flow should be allowed from 'b' to both 'd' and 'e'. As a result, flow coming from link 'a' can go to link 'e' and the one from link 'c' can go to link 'd'. As it might be the case that no stop exists at node n_2, the GIS would hence generate wrong routes when a link belongs to multiple routes.

Many GISs have recently implemented a newer data structure that allows "routes" to be abstracted from street segments. This new data structure, however, does not allow the utilization of the the "route" features for performing routing algorithms. They are more useful for querying and displaying objects along linear objects using the "base point" referencing scheme (whereby the location of objects is measured as an offset from a base point).

5.1.4.6. Limitations of Arc/Info's ALLOCATE Function

The ALLOCATE function in Arc/Info is used to assign resources (links) to centers (stops). Centers in Arc/Info should be always located at nodes. In TIGER files, nodes represent street intersections only. Therefore, in the ALLOCATE module, bus stops can be created at street intersections only. In a city however, it might be true that most of the bus stops are located at street intersections, but still there are many stops located along some of the links. The problem of creating nodes at these locations is discussed above (Section 5.1.4.4). Relocating stops at intersections might be an inaccurate (but to some extent acceptable) approximation. The ALLOCATE module has the capability of locating addresses but lacks the capability of setting centers at certain addresses (which is needed for many other useful applications).

5.1.4.7. Limited Capabilities of Macro Language

The macro language used by Arc/Info is somehow limited. While it provides numerous ways to store variables and return function values, it lacks the capability of setting the output of one operation as the input for another operation within a different Arc/Info module. The results of an operation have to be written into a file which can be read by another operation as the source of input. These operations of opening files,

writing, reading, closing of files, and loading modules in out of memory result in a low efficiency in terms of running time. The point is that the limitations are not just related to the macro language itself, but also to the high time cost of implementation overhead for many operations and information transfer among modules. We elaborate more on these limitations in Chapter 7 when we discuss the software-related complexities of GIS.

5.1.5. Model Evaluation / Concluding Remarks

In the comparison of the GIS-built model to the customized one used by the MBTA in boston, the following issues are considered: network size, running time, form of output, data ownership, data maintenance, platforms, software design, and estimated cost (see Table 5.1).

(1) Network Size: The network used by the MBTA's PIS is based on DIME files and consists of more than 90,000 links, around 350 bus routes (including variations), and 7500 stops. The GIS-built model is based on TIGER files and consists of 200 links, 4 routes, and 12 stops.

(2) Form of Output: The output of queries in the customized system is displayed in the form of text and consists mainly of stops and bus route numbers, and times of travel. In contrast, the query results of the GIS-built models are both graphical and textual. A map showing the origin and destination addresses, the nearest stops, and the routes is drawn.

(3) Data Ownership: Although the MBTA paid around $1.5 million for their system (including the hardware), the developer of their PIS owns the proprietary rights for the code and the data structure used by the system as well. Such a problem is more easily negotiated if standard GIS tools are used to build the model and if the model can input and output data in a standard non-proprietary formats in which much data are already available (e.g., TIGER files).

Table 5.1 - GIS-Built versus Custom-Designed PIS		
ISSUES	GIS-BUILT MODEL	CUSTOMIZED PIS
Network Size	200 Links	90,000 Links
	4 Routes	350 Routes
	12 Stops	7500 Stops
Running Time	40 sec (DECstation)	10 sec (Amdahl)
Form of Output	Graphic and Text	Text only
Data Ownership	Public	Proprietary
Data Maintenance	Flexible	Difficult
Platform	IBM PS2 / DEC 3100	Amdahl Mainframe
Software Design	Standard Tool	Customized
Modularity	Front-End to Standard Tools	Black Box
Estimated Cost	?	$1.5 Million

(4) Data Maintenance: The lack of graphical tools and the overlaying capabilities in the customized PIS are the major handicaps to the data maintenance process. The PIS used by the MBTA, for instance, is fitted with some tools for the updating of the databases. However, almost 10% of the DIME file records used by the system are

believed to be inaccurate. As a result, for two years, the MBTA's marketing department has worked on updating these records. In the DIME files, for example, many of the streets cut through buildings or are connected to other streets where in reality no connection exists. Field checks are needed to identify these records. The overlaying capability of the GIS, however, would save the trouble of site inspections in many situations. As more municipal agencies adopt GIS, accurate street network maps that will help edit transit routes will be accessible to a PIS tool that handles standard GIS data formats. For example, the map of Boston, at the block level (digitized by the city from aerial photography and transformed into a format readable by standard GIS tools), could be overlayed on top of the existing DIME file to facilitate the identification and updating of wrong records. Moreover, the GIS-based system can more readily accommodate standard road network data that could be shared across applications in the transit agency or across agencies (as we shall in the following chapters).

(5) Platforms: The MBTA's PIS runs on a mainframe (Amdahl), while the GIS-built model runs on a DECstation 3100. The MBTA's PIS is a multi-user system which can run many queries simultaneously by accessing the same databases and the same programs from different terminals. The GIS-built prototype is capable of supporting multi-user functions (although some parts of the macro would have to be changed to avoid conflict over filenames). By Multi-user PIS, we mean a system where the database, programs, and graphics components are accessible and executable by different users from different terminals at the same time. The GIS-built model is characterized by having all its components accessible by different users simultaneously but having some of its programs executable one at a time. The graphics component, for instance, can be accessed by different users at the same time and maps of the same region can be drawn simultaneously. However, many of the intermediate

steps in the macro require the use of intermediate files whose names must be altered to accommodate different simultaneous users. This was not done for the prototype. If multiple users ran the current prototype simultaneously, they would be writing and deleting the same files and would get unpredictable results.

(6) Software Design: The Customized PIS used by the MBTA is very efficient at performing routing queries, but lacks the flexibility of integrating, or being integrated into, other systems. The proprietary rights of the builder, however, refrained us from investigating the software design details. The GIS model, in comparison, is built as a "front-end" to standard GIS tools. The address-matching, finding of shortest path, allocation of resources, and graphical display capabilities are standard/general purpose GIS tools that can be used to build a PIS model. In Arc/Info these tools are packaged in different modules and a macro language is used to create the link between the different modules. This modularity added to the weakness of the macro language contributes to the low efficiency, in terms of running time, of models built on top of these modules.

(7) Cost: Cost comparisons are difficult since the prototype was not designed for multi-users and high transaction operations and since very little data are available from the MBTA about the cost details of their system. It would have been interesting to breakdown the cost into initial, recurring, and dependent as suggested by Shier and Gilsinn [1977], but for the same reasons such a comparison is not possible. Also, the cost and benefit associated with each option can be direct or indirect. The GIS-built models have the advantage of cheaper initial cost, but as illustrated above, the GIS tools are not geared at specifically performing the PIS functions and hence are not as efficient as the customized systems, which have additional indirect cost. On the other hand, the cost of adding a GIS to a PIS in order to be used as the tool for the graphical

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display of query results might be negligible compared to the initial cost of a customized PIS. However, the benefits gained from such an operation may not be worth the effort if the "black boxish" feature of the system remains unchanged and the ability to update and share data remain very complex.

(8) Running Time: In the custom-designed PIS, the average running time of a query is around 10 seconds, compared to 40 seconds on the GIS-built model. To understand the difference in running time we had to examine where the time is spent. We found that most of the times is spent on the overhead caused by the modularity and the structure design of Arc/Info rather than on the effective computational time of the programs. We shall elaborate more on this issue later in Chapter7.

As mentioned before, the question of whether Arc/Info is an appropriate tool or not, can not be easily answered, especially since some GIS software that can overcome some of Arc/Info's limitations lack some of its other capabilities and functions that are quite useful for the PIS example. Also, the question of whether the characteristics of the PIS used by the MBTA are typical of PIS's used by transit agencies in general or not, is also hard to answer. It is worth noting, however, that Southern California Rapid Transit District (SCRTD) and Regional Transit District in Denver, were using early versions of the same PIS software used by the MBTA.

The primary advantage of building a PIS on top of a GIS is flexibility. Obviously the ability to visualize query results and the comparative ease in editing data are the direct benefits of using GIS in general. In a transit agency, where the same data is used for different applications in different departments, the data sharing issue can be of great importance. The use of GIS to build a PIS allows the importation/exportation of updated network data from/to other applications which saves all duplication work

between departments and results in the standardization of data coding across the agency.

Finally, the current structure, modularity, user interface, and macro languages of GIS software are limiting the usefulness of building a PIS on top of a GIS. These factors render the "out of the box" GIS imperfect in handling complex operations, such as building a PIS, which require the use of more than one module and the transfer of results between programs. As GIS technology becomes more unbundeled and modular, the need for improved internal programming language will increase. Together with advances in workstation technology, then changes will make it much easier to build efficient tools for PIS type applications. Most likely, such applications will enable complex and modular routing algorithms to handle PIS routing problems while using data and displaying results through convenient links to standardized GIS packages. We shall dwell more on these issues later in this thesis.

5.2. GIS-Based Ridership Forecast Model

The second prototype we built for this research is a GIS-based ridership forecast model. The objective of this prototype is to examine the benefits of using Geographic Information Systems (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 the characteristics of a transit service. The transportation literature describes a large number of models developed for the estimation of transit ridership. However, most such models require a considerable amount of data and computational power and are complex enough to make them difficult to use given the resources available to

the average transportation planner. Less complex models with decreased data requirements and relatively simpler algorithms also exist. While these models may be less accurate in forecasting the system equilibrium effects of major changes on routes, they can be helpful in analyzing the (quasi-static) effects of changes on individual bus routes and corridors. In this prototype, one of these simpler models is encoded inside a GIS in order to explore the potential of the geographical capabilities of GIS technology to make such models more user-friendly and flexible.

5.2.1. Selection of Transit Ridership Forecast Model

As discussed in the literature review chapter, the four-step travel demand models are generally used to determine transit ridership between each traffic analysis zone of a study area. The sequence of trip generation, trip distribution, modal split, and trip assignment models generate transit trip tables. Calibration models which use on-off passenger counts are used to correct the transit trip tables. See Stopher and Meyburg [1975], Morlok [1978], Manheim [1979] for further reading about the 4-step travel demand models. In Chapter 2, we also discussed some of the literature related to the potential benefits of GIS in improving the various phases of the four-step travel demand models [Nyerges and Dueker 1988, Nyerges 1989, Lewis 1990, Shaw 1993]. These 4-step travel demand models are generally good at forecasting ridership, although sometimes they are not as reliable as desired because of the many assumptions often made due to lack of data. Moreover, the process of data procurement, model calibration, and results validation is so complex that simpler models [e.g., Smith 1979, Batchelder et. al. 1983, Krechmer et.al. 1983, Tri-Met 1983] start to look desirable.

These simpler models are appropriate for exploring short-range, route-level effects where the route alignment and scheduling changes under consideration are local in nature and unlikely to have significant system-wide repercussions that would necessitate recalibration of the trip generation, trip distribution, or modal split patterns. Such situations are the focus of concern in this prototype. That is, we are interested in how GIS can help transit planners explore the sensitivity of ridership to local changes in route alignments and schedules by providing interactive tools for re-computing and displaying routes and ridership patterns that are likely to result under various 'what-if' scenarios. In particular, we are interested in models 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. The "Period Route Segment" (PRS) model, developed by Batchelder et al. [1983], most closely matched these interests and was selected for use in this prototype as an example of the type of (simpler) model that could be incorporated into useful GIS tools for exploring routing alternatives.

We expect the value of using GIS technologies to extend beyond providing a map-based 'front end' to the demand model. Even when route, ridership, and demographic data are readily available, calibrating and running the models requires the integration of many layers of information in a useful and meaningful fashion. Merging information about local land use and the socio-economic characteristics with the relevant transit routes and ridership data is quite complex. This complexity is related to the many layers of detailed information that need to be stored and maintained and to the need, on occasion, to investigate the effect of more than one layer at a time. Moreover, as digital land use information and

related maps become more common place, it is increasingly likely that some of these layers are generated and maintained outside the transit agency. Hence, there is an increasing need to have systematic and robust capabilities for integrating and managing large sets of geo-referenced data and computing spatial overlays (i.e., combining several layers of information together based on geographic location). This is especially true for analytic tools aimed at providing interactive, exploratory capabilities.

5.2.2. Period Route Segment Model

The "Period Route Segment Model" was developed for the Southern California Rapid Transit District (SCRTD) by Multisystems[9] as part of Urban Mass Transportation Administration (UMTA)[10] research aimed at developing and testing improved route-level ridership prediction techniques. This model estimates the A.M. peak and the midday boarding in each direction for every segment of a route based on the characteristics of the route and the service provided. Separate calibrations are developed for each period of time.

Ridership on a segment is a function of three factors, according to this model: (1) a "production factor" related (via demographics) 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 the service provided along a route. The

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[9] Multiplications Inc., Multisystems, the Consulting Division, 1050 Massachusetts Avenue, Cambridge, MA 02138.

[10] Now known as Federal Transit Administration (FTA).

general form of the model is:

$$BOARD_i^d = PROD_i * OPP_i^d * LOS_i^d$$

where:

$BOARD_i^d$ is the boarding count on segment i in direction d;

$PROD_i$ is the trip production factor in the area around segment i;

OPP_i^d is the trip opportunity factor in direction d from zone i;

LOS_i^d is the quality of service in segment i in direction d.

The production factor represents the ability of the area surrounding a transit route segment to generate trips. Trip production is directly proportional to the number of adults, the total population, the employment, and the route distance in each analysis zone; and is inversely proportional to the level of income in an area. An adjustment factor, based solely on the average monthly rent in a zone, is used as a surrogate for the income level in each area.

The opportunity measure used by the model reflects the capability of area around a transit route segment in the down-stream direction from the origin zone to attract transit trips. It is assumed that passengers are ready to select the transit mode if their destination is at least a 6 minute ride from their origin and at most a 35 minute ride. Transferring passengers are expected to remain on board a second bus for not more than 15 minutes or less than 3 minutes. The opportunity factor is therefore related to population and employment within a quarter mile of the route, for trips between 6 and 35 minutes and (3 to 15 minutes of transfer bus ride time) from an origin.

The level-of-service factor is based on the expected wait time for service and the seat availability on a bus. The wait time is directly related to the average headway between buses, whereas the seat availability is dependent on the cumulative

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running time of a bus. It is assumed that at peak hours seats become less available as the bus approaches the end of a route[11]. The specific model formulae and variables are given in Appendix 3.

5.2.4. Encoding the Model Inside a GIS

The Period Route Segment (PRS) model requires the computation of several variables which have a spatial attribute. 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, can be manually calculated or approximated from maps. A GIS system, in addition to its capability of more accurately and quickly computing these variables, is also useful in permitting visual examination of the alignment of transit routes and the results of "what if" adjustments to the characteristics of these routes.

Some of the variables that are required by the PRS model are readily-available while others require significant manipulation. U.S. Census block group boundaries and related census data are sources of much of the needed information. The transit analysis zones are defined by sets of block groups around a segment of a route[12]. Following is a list of the required variables with the strategies adopted for

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[11] Batchelder also assumes that the transit route originates from an area of trip productions and terminates in an area of trip attractions. As a matter of fact, seats may not become less available as the bus approaches the end of the route. Seat availability can be thought of as a function of the number of trip production points (stops) and trip attraction points which have already been passed. Thus a bus that originates in a residential area will have its seat availability decline until it begins to pass bus stops which also serve some trip attractions (i.e., employment, transfer or shopping) sites.

[12] Many metropolitan planning organizations (MPOs) in the U.S. have estimates, at the block group level, on job locations and employment data. Transit planners can refer to their local MPOs for such information. Alternatively, at the cost of reducing the accuracy of forecasts, the analysis can be conducted at the census tract level instead of the block group level.

computing each:

5.2.4.1. Production Factor

The production measure for each analysis zone is based on the average monthly rent, total population, adult population, number of riders on routes that cross or feed the study route, and the route length within the traffic analysis zone. Rent and population data are available from the U.S. census, whereas the number of potential transferring riders and the route distance need to be computed. As discussed above, the model assumes that the area that produces transit trips is the one within walking distance from a route (i.e., a quarter mile)[13]. To estimate the adult and total population that generates transit trips, it is first assumed that the population density is evenly spread and then the buffering capability of GIS is used to compute the number of people in every census tract within walking distance from the bus route.

Many GIS tools have routing capabilities which are useful for calculating some of the other variables. They can, for example, calculate the cumulative length for every arc[14] of a route, which can be attached as an attribute to that arc, and then used to divide a route into segments of a specified length. This capability is first

[13] A better measure for determining the area that produces transit trips is the walking distance from bus stops instead of bus route segments. The GIS has the capability of buffering around both bus stops and bus route segments. However, in many instances, stops are close enough to each other (less than a quarter mile) that the assumption made by the PRS model is quite reasonable. Furthermore, given that the walking distance is a very subjective measure (varies from one to three quarter of a mile depending on individuals), buffering around stops instead of segments does not really add much to the accuracy of the model.

[14] In our model, arcs were defined by street intersections. Each arc starts and ends at a street intersection. A bus route segment is a set of consecutive arcs. For bus route studies, segments that begin and end at stops would be preferable. However, it is often useful to define routes in terms of a widely used street network file (such as those provided in DIME and TIGER formats) that are topologically encoded (refer to Azar & Ferreira, 1991). Since the differences are generally significant only for long streets with midblock stops, we have retained the normal street segmentation for this study.

used to determine the segmentation of the route and to calculate the route-distance variable for every analysis zone.

Estimating the number of riders coming from routes that cross or feed the study route is not so straight forward. The PRS model uses the number of riders on cross routes to estimate the number of transfers. The GIS can be used to automatically identify the routes that cross a segment of a route. Alternatively, other available data can also be used to estimate the number of transfers. Ridecheck data, specifically the number of passengers alighting at every stop, are used in our model to determine the number of potential transfers from stops which are within walking distance from every segment. It is true that this variable is not exactly equal to the number of riders on routes that cross the study segment but since the model needs some calibration, as will be discussed later, and since the number of passengers alighting at stops within a quarter of a mile is highly correlated to the number of transfers, this measure can be considered as a reasonable surrogate to the one used by the PRS model.

5.2.4.2. Opportunity Factor

Four variables need to be computed for the opportunity factor. The variables are the employment and the population within a quarter mile of the route between 3 and 15, and 6 and 35 minutes of bus ride downstream from the study segment (i.e. $EMPL^d_{3-15}$, $EMPL^d_{6-35}$, POP^d_{3-15}, and POP^d_{6-35}). The cumulative length of the arcs is used as the measure of how far an arc is from a study segment. The model uses the average speed of the transit vehicle (i.e., route length divided by total running time), with the cumulative length to identify the arcs that are within a certain range of ride time from an origin segment. The method used to calculate the employment

and population number in these zones is to first identify the included arcs, then to create a quarter mile buffer around them, and finally to intersect that buffer with the block group boundaries to calculate the proportion of these block groups falling within the buffer and the corresponding number of people or employment in those areas[15].

5.2.4.3. Level-Of-Service Factor

The average headway of buses and the cumulative running time from the beginning of the route to the analysis segment are the only required variables. The average headway is a variable that can be specified by the transit planner. The model is very sensitive to this variable and ridership estimates can change drastically between a headway of 10 and 25 minutes, for example. Seat availability is dependent on the cumulative running time of a bus. This is related to the assumption that the PRS model makes, that is, bus routes, in general, run from zones of trip production and end in zones of trip attraction (i.e., from residential areas to central business districts). The cumulative running time can be computed, as above, by using the cumulative length of the route and the average speed of the bus.

5.2.5. Model Results / Calibration

Basemaps and 1990 census data for Boston were used to build a working prototype. 1990 TIGER line files and census block group boundaries were loaded

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[15] The "Journey to Work" data that the U.S. Census Bureau releases contain employment information at the block group level. Some aggregation and manipulation processes need to be done to these data bases before being used to build the PRS model.

into Arc/Info software along with population and employment location data from the 1990 census and selected ridership data and route alignments and schedules for Metropolitan Boston Transit Authority (MBTA) bus routes. In this prototype we use Route 10 to apply our prototype forecast model. This route connects a residential neighborhood (South Boston) with Back Bay Station (the northwest terminus of the route). Arc/Info has the spatial data processing tools required to calibrate and run the PRS model as described above. It also has a macro language that allowed us to build an interactive user interface for computing and graphically displaying the model results. The model requires as input a route file (coverage) and some calibration factors including expected average speed and the headway of buses. The model displays a street map, bus routes, and other features as shown in Figure 5.1 and prompts the user to point to an end of the route which is to be used as the origin for the analysis. The model then displays the selected route, divides it into modeling segments of approximately one mile lengths[16], and shows the estimated AM peak and midday riderships on each modeling segment plus the total ridership on the whole route for both time periods (see Figure 5.1). On screen, the modeling segments are shown in different colors so that it is easy to relate the ridership estimates to their physical location. Likewise, the coloring and the use of line weights enable the route segments and buffers to be displayed on top of the road network and the thematically shaded demographic information (population density in this case) without being too confusing.

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[16] The GIS was used to create these modeling segments. The procedure used for defining segments consisted of first starting at one end of the route and then picking individual street segments until the target length of each modeling segment is at or just above 1 mile.

FIGURE 5.1

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FIGURE 1

LEGEND: ⊠ BUS STOPS OF ALL ROUTES

POPULATION DENSITY:

VERY LOW   LOW   MEDIUM   HIGH   VERY HIGH

SEGMENT 1   Peak Boarding   : 73
             Midday Boarding: 134

SEGMENT 2   Peak Boarding   : 82
             Midday Boarding: 162

SEGMENT 3   Peak Boarding   : 21
             Midday Boarding: 47

SEGMENT 4   Peak Boarding   : 63
             Midday Boarding: 130

SEGMENT 5   Peak Boarding   : 80
             Midday Boarding: 175

ROUTE 10
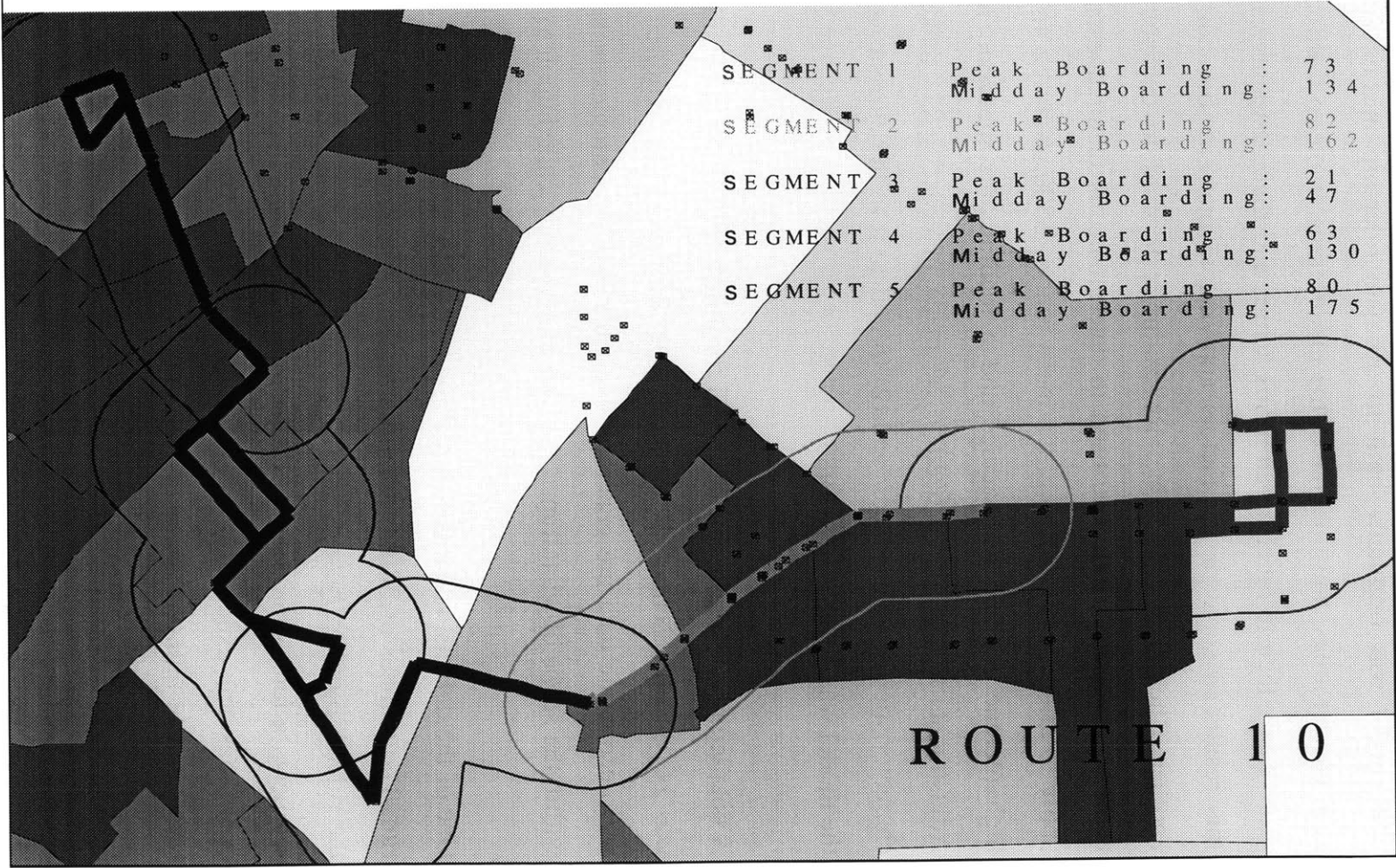
The model was originally built to estimate ridership in Los Angeles and its surrounding areas, and this makes the model transferable to California-type cities more easily than to other urban forms. Cities and their residents vary widely, and this results in some of the factors applying to one city but not necessarily to another. The mean rent value, for example, is used to determine the income adjustment factor. The curve used to determine this factor does not necessarily apply to all cities. For example, a mean rent of $500 might be an indicator of a high income zone in some cities and a medium income zone in other cities. Adjustments to this curve need to be made in order to (1) make it match the characteristics of other places; and (2) to update it to the current rent values since the model was developed in 1983.

A detailed re-calibration of the model for a metropolitan area outside Los Angeles was beyond the scope of this prototype. However, the required ridership and socio-economic data are generally available and the complexity and accuracy is within the scope of what transit analysts are typically called upon to do.

One of the defects of the GIS-based model developed here is that it is very slow to run. The number of buffering and intersection operations needed for determining the ridership on every segment is large (9 operations). For a route made up of 5 segments a total running time of 70 minutes is required.[17] However, once these operations are executed, the effects changing model parameters route can be calculated in quite a reasonable time (10 minutes) if the route alignment is held fixed. For example, one might change the value of one parameter in some equation or change one of the values for a global variable (headway, for example), without

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[17] These times were obtained using ARC/INFO software version 6.1 running on a 5100 DECstation with both the data and the ARC/INFO software stored locally.

altering the realignment of the route. In this case, the program can provide relatively quick answers.

Another shortfall of the current GIS-based implementation of the model is that when it calculates the total ridership for the whole route it sums up all the riderships for each segment. This problem is better clarified by examining the picture of the buffers around each segment (refer to Figure 5.1). Notice that there is a large overlap between these buffers, and that double counting of ridership occurs when adding the single estimates for each segment to obtain the overall estimate. The estimates for each segment, taken individually, are correct; but adding them all together to get the total ridership includes each overlapped area twice. This problem could be taken care of by calculating the areas of the overlaps, and then subtracting them off, or by taking longer segments to reduce the number of overlaps and minimize the double counting effect. However, such adjustments would add significantly to the processing time and, often, may not be worth the effort.

5.2.6. Analysis and Conclusions

One advantage of integrating PRS-like models with GIS technologies lies in the resulting ability to see how ridership estimates depend upon the spatial relationships between route alignments and demographic patterns. For example, busy routes tend to be those that traverse areas of high residential or job density (for socio-economic groups likely to use transit). The data overlay capacity of GIS allows these models to better integrate information related to the characteristics of city block groups with the geographical layout of transit routes. Using socio-

economic information, such as population density, income, race, and the like, as the backdrop for displaying transit routes provides a rich set of information enabling analysts to target specific places or groups of people needing improved services. Low income neighborhoods, high population density blocks, or large employment centers are some examples of the data that analysts use for evaluating and designing transit routes and that can be easily displayed and overlaid as the background for viewing route alignment choices. GIS-based models have the advantage of easily capturing and quantifying these information.

The PRS model is successfully replicated inside the GIS. It is fully automated. One can easily display the ridership estimates and give a textual listing of these estimates for each segment and for the whole route. The strongest advantage of the GIS is that it has the capability of doing spatial calculations needed by the model, such as calculating the number of employees or population within a quarter mile from a route or determining the stops where people might make transfers to the study segment. Since the model is embedded as a small set of generic (spatial and algebraic) calculations inside a general-purpose GIS, the basemaps, routes and demographic data can be independently updated, maintained, and shared for an assortment of multi-purpose applications.

Another advantage of the GIS-based implementation is that ridership estimates are visualized on each segment on the screen relative to their geographical locations. This gives the planner some visual explanation of the results the program is producing and provides a useful means to check the validity of the estimates. Moreover, the visual aspect of the model output is very useful in the planning step of realigning routes based on the results of previous runs. For example, along the prototype route, segment 3 has the lowest ridership compared to the other

segments (refer to Figure 5.1). A transit planner might replace the kinked segment 3 by another more straightened segment. The model can then be rerun and the new estimates compared to current ones. In other words, the visual aspect of the model helps in understanding the relationship between the geographic location of the route and the demographics, and also provides additional suggestions for other "what if" scenarios for the planner to test and explore.[18]

PRS-like models are becoming increasingly useful for route-tuning activities. They provide the ability to test the effect of minor changes to transit routes characteristics on the level of ridership along theses routes. This usefulness is underlined by the fact that the socio-economic data that these models use are now coming more on line. Disaggregate demographic information are now collected by local MPOs and are becoming more accessible to transit analysts. Data sharing between agencies is becoming more of a common practice. Highly detailed information (sometime at the individual block or even parcel level) can now be accessed by transit planners as a result of the data sharing. GIS tools are especially useful in organizing and analyzing such detailed information.

These models could also be used as tools in pro-active route planning. They might be used to evaluate the effects of modifications to the characteristics of routes in order to meet equity and social issues requirements. For example, instead of using trial-and-error to change routes and track ridership changes, the demographic data can be displayed in the background and then used to test different routes alignments with the goal of targeting a specific category of people. Furthermore, if

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[18] In some cases, such 'kinks' result from one-way streets, turn restrictions, limited width roadways, etc. As more and more such characteristics are added to the underlying road network in the GIS, the relative value of integrating PRS-type models with general purpose GIS tools increases.

addresses of employees of large employers are available, they can be matched geographically on the map and bus routes can be redirected in order to target their residences in the most efficient ways. Bus routes could be designed to pass through large concentrations of employees and through their employment locations. The model developed in this stage can be used to estimate the ridership on these routes, and to display the effects of the proposed changes to current routes.

The biggest limitation of the prototype is its slow processing speed -- 70 minutes for the complete analysis of a realigned route on a typical 1992-generation UNIX workstation. Such times prevent the analysis of alternative routes from being the highly interactive and exploratory endeavor that was envisioned. Even the 10 minutes to compute the effects of altered parameters is too long. However, several consideration suggest that time improvements of one or two orders of magnitude will soon be practical. First, technological advances in hardware already enable current (1994-generation) UNIX workstations to be 2 or 3 times faster. Second, the prototype was built using Arc/Info's AML macro language without any restructuring of basemaps and datasets to speed up the types of computations needed for these analyses. Implementing the PRS model at this upper level of programming results in significant system overhead delays as the various modules and tools of Arc/Info are invoked to call each computational and graphical function.

Re-writing the model to take advantage of special data structures and/or by calling lower level Arc/Info functions directly could speed up the process considerably. Of course, such an approach would also defeat the goal of encoding the model using general-purpose GIS tools and standard basemaps and data representations.

However, improvements in software engineering and computer science are gradually allowing GIS tools, functionality, and data representations to be repackaged in ways that are more modular, efficient, and conducive to parallel processing and client-server architectures. In the next several years, such improvements are likely to provide an order of magnitude improvement in performance for the types of transit applications we have considered. Hence, these changes and a continued improvement in processing speed can combine to provide a hundred-fold increase in overall speed in the not-to-distant future while enabling the modeling and mapping tools to be distributed more easily to the transit planner's desktop.

5.3. GIS-Based Tool for Targeting Major Employment Centers

The previous prototype showed one potential application of GIS in transit management and operation, i.e., ridership analysis and forecast on transit routes. Large employment centers, however, need to be conveniently served by transit routes in order to reduce traffic congestion and minimize the need for parking spaces. This prototype describes how planning transit routes can be transformed into a more pro-active process, and how GIS technologies can be used to reach that goal. Our methodology includes using the address-matching capabilities of GIS to pin point the residences of the employees of large employers and to map these locations with respect to existing transit lines and employment sources. A statistical analysis of current accessibility is then completed. This application of GIS technology aids in diagnosing major gaps with existing services to major centers and in proposing improvements to these services.

To provide a concrete example, we use data from three large medical institutions in the South-End Medical Area of Boston. These employers currently claim to be under-

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served by public transport. We examine how well the existing lines are serving these institutions.

5.3.1. Introduction

The traditional process of designing routes can be improved by identifying the potential riders for specific destinations, and re-aligning and re-scheduling routes so as to target the highest possible number of potential riders. This pro-active planning process can be used, for instance, to identify the location of residence of employees of large firms and redirect buses to target these employees. This improved planning process is now possible because of the increased availability of detailed data and the development of tools allowing richer analysis of geographic relationships.

Geographic Information Systems technology provides useful tools for transportation planning and analysis. GIS can be used as a decision-support tool in route planning applications since it is well suited to identifying spatial relationships between an identifiable commuter group traveling to the same location and the location of existing transport services.[19]

In this prototype, we (1) explore the feasibility and practicality of applying, using real-world data, one pro-active route design and route performance method and (2) test whether this analysis can be done in a setting that enables the analysis of the impact of re-routing on broader social goals. This research is intended to serve as a proof of concept and its purpose is to check the complications associated with doing this type of analysis, its usefulness and disadvantages, and its potential impact on decisions

[19] Lycan, Richard and James D. Orrell, "An Analysis of Bus Ridership Potential to Oregon Science University", Transportation Northwest, Final Report TNW90-12, February 1990.

made by transit planners.

5.3.2. Selection of Employment Center

In order to investigate using GIS in a pro-active bus route analysis, real-world data were desirable. A list of major employment centers in the Boston area was obtained from CTPS and the location of each center of employment with respect to the subway lines was examined. GIS tools were used to draw a pin map of these centers on top of the subway network.[20] Employment centers that are within walking distance from any subway stop were eliminated from our selection set. It was assumed that employers close to subway lines have accessibility to the rest of the Boston area by employees making at most one bus to rail transfer. The network of bus routes provided by the MBTA is quite large and covers most of the Boston area.[21] The criteria for selecting employment centers for the case study was that a center must only be served by bus lines (or not served by transit at all). The reason for this criteria was that adjustment to bus services are easier to make than to subway lines.

This criteria also assumed that riders are not likely to make more than one transfer from their origin to their destination. According to a study on bus route demand done in Cleveland[22], it was found that the bus to bus transfer is very minimal and is related

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[20] In the subway network, we included heavy rail and light rail subway lines and excluded the commuter rail (i.e., the red, orange, blue, and green lines of the "T").

[21] The MBTA serves 78 cities and towns in the Boston area. Their network consists of 178 routes and 10,231 stops, and provides 12,905 daily vehicle trips on 1,045 of route-miles. (Source: Massachusetts Bay Transportation Authority, Fiscal Year 1992 Budget Report.)

[22] Krechmer Daniel and Gregg Lantos, "Bus Route Demand Models: Cleveland Prototype Study," SG Associates, Inc., Final Report, August 1983.

to the service frequency on the trip origin bus route and service frequency on the bus route transferred to, whereas the bus to rail transfer is solely related to the in-vehicle travel time from origin segment to the rail station. Applying the model that was developed for estimating the bus to bus transfer, one can get an idea of how minimal these transfers are:

$$PT_{ab}= \begin{cases} 0.498 - 0.1242 \left[\ln (CH_a + CH_b) \right] & \text{if } (CH_a + CH_b) < 55 \\ 0 & \text{if } (CH_a + CH_b) > 55 \end{cases}$$

$$(R^2 = .55, t = 4.68)$$

where:

PT_{ab} = Percentage of passengers on bus route "a" transferring to bus route "b";

CH_a = Combined headway (minutes) for route "a";

CH_b = Combined headway (minutes) for route "b";

Of the 38 largest employment centers[23] (each having more than 1,000 employees) within the Boston area, the Boston City Hospital (BCH), the University Hospital (UH), and the Boston University Medical Campus (BUMC) were identified as good candidates for our research. After getting in touch with these institutions, we learned that the three institutions have recognized transportation problems and are cooperating

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[23] MAJOR BOSTON EMPLOYERS in 1990: Bank of Boston (7,000), Blue Cross /Blue Shield (3,500), Boston Company (2,500), Boston Edison (1,440), Boston Safe Deposit & Trust Company (2,600), Brigham & Women's Hospital (7,200), Children's Hospital (3,700), Boston City Hospital (4,000), Coopers & Lybrand (1,500), American Airlines (1,500), Delta Airlines (2,100), Employers Fire Insurance Company (2,000), FMR Corporation (4,401), Federal Reserve Bank of Boston (1,350), Mass General Hospital (9,900), IBM (1,000), John Hancock Life Insurance (8,359), Jordan Marsh (1,500), Liberty Mutual Insurance (2,750), Mass Eye & Ear Infirmary (1,100), New England Baptist Hospital (1,200), New England Deaconess Hospital (2,248), New England Medical Center (3,800), New England Mutual Life Insurance (3,400), New England Telephone (1,800), Northeastern University (2,500), Boston University (4,800), Shawmut Corporation (2,100), St Elizabeth's Hospital (2,500), State Street Bank & Trust Co. (1,350), Stone & Webster Engineering (3,400), Beth Israel Hospital (4,200), First National Bank of Boston (4,000), Gillette Company (5,000), Filene's (3,000), US Postal Service (4,000), University Hospital (2,000).
Source: Central Transportation Planning Staff (CTPS), Boston.

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together to address these problems. As a matter of fact, they have organized a transportation organization, the Inter-Institution Transportation Management Association (ITMA), to deal with their common transportation problems.[24] The area including these three institutions is called the South End medical area.

On the average, according to the schedule cards of the routes serving the South End Medical area, the headway varies between 30 minutes at off-peak periods and 10 minutes at peak hours. Therefore, applying the Cleveland model, the percent transfer between buses at peak and off-peak periods varies between 0 and 12.59% :

$$PT_{peak} = 0.498 - 0.1242 \, [\, \ln \, (\, 10 + 10 \,) \,] = 12.59 \, \%$$

$$PT_{off\text{-}peak} = 0 \qquad \text{since } (CH_a + CH_b) = (30 + 30) = 60 > 55$$

It might be argued that the Cleveland model does not necessarily apply to Boston because of different socio-economic and geographic factors between the two cities. The validity of this argument might be true, but the purpose of using this model is to provide evidence that the assumption of little bus to bus transfer is a reasonable one.

5.3.3. Transportation Problems at BCH, UH, and BUMC

The major problem of transportation for these institutions is that many of their employees drive to work. As a result, the parking spaces available for the hospitals are filled up. The total available parking supply in the South End Medical Area is approximately 7,400 spaces, of which 3,100 are open to the public and 4,300 are

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[24] Source: Interview with Maureen Flauherty, transportation coordinator between the Boston City Hospital, The University Hospital, and the Boston University Medical Center, March 5th, 1991.

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private. Over half of the spaces (4,400) are in surface lots, and 2,200 are on-street. Only 800 spaces are in garages. Parking rates in the off-street facilities approach market rates ($8-$10 per day) for visitors, but are very low (no charge to $5/day) for employees.[25] The problem of parking-availability is expected to worsen in the near future when UH constructs a large new bio-medical building. This will have a significant impact on parking spaces availability since the new building will be erected on the site of an existing parking lot, and the new offices will attract additional trips to the hospital area.

Transport officers from the three institutions feel that the public transport provided by the MBTA does not meet the transportation needs of the South-End Medical Area. Five current bus lines pass by the three institutions: routes 1, 8, 10, 47 and 49.[26]

While it is true that five bus lines pass by the South-end Medical Area, the hospital transport officials believe that these lines were not designed to serve the medical area specifically, but rather happen to pass through it while serving other areas.[27] Furthermore, some of these lines, such as Route 1, are considered unsafe or overcrowded during some hours. Unreliability and non-adherence to schedules, which

[25] Howard, Jane, "South End Medical Area Planning Study, Final Report: Transportation Elements", Howard/Stein-Hudson Associates, 38 Chauncy Street, Boston, MA 02111.

[26] Route 1 serves between Harvard/Holyoke Gate and Dudley Square and has a stop next to BCH;
Route 8 runs between Harbor Point/UMass and Kenmore Station and passes by UH and BCH;
Route 10 runs between City Point and Coupley Square and passes by the South End Medical Area;
Route 47 operates between Central Square in Cambridge and Albany Street and passes by each of the three institutions;
Route 49 runs between Dudley Square and Downtown passing by BCH.

[27] Interview with John H. Sullivan, Office of Auxiliary Services, Boston University Medical Campus, March 1992.

are some of the general problems with most MBTA lines, are among the complaints about the lines serving the Medical Area.

The ITMA is also assessing the impact of the Central Artery project on accessibility to the Medical Area and on parking availability. The space underneath one of the highway connectors, that will be used by the central artery tunnel, is now being used as a parking lot. This space, if occupied by the Central Artery, will reduce the available parking spaces for the Medical Area.

5.3.4. Available Data

The route description for the five routes that currently serve the South End Medical Area was procured from the CTPS. The ITMA provided us with the addresses of the employees for the three hospitals. Names were suppressed from the addresses because of privacy issues. As a matter of fact the addresses were released only after the approval of the ITMA board. The University Hospital, in addition to the addresses of the employees, has provided us with the job title, department, and shift data. The other two institutions were not able to provide similar data.

In order to gain a better understanding of the behavior of the employees and their mode choices, we requested some data about the current users of the parking facilities of the hospitals. The BCH does not have any data in digital form, only in a card file, whereas the UH and the BUMC have some data computerized. As a result, The BCH parking-data was not used. Again names were suppressed from these lists of parking-users, making it extremely difficult to link this database to the other residence, occupation, and shift databases. The address was the only common item between the

two datasets. The following table summarizes the data acquired from each of the three institutions:

TABLE 5.2 - Data Collected From UH, BCH, and BUMC			
INSTITUTION	DATA ITEMS	# Employee	# Record
University Hospital	Address, Title, Dept, Shift	2,300	2,327
Boston City Hospital	Address	4,000	3,017
BU Medical Campus	Address	2,800	2,095
Total UH, BCH, BUMC		9,100	7,439
Employees with Parking Stickers (UH & BUMC)	Address	5,100	4,997

Looking at the number of records supplied by each institution compared to the number of employees at each hospital in Table 5.2, it can be noted that BCH and BUMC did not supply complete datasets about their employees. This can be confirmed by the fact that the number of parking users from BU and BUMC (4,997) is larger than the total number of records supplied by both institutions (4,422). As a matter of fact, after cleaning the parking data and eliminating duplicate records, the number of parking-users records dropped to 4,855 which is still larger than the number of records supplied by BU and BUMC together. Upon contacting the three institutions we were informed that BCH staff did not provide the data for all of its employees, the BUMC data might have skipped some employees, including some of its students' addresses. As far as the high number of parking-sticker holders is concerned, it was attributed to the many fellows and visiting scholars who are not included in the list of permanent employees and who are using the parking facilities. Unfortunately, it was hard to identify these users in order to eliminate them from the parking-user database.

FIGURE 1

Boston Area:
Road Network, Subway
& Bus Route 10 (Thick Line)
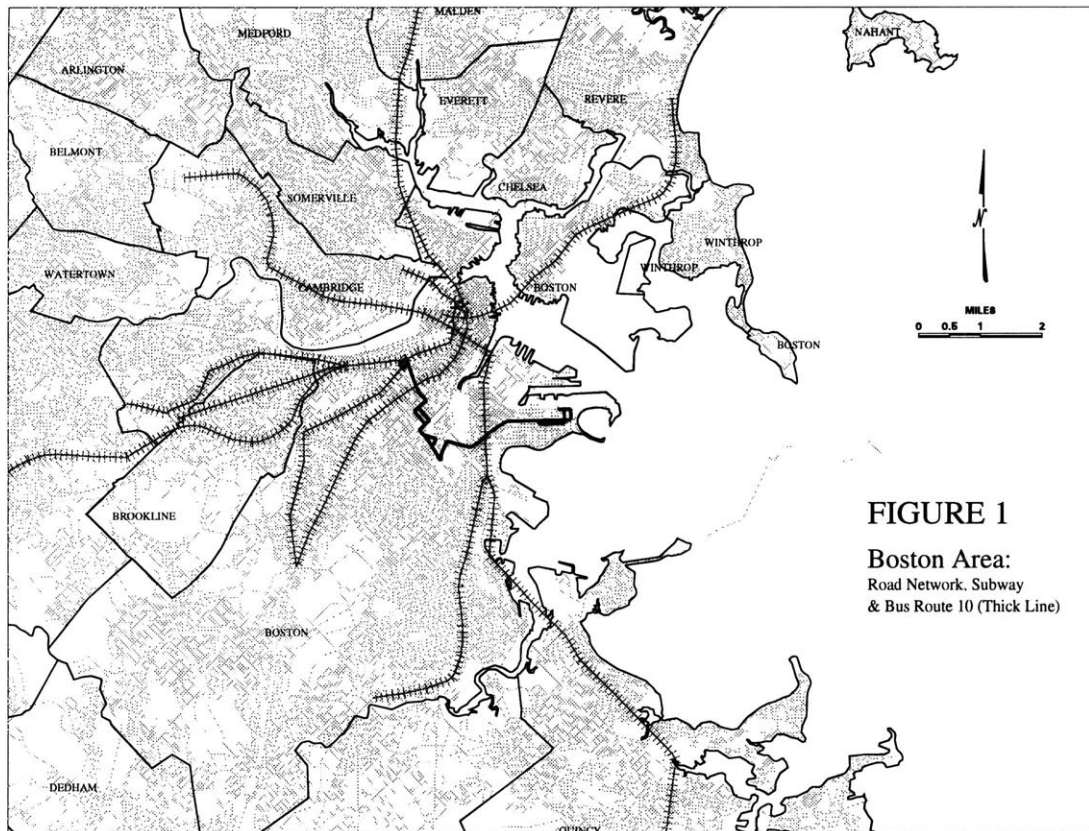
FIGURE 5.2

The final source of data is the US census bureau TIGER/Line files[28] . TIGER street network files are major digital databases developed in preparation for the 1990 decennial census of the Unites States. They are "the first comprehensive digital street map of the United States, containing digital data at a scale of 1:100,000 for every street and road in the nation, the range of address numbers located along each section of every street in the 345 largest urban areas."[29] In other words, TIGER/Line files contain geographic data coordinates for linear physical features, such as street centerlines,

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[28] TIGER: Topologically Integrated Geographic Encoding and Referencing, U.S. Department of Commerce, Bureau of the Census, Washington DC 20233.

[29] Antenucci, J., C., et al., "Geographic Information Systems, A Guide to the Technology," Van Nostrand Reinhold, New York, 1991.

railroads, streams, and census area boundaries, as well as address ranges and census codes for each feature. These files were processed using a GIS to create a network of roads, streets and highways for all the cities and towns within the Route 128 metro area (see Figure 5.2). Census tract boundaries for the same area were also extracted from the TIGER files.

5.3.5. Methodology

First, we had to select an area that had enough coverage for our study. We had to decide which cities and towns were to be included in the study area in order to have good representative and yet manageable datasets. Second, the transit network in addition to the street network were to be generated from the TIGER line files. The third step involved determining the areas that are considered as "accessible" to the transit service. We assumed that areas within a quarter mile from transit lines have good accessibility. Buffers of quarter mile widths around transit lines were drawn to represent those areas. Finally, the address-matching capability of GIS was used to geographically locate the employees' residences and calculate the percentage of employees who live inside the accessible areas.

5.3.5.1. Study Area Delineation

The study area first considered for this research encompassed only the city of Boston. The study area was later extended to cover all the cities and towns within Route 128,[30] since a small proportion of the employees of the three institutions live in Boston, and

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[30] The following cities and towns were included in the study area: ARLINGTON, BEDFORD, BELMONT, BOSTON, BRAINTREE, BROOKLINE, BURLINGTON, CAMBRIDGE, CANTON, CHELSEA, DEDHAM, DOVER, EVERETT, LEXINGTON, LINCOLN, LYNN, LYNNFIELD, MALDEN, MARBLEHEAD, MEDFORD, MELROSE, MILTON, NAHANT, NEEDHAM, NEWTON, NORWOOD, PEABODY, QUINCY, RANDOLPH, READING, REVERE, SALEM, SAUGUS, SOMERVILLE, STONEHAM, SWAMPSCOTT, WAKEFIELD, WALTHAM, WATERTOWN, WELLESLEY, WESTON, WESTWOOD, WEYMOUTH, WINCHESTER, WINTHROP, WOBURN.

since some of the bus routes that serve these institutions, and all the subway lines go far beyond Boston. Figure 5.3 shows the study area with the boundaries of cities and towns, the subway lines (red, green, orange, and blue lines), and bus routes 1, 8, 10, 47, and 49. The cities and towns within 128 were first used to examine patterns in the distribution of the employees' residences for the three institutions, and then a smaller area was used to address more specific and focused problems.
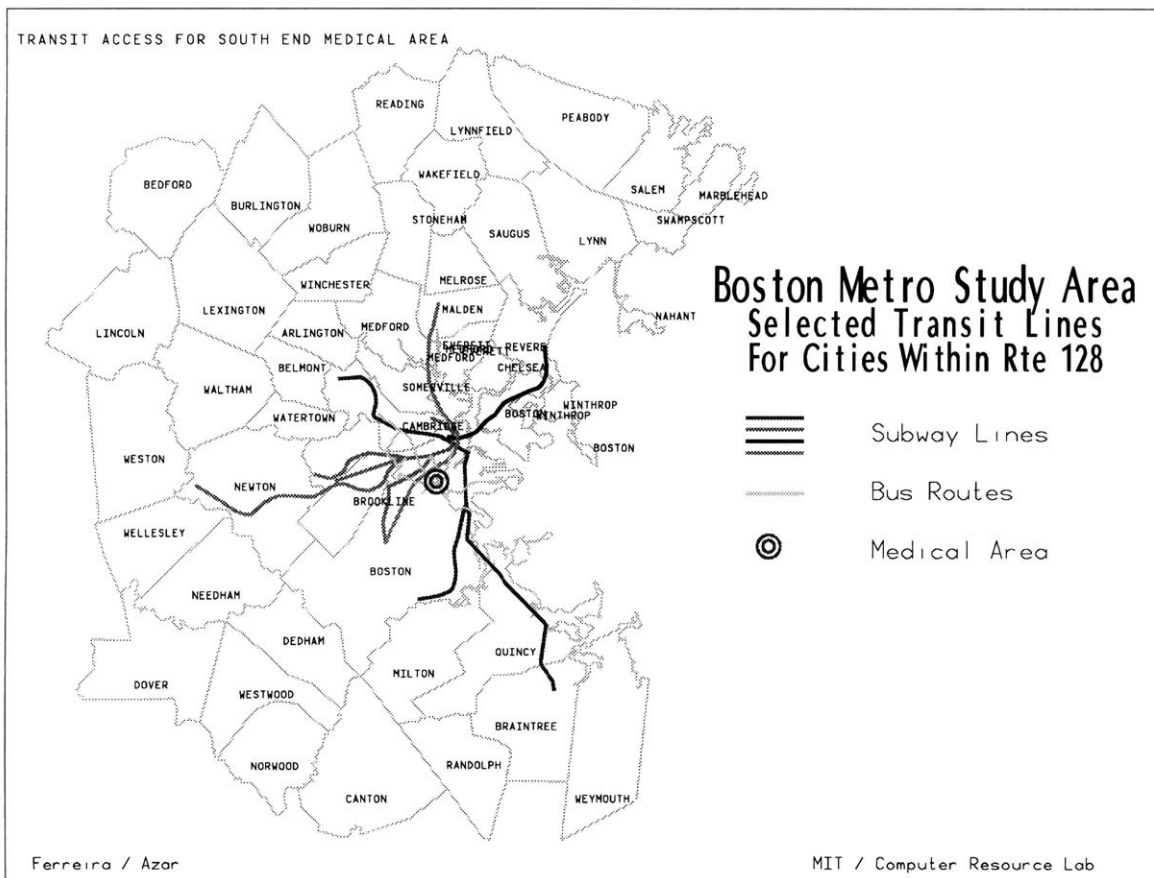
FIGURE 5.3

5.3.5.2. Creation of Street Network and Encoding Transit Routes

The TIGER/Line files were read into the GIS to create the street network for all the roads within Route 128, and to encode the bus routes that serve the South End Medical Area. The process of creating the street network starting from TIGER/Line files was far more complex than expected. The Census Bureau uses the County as the geographic area to divide the TIGER files. Since the area within 128 falls between four counties (Suffolk, Norfolk, Middlesex, and Essex counties), the street network for each of these counties was created inside the GIS first, and then streets within Route 128 from each county were selected. The last stage of the street network creation process was the appending of all the streets from the four counties into one file.

Unfortunately, the TIGER/Line files do not generally include subway lines. In order to create the subway lines, we had to digitize these lines from a fairly accurate map published by the MBTA. The digitized lines were then read into the GIS and their coordinates were transformed into state plane coordinates, and projected to the same projection used to create the street network from TIGER. After examining the projected coordinates of a few subway stops, it was found that the accuracy and the alignment between the digitized subway lines and the TIGER streets were quite high.

In order to avoid the problem of digitizing bus routes and re-projecting them to match with the TIGER data, a semi-automated program was used to extract from the street network file the arcs that belonged to certain routes. This program basically uses the textual description of bus routes (i.e., the starting point of a route, its turn movements at intersections, and its ending station), to first select the intersection points that a route follows and then to extract the links that belong to that route.[31]

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[31] For more information about this model, refer to Thomas H. Grayson, "Digitizing Bus Routes Using Textual Route Descriptions and TIGER/Line Data," unpublished paper, Massachusetts Institute of Technology, Computer

TRANSIT ACCESS FOR SOUTH END MEDICAL AREA

MILES: 0 1 2 4 8

UH + BCH + BUMC
Employee Residences
Transit Accessibility Buffers
and Racial Distribution

Subway Lines

Bus Routes

Medical Area

Percent Minority
(1990 Census Tracts)
0% - 10%
10% - 50%
50% - 80%
80% - 100%

Ferreira / Azar

MIT / Computer Resource Laboratory
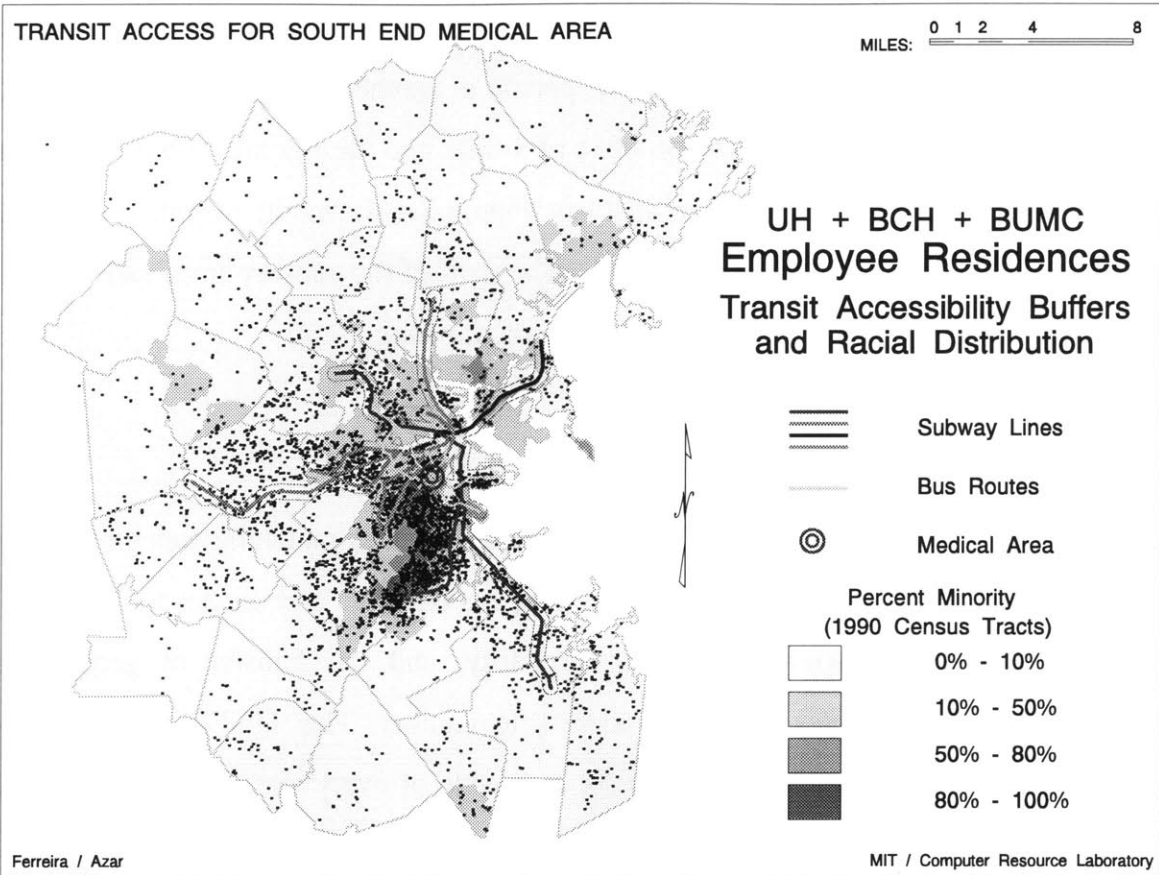
FIGURE 5.4

5.3.5.3. Buffering Around Routes

In order to determine the accessibility of employees to the current transit services provided by the MBTA, we assumed that all employees who were located within walking distance from the subway lines or from routes 1, 8, 10, 47, and 49 had access to the service. A walking distance of ¼ of a mile was assumed to be a reasonable one. Buffering around routes, the most common technique for determining the service area of a transit route, was used. Other procedures of circular buffering around bus and

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Resource Lab, December 1991; and to Thomas H. Grayson "A prototype Tool for Modeling and Visualizing the Accessibility of Public Transit," Masters Thesis, Massachusetts Institute of Technology, January 1993.

subway stops, or using network distance, as opposed to Euclidean distance, might be preferred to identify the streets or segments with access to a transit system[32], but since the walking distance limit varies from one person to another (between less than ¼ and more than ½ mile) the generalization of ¼ of a mile and the Euclidean buffering was commensurate with the level of our analysis. Figure 5.4 shows the ¼ mile buffer that was created using a GIS to identify the service areas of the subway lines and the five bus routes (running through the South End Medical Area).

5.3.5.4. Address Matching

One of the most useful features of GIS tools is the address matching capability. This capability permits the assignment of approximate geographic coordinates to addresses, the comparison of two addresses for similarity, and the transfer of geographic coordinates and attributes from one address to another. The TIGER/Line files, as mentioned above, have address ranges for each side of every street within our study area. The address data that was acquired from the three hospitals were also read into the GIS system to create tables required by the address matching program. The matching program creates for every address that matches against a street segment, a point record (containing the approximate geographic coordinates of that address). The files containing the point records were used inside a GIS to produce pin maps representing the approximate geographic location of each address. The address matching program also creates a file for the addresses that did not match against any street segment. These rejected addresses are useful for determining the reasons behind their failure to match. The rates of successful matching are given in the next section.

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[32] For more details about ways of finding streets that are accessible to transit service, refer to Wende A. O'Neill, Douglas Ramsey, and Jaching Chou, "Planning and Analysis of Transit Routes and Stops Using Geographic Information Systems," Transportation Research Board, 71st Annual Meeting, Washington, D.C., 1992.
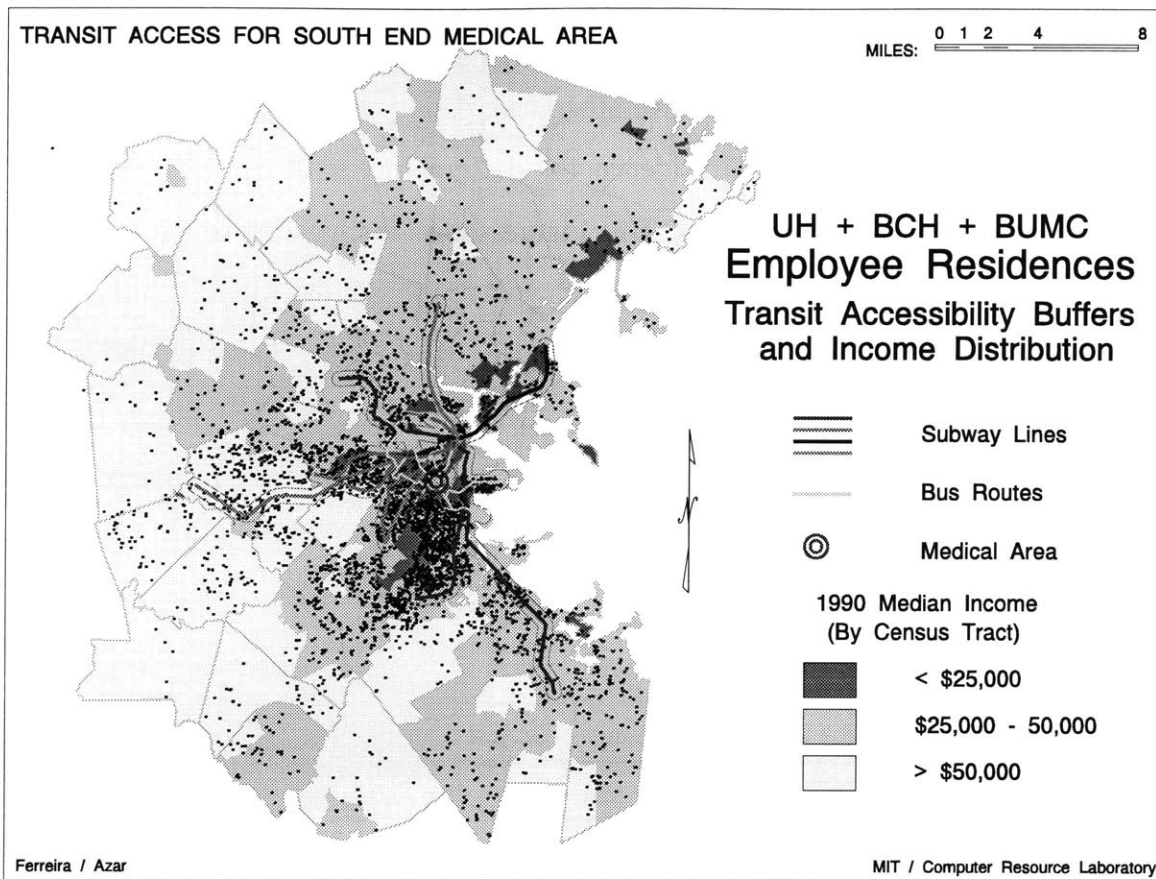
FIGURE 5.5

5.3.6. Geographic Analysis of Data

In the process of analyzing the data, locations of employees of each of the three institutions were first plotted separately in order to check whether there was any distinguishable pattern of employment distribution between the hospitals. The aggregated data was then plotted and compared to the layout of the current transit system and routes that serve the South End Medical Area. The parking data was finally drawn in to confirm the patterns and to suggest possible recommendations or alterations to improve the transit system.

5.3.6.1. UH, BCH & BUMC Employees Residences (all together)

In order to better understand the overall transportation problems at the South End Medical Area, the location of residence for the employees of the UH, BCH, and BUMC are all plotted in Figure 5.4. This Figure shows the location of the UH, BCH, and BUMC employees all together with their racial distribution. Figure 5.5 shows the income distribution of all the employees. A buffer of ¼ mile is drawn around the bus routes and subway lines serving the area in order to examine the accessibility of those employees to the existing transit services. The GIS tools were used to determine the number of people living within the buffer for each of the three institutions. The results are summarized in the Table 5.3.

TABLE 5.3 - Percentage of Employees Accessible to Public Transport				
HOSPITAL	# of Records	# Matched	# Accessible	% Accessible
UH	2,266	1,554	480	30.88%
BCH	3,016	2,301	923	40.11%
BUMC	2,047	1,266	393	31.04%
TOTAL	7,329	5,121	1,796	35.07%

Notice that approximately one-third of the employees of the three institutions have convenient accessibility to the existing service. To improve this percentage actions need to be taken to modify existing bus service in the area. In Figure 5.6, note that the southern part of Boston is an area where high concentrations of employees of the three hospitals live, but where a low percentage of the employees are within walking distance from the current service. We decided to focus our study of bus service alternatives on this area.
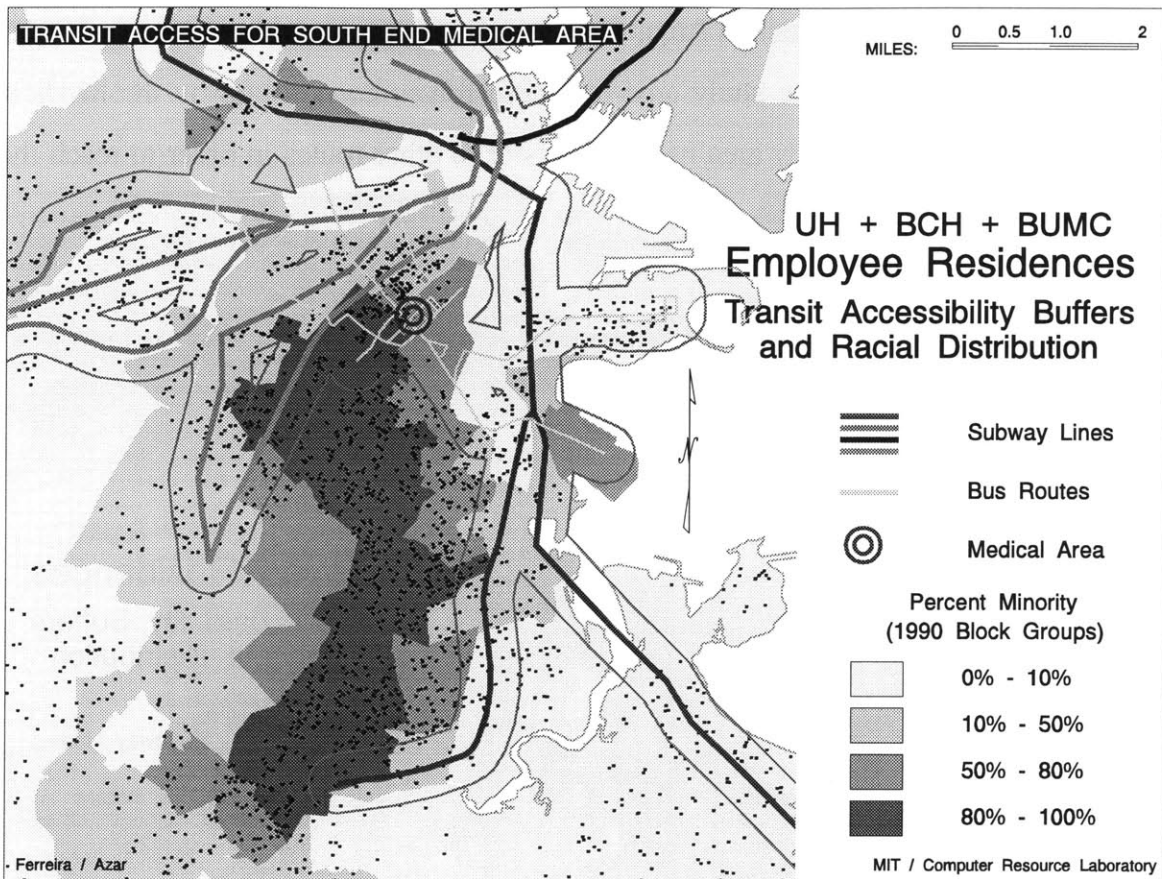
FIGURE 5.6

5.3.6.5. Southern Area of Boston

Figure 5.6 shows the study area. The area is delineated by the Orange Line to the west, bus Route 8 to the north, and the Ashmont-Mattapan Red Line to the East and South. This study area is comprised of parts of the Roxbury, Dorchester, and Mattapan neighborhoods. It is a low income area, has high percentages of minority residents (African-American and Hispanic communities).

In Figure 5.7, the approximate locations of the employees of UH, BCH, and BUMC are plotted for the study, overlayed with the transit lines and the accessibility buffer

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around these lines. Note that the transit coverage for this area is not convenient for travel to the South End Medical Area. Other transit routes, such as routes 15, 16, 42, 44 and 45, run through the study area but these routes do not pass by the Medical Area. Residents of the study area need to transfer to other routes in order to reach the Medical Area.
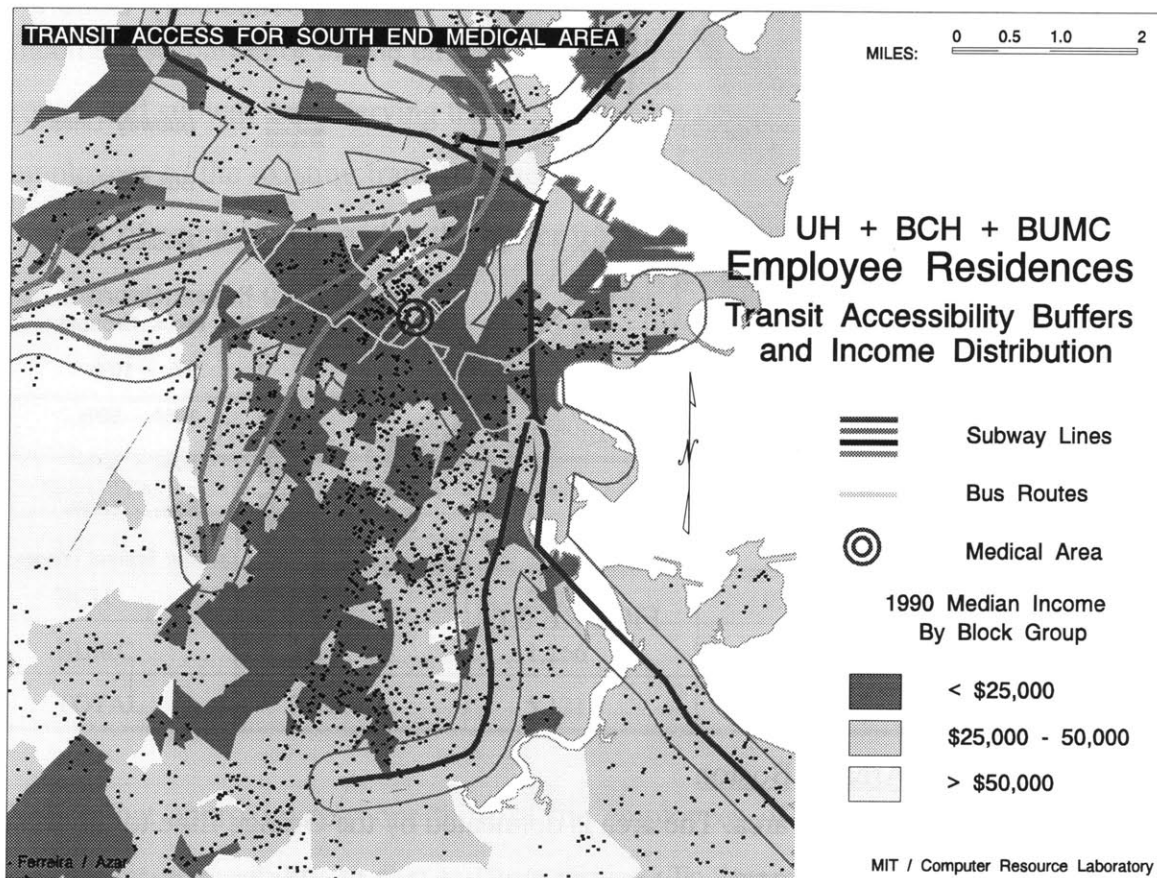
FIGURE 5.7

In order to check whether the employees who live in the study area can afford to drive their cars to work, and whether they are contributing to the parking load in the Medical Area, the parking data was used to map the distribution of drivers living in the southern part of Boston. The address-matching capability of GIS was used again to

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find the geographic locations of the employees who use parking and live in the study area. Since BCH did not have any data about its parking users in digital form, the data available to us was the one from UH and BUMC.
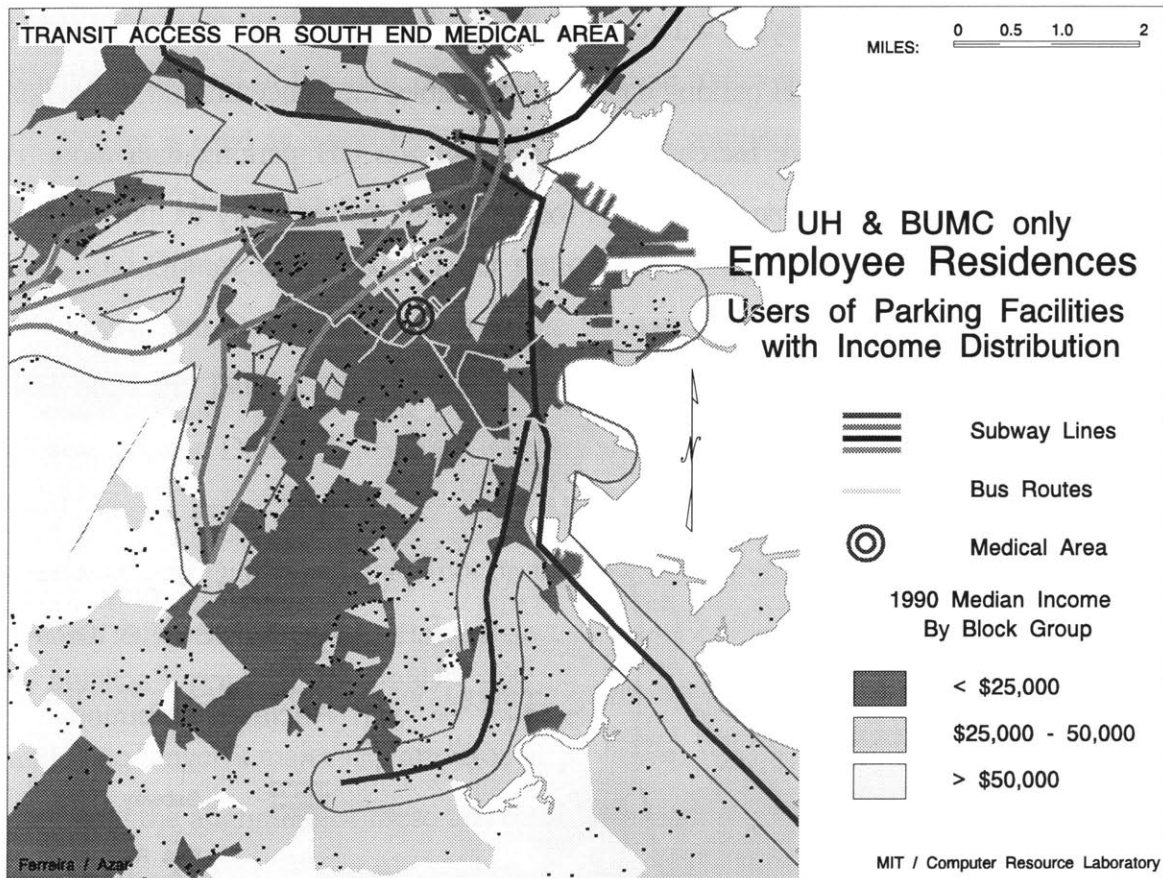
FIGURE 5.8

Of the 4,997 parking records, 142 were duplicate records and 1,520 were for addresses outside the 128 beltway. Explanations include employees who provided wrong addresses in remote areas to justify their request for parking spaces, or by employees providing their summer addresses (in some records, addresses were as faraway as California). The address matching rate of the parking data was a reasonable 71%, with 2,371 records out of the 3,335 records in the study area matching against the

TIGER/Line database.

Figures 5.8 and 5.9 show the residences of employees (with their income and racial distributions) who are drivers in the study area. This map largely represents the residences of the UH employees who drive to work, since few BUMC employees live in the study area. If the BCH parking data were available, the concentration of dots on this map would likely have increased. Nevertheless, the UH parking data alone is sufficient for prompting some suggestions for improving accessibility to the Medical Area.
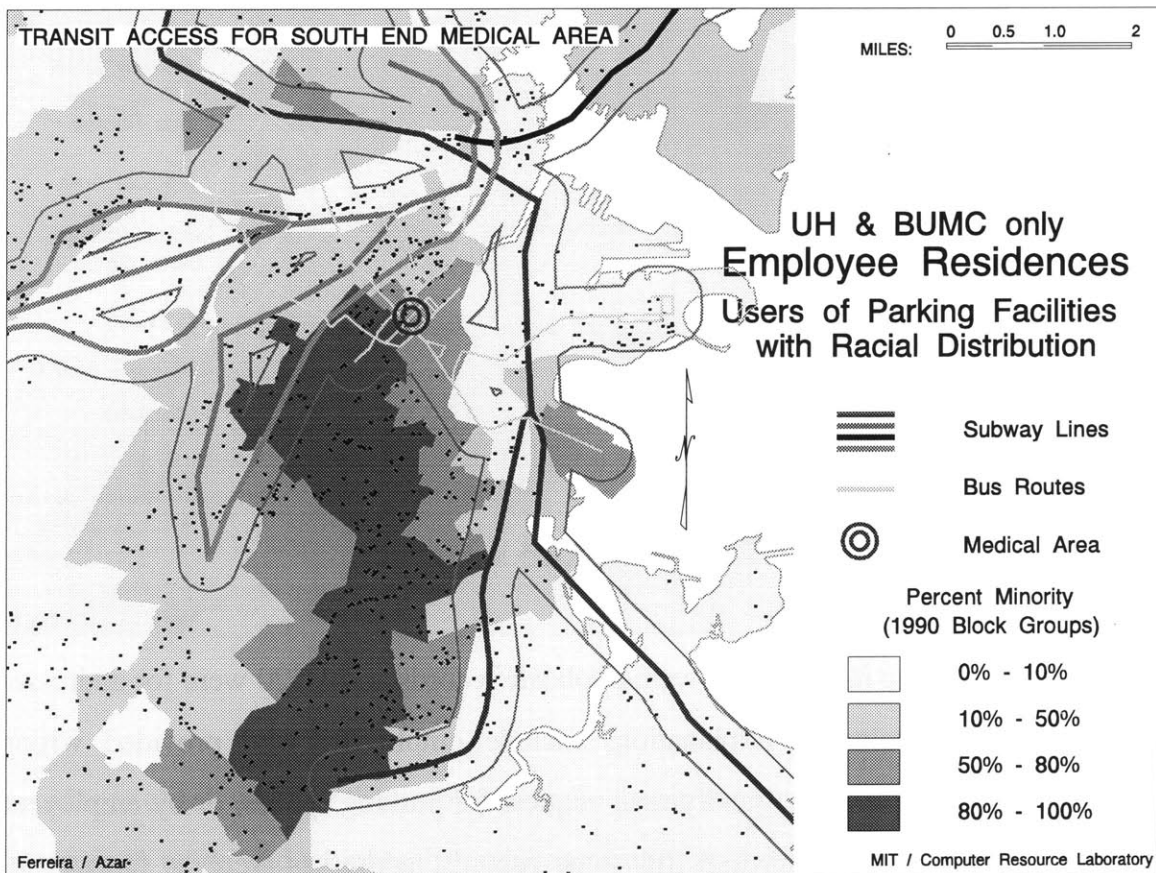
FIGURE 5.9

5.3.7. Analysis of Existing Service

Many bus routes that serve the southern part of Boston run through the study area. Bus routes 15, 16, 17, 19, 23, 42, 44, 45, and 48 all operate in this area. These routes all converge to one point in Dudley Square. They operate radially starting from Dudley Square to the rest of the area. Since none of these routes goes beyond Dudley Square, the Square is used as a transfer point between the southern part of Boston and the rest of the city. The importance attached to Dudley Square can be historically explained. The "Old Orange Line" had a major station at that square and most of the bus routes converged into Dudley to connect to the Orange Line. In 1987, a new Orange Line was built and Dudley Square was not on the new line. In the new line layout, the closest stops to Dudley Square are Ruggles and Roxbury Crossing which are at least 6 to 7 blocks away from the Square. Although the Orange Line has been shifted westward and Dudley square is not on the new line, all the bus routes still converge to Dudley Square. In the past this square was a major commercial area and attracted a lot of trips as a destination. Today, Dudley Square has lost much of its commercial value and is no longer a major trip attractor or producer. Yet, the MBTA has not considered changing the alignment of these bus routes. Instead, after demolishing the old subway station, the MBTA is building new bus station at Dudley Square as a transfer point although it is at least ½ mile away from the nearest subway station.[33]

This example illustrates one of the most interesting dilemmas faced by transit planners. When designing routes, should a planner's main concern be to provide service that adequately provides for the transportation needs of an area or should the planner also consider the revitalization efforts ongoing in some parts of the city? In the southern

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[33] Source: Massachusetts Bay Transportation Authority, "Fiscal Year 1992 Budget" Report, FY91 Goals, New Vehicle New Service New Stations, Boston, 1991.

part of Boston, the question of whether the convergence point of all buses should be moved to Ruggles station on the Orange line or whether it should be kept at Dudley Square is a controversial one. In order to expand an employer's labor market to include potential employees who depend on or prefer public transport, especially for employers with diverse labor needs, a transit planner should design transit routes in a way that provides a direct access to job locations from the residences of those employees. For the southern part of Boston to have access to rest of the city, where most of the buses serving that area meet should be connected to the subway system. This implies that Dudley square should not be the transfer point for all travelers between the rest of the city and its southern part.

Shifting the transfer point from Dudley square to the Ruggles station has serious implications for the structure of the city in general, and on Dudley square specifically. Efforts are being made to revive Dudley Square and return some of its lost commercial enterprises. The MBTA is involved in these revitalization efforts. The rebuilding of the old Orange Line station at Dudley Square, and its transformation into a major bus station for transfers between different bus routes is a direct involvement by the MBTA. The dilemma faced by MBTA's planners is whether this station will conveniently serve the transit needs of the people living in the southern neighborhoods of Boston.

Another argument for not changing the layout of the routes serving the southern area of Boston is that in addition to preserving the commercial and historical value of Dudley Square, the MBTA planners are also concerned with preserving the safety and the level of service in the rest of the transit system. Providing direct and easy access to residents of certain areas into the city might be accompanied by easier access of criminals and gang members into the city too. Keeping the connection point between the buses away from the subway lines, furthermore, lowers the accessibility of some of

these undesirable individuals to the main rail transit system. In such instances, the dilemma that planners face has another social aspect. Is it fair to penalize the majority of a neighborhood's population because of a few deviant individuals in order to maintain a certain level of security in the system as a whole? Is it also equitable to make residents of the low income areas, which are more in need of the transit service than any other areas, hustle more in order to use the transit service than the affluent neighborhoods?

According to the Medical Area employment data, the low income neighborhoods had lower accessibility to the transit system than all other areas. Table 5.4 compares the percentage of employees at the three institutions who have access to the transit system.

TABLE 5.4 - Comparison of Accessibility To Transit Between Low & High Income Areas				
HOSPITAL	All of Boston	Southern Areas	Rest of Boston	Study Area
UH	41.5%	21.7%	77.4%	30.9%
BCH	46.2%	32.4%	83.4%	40.1%
BUMC	55.9%	21.8%	83.3%	31.0%
Average	47.9%	25.3%	81.4%	35.1%

In Table 5.4, the "Southern Areas" column represents the southern parts of Boston, (i.e., Roxbury, Dorchester, and Mattapan), while the "Rest of Boston" column represents all of the rest of Boston. The "All of Boston" column includes both areas. Note that the percentage of employees who have access to adequate transit service in the southern parts of Boston is low compared to the rest of Boston. On the average one out of every four people living in the southern neighborhoods of Boston has easy access to the transit system whereas eight out of every ten people in the rest of Boston are conveniently served by the system.

5.3.8. Recommendations

Before making any recommendations, it is useful to recapitulate and briefly re-state the problems and our findings:

> The three medical institutions in the South End Medical Area have problems related to overcrowding in available parking caused by the large number of employees driving to work. The institutions are interested in shifting many of their employees from autos to public transit. By examining the location of residence of the employees of each of the three hospitals and by comparing it to the layout of the current transit system, we observed that one out of three employees, on average, is conveniently served by the existing system, and that one out of four of the employees living in the southern part of Boston has easy access to the system. Since the southern part of Boston is characterized by its low income population and its closeness to the Medical Area, it is critical to know what kind of measures might be taken to induce the shift from autos to transit in general, and in the low income neighborhoods, in particular.

In order to make our recommendations feasible and easy to implement, we suggest fairly reasonable changes to the system to improve access to the South End Medical Area. Since the MBTA is building a new bus station at Dudley Square, it is unlikely that they will now consider the relocation of the transfer point between all buses from Dudley Square to another location. If such relocation were possible, the South End Medical Area, which is as far from Dudley Square as are the Ruggles and Roxbury Crossing Orange Line stops, would benefit most from shifting the transfer point to a nearby area. Alternatively, some of the routes serving the southern part of Boston could be extended to reach the Medical area instead of stopping at Dudley Square. Our recommendations include:[34]

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[34] For more details about these recommendations, please refer to Azar K.T., L.L. Wiggins, and J. Ferreira Jr., "Using GIS Tools to Improve Transit Ridership on Routes Serving Large Employment Centers: The Boston South End Medical Area Case Study," Computers, Environment and Urban Systems, Volume 18, Number 3, ISSN 0198-9715, May/June 1994.

1. *Extension of Existing Bus Lines* serving the southern area of Boston beyond Dudley Square towards the Medical Area while keeping Dudley Square as a hub for transfer of other riders.

2. *Subsidy for T-Pass*

3. *Provision of Shuttle service to Dudley Square:* Until the MBTA approves the extension of its bus services beyond Dudley square, the three medical institutions could provide their own services to Dudley.

5.3.9. Conclusion

In this prototype, we used a real-world example to show the ways the route design process can be changed in order to take advantage of the availability of more detailed data and the development of more powerful tools capable of processing large data sets and, specif...lly, data of a geographic nature. The results show the usefulness of the GIS capabilities for improving the design and the performance checking of transit routes. The address-matching capabilities and the visualization tools of GIS systems allow the development of new analysis techniques that provide planners with different kinds of useful information for pro-active planning. The ability to locate more than 8,000 employees on a map and to display their location with respect to the transit system enabled us to create a visual measure of accessibility to the service and to identify under-served areas. Knowing the demographic and socio-economic characteristics, as well as the land use of the under-served area, we were able to come up with recommendations that might help in improving the mobility of the employees of the medical institutions while not affecting the revitalization of Dudley Square. The new techniques and the additional information proved to be viable and applicable to

real-world problems.

However, the preparation and cleaning of data and the manipulation of the off-the-shelf GIS tools were more complex than anticipated. Building the TIGER/Line streets database using current GIS's for a large area[35] was not an easy task. The limitations of some GIS software in handling extensive databases made the cost of building these large databases very high. To give a better idea (in terms of time) of the complexity of building the databases, more than 70% of the research time was spent on creating the street network database and encoding the transit routes. As mentioned earlier, the TIGER/line files for 4 different counties were first used to create 4 street network databases. Appending these networks together to create one large network was the most problematic step. This was caused in part by the limited capabilities of the software to handle huge databases and by the data inconsistencies in TIGER. A few commands, for example, which had a limit on the number of nodes in a network failed to work on the large network file. The difference in node numbering of common points between two network files is another problem that we had to face while appending the different files.

Similarly, cleaning the address databases was another time consuming job that contributed to the increase in cost of building the databases. The lack of standardization and accuracy in address coding between the different sources of data added to the cost of building the large databases. Nevertheless, once the hurdle of building and setting up the TIGER network and the address databases is surmounted, the usefulness of these databases in developing new analysis techniques compensates for all the expenses incurred in building them.

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[35] The street network for all roads, streets, and highways with 128 comprised 92,000 links and 64,000 nodes.

The visualization aspect in the analysis was the most important factor in allowing the new pro-active planning techniques. Once all the addresses were given approximate real-world coordinates, the visualization of these points on top of the existing services helped in clearly and quickly understanding the nature of the problem. Such tools would help transit planners become aware of problems that would be hard to notice otherwise. Furthermore, "what if" scenarios can be generated more easily by being able to graphically visualize the problem. The planner can quickly see some options that can be tested without additional data collection.

Finally, more sophisticated techniques can be used to choose between different possible scenarios. In this study we examined how accessibility to a major employment center could be improved. When more than one center is considered, different alternatives might suit one center more than another. More sophisticated algorithms with optimization between different interests can be explored. This type of optimization between transport interests is a problem that transit planners have been trying to tackle for some time and GIS tools can no doubt be of great help to their solution.

In this chapter we used three examples of GIS applications in transit planning and operations. We examined in detail the data needed for each application, the methodology used to build these applications, and the advantages and problems/ limitations related to the use of GIS. In the next chapter, we summarize all the complexities related to the use of GIS in order to find a way for addressing these complexities. We will use these three prototypes to illustrate these complexities in addition to other problems that we were able to uncover during the course of our research.

Addressing these complexities is not only related to the technological complexity of these problems. It has also a lot to do with the strategies for building databases, sharing information, and creating the mechanisms for propagation of information and data updates between user and departments. In chapter 7 we shall examine the different development strategies in a transit agency in order to be understand the nature of the complexities and to set the proper framework for addressing these complexities.

Chapter 6

Complexities of GIS-Based Applications

In this chapter we summarize and classify the complexities that are facing GIS use in transit agencies. We use the prototypes that we described at length in the previous chapter to illustrate these complexities plus some other problems that we were able to uncover from our interviews with the MBTA and CTPS staff and from our survey of the largest 30 transit operators in the US (refer to Chapter 4). These complexities are twofold: (1) technical and (2) organizational. In this chapter we describe all these complexities.

The goal of this chapter is to show and recognize the existence of GIS implementation complexities and then to narrow down the range of options regarding how an agency can choose to deal with these complexities, and to change the focus of these choices from one of picking an option or a tool to selecting a database and application development strategy. In other words, in this

chapter, we first start by showing the nature of the difficulties and the complexities that emerge in managing them. We then try to shift the prevailing view that transit agencies must find a one time solution by "picking the right tool" or "selecting the appropriate basemap" to a focus on creating a robust strategy for managing the inevitable complexities involved in evolving a useful GIS capacity.

In Chapter 7 we look at the developmental pathways of GIS in transit organizations in terms of which choices do these organizations have to make about how to get started with GIS applications, what data to use, which other agencies to connect to, and what kind of short cuts to make along the way to get going. In the conclusion chapter, we try to understand the scope of what it means to bring GIS to transit agencies in the context of how these agencies fit into the metropolitan infrastructure development in order to get some sense of what pathways are viable or whether transit agencies are in a position to deal with these issues and what key choices they have to face.

6.1. Introduction

In Chapter 3 we discussed many of the potential applications of GIS in transit agencies, their data structures, and the benefits they can derive from utilizing GIS. Each of these applications, however, has a special requirement in terms of data structure, segmentation of routes, and encoding scheme. Building databases for each of these applications is by itself not a hard task, but the coordination and data sharing requirements among the agency's departments add great complexities to the process of building these data. These complexities are caused by the fact that different representations of the same data item (e.g., a bus route) are needed for different

applications or different analyses. In order to better illustrate these complexities, an example of a street map with two bus routes crossing it is used to show the different representation for the different applications (refer to Figures 6.1 to 6.6):

6.1.1. Typical Street Map, Figure 6.1:

Figure 6.1 shows a typical street map with two bus routes on it (route 1 and route 2) and four stops belonging to either or both routes. Route 1 runs along 18th street and turns right to M street, whereas route 2 comes from I street turns right to 18th street and then turns left to M street. Routes 1 and 2 share the links on 18th street that are between I street and M street and they also share stop 1. Stops 2 and 3 belong to route 1, whereas stop 4 belongs to route 2. In this figure, the streets have width and are divided into lanes with different directions. This figure could have been more complicated by adding the inbound routes (assuming the shown ones are outbound routes) and bus stops could have been on both sides of the streets. For simplification purposes, and since the current layout of stops and routes clearly depict the nature of the problem, such complications were not considered.

6.1.2. TIGER Format, Figure 6.2:

The US Census Bureau provides street network files (TIGER[36]) that are very useful for transportation applications. Transit applications can also make use of these files especially since these files are relatively cheap, widely used, periodically (every 10 years) updated by the Census Bureau, and readable by many commercial GIS

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[36] TIGER: Topologically Integrated Geographic Encoding and Referencing, US Department of Commerce, Bureau of the Census, Washington DC 20233.
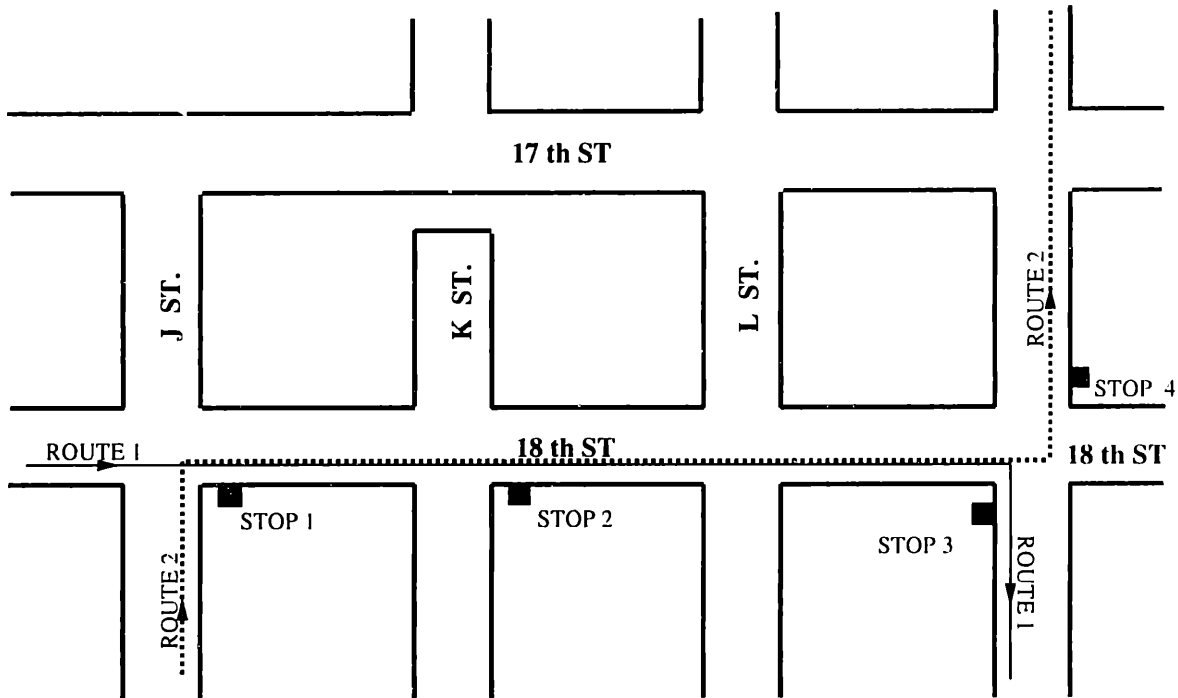
Figure 6.1 - Typical Street Map With Bus Routes and Stops

Node 10: -77.0415 389010
Node 11: -77.0415 389021
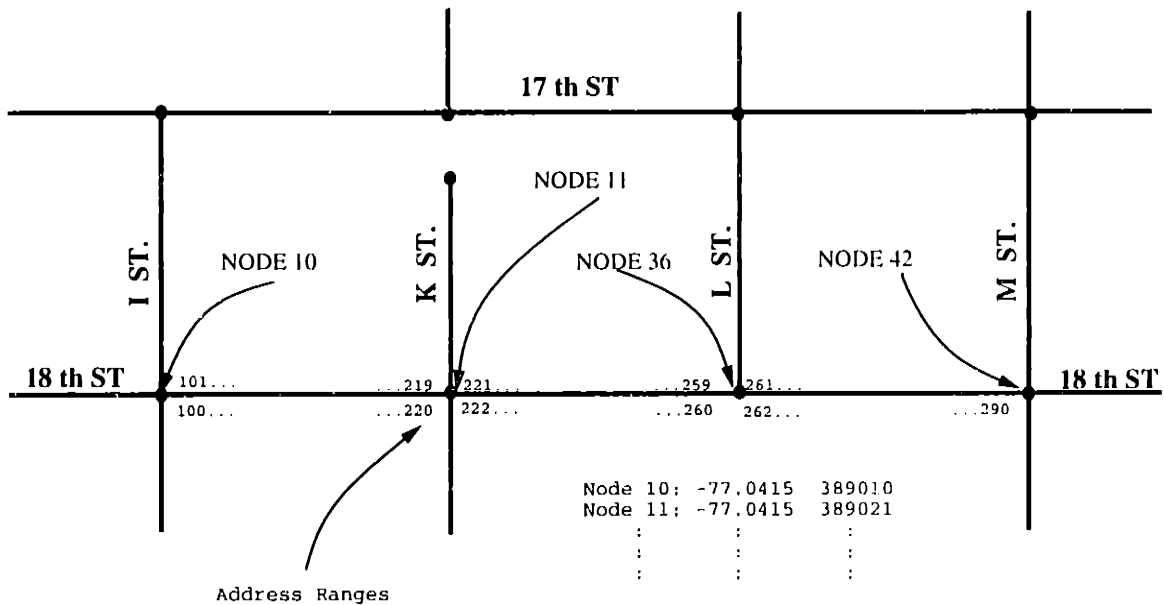
Figure 6.2 - TIGER Representation of Street Networks

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software. These files consist of street centerlines with the link-node topology which is useful for routing applications. Address ranges for each side of the street are also provided. Street intersections are defined by nodes and the coordinates (longitude and latitude) for each node at both ends of a link are included in these files. Since streets are not always straight lines, shape points are also included in TIGER files. They can be used to approximate the shape of curved streets. In Figure 6.2, node 10 represents the intersection of I street and 18th street and has the coordinates of -77.0415 & 38.9010. The link of 18th street that is between I street and K street has right addresses starting at 100 and ending at 220, and left addresses starting at 101 and ending at 219. Other useful information that come with these files are the census tracts and blocks adjacency to each link. To every link, information about the tracts, blocks and zips to its right and to its left are attached. Such information can be used to determine the boundaries of census tracts, block groups, and blocks which can be linked to the demographic data supplied by the census for each of these census areas.

TIGER files are usually available in major metropolitan areas. For the 1990 version of TIGER files, the address range information is about 75% accurate[37]. However, this accuracy varies between states and between urban and rural areas. The address information is very useful for conducting address matching operations but the positional accuracy of the TIGER files is not really high. The Bureau of the Census claims the accuracy of 1:100, 000 scale maps in most of the US and that of 1:24,000 scale maps in some metropolitan areas. As we shall see in this chapter, the particulars about the road network file are important in developing GIS implementation plans.

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[37] By 75 % address accuracy, we refer to the percentage of correct matches that on the average occur. This has to do with the accuracy of the street number, name, prefix, and suffix information and whether these information are attached to the right segment or not.

6.2. Complexities By Application

We now describe examples of difficulties that are associated with the use of GIS in different applications. We discuss those difficulties related to the corridor analysis, trip planning, and production of maps applications.

6.2.1. Corridor Analysis - Representing Ridership, Figure 6.3:

GIS can be used by planning departments to automate some of the manual work involved in corridor analysis. Buffering 1/4 mile around routes and calculating areas of tracts falling within the buffer can be automatically computed by a GIS. Another use of GIS is the representation of ridership on each segment of a route[38]. Figure 6.3 shows one way of representing ridership on each segment of routes 1 and 2. The bandwidth is proportional to the number of people on board of a bus between each 2 stops. For this type of representation the segments that are shared by both routes need to be double encoded in order to graphically display the ridership on each of the two routes at the same time. As seen in Figure 6.2, TIGER files represent .. street by its centerline which necessitates some modification to the TIGER representation in order to suit this type of application. On the other hand, since transit planners are interested in studying the ridership between stops, the segmentation of a bus route in such a case is defined from stop to stop. Since TIGER's segmentation is determined from street intersection to street intersection, the links, for example, between node 11 and node 42 (see Figure 6.2) need to be aggregated into one segment as shown in Figure 6.3 (segment between stops 2 and 3 corresponds to the links between nodes 11 and 42).

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[38] For more details about the use of GIS for automating the manual work and forecasting ridership, refer to [Azar and Ferreira, 1992].

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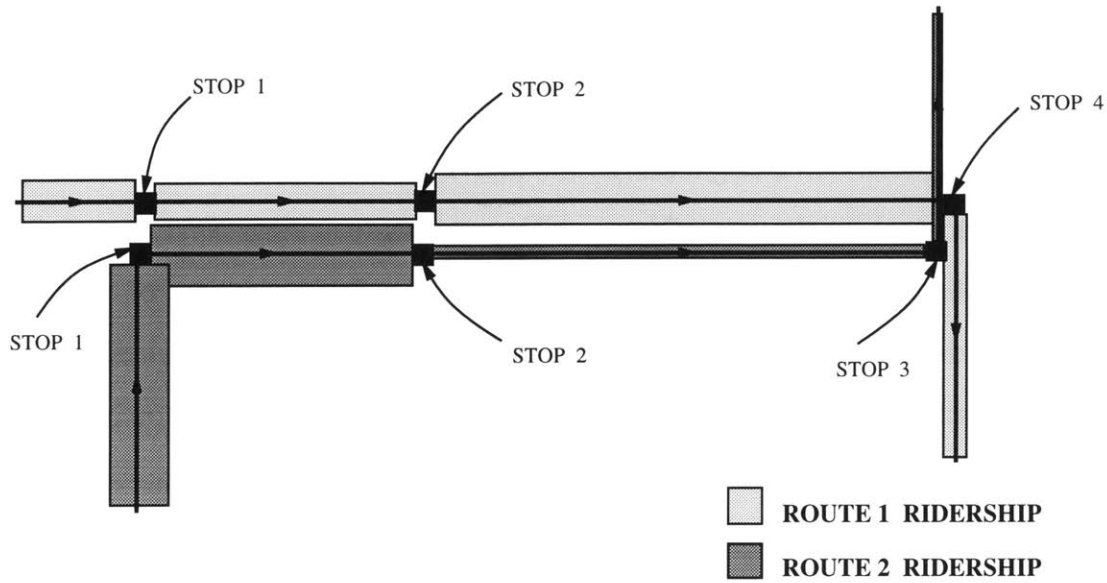
Figure 6.3 - Corridor Analysis - Representing Ridership
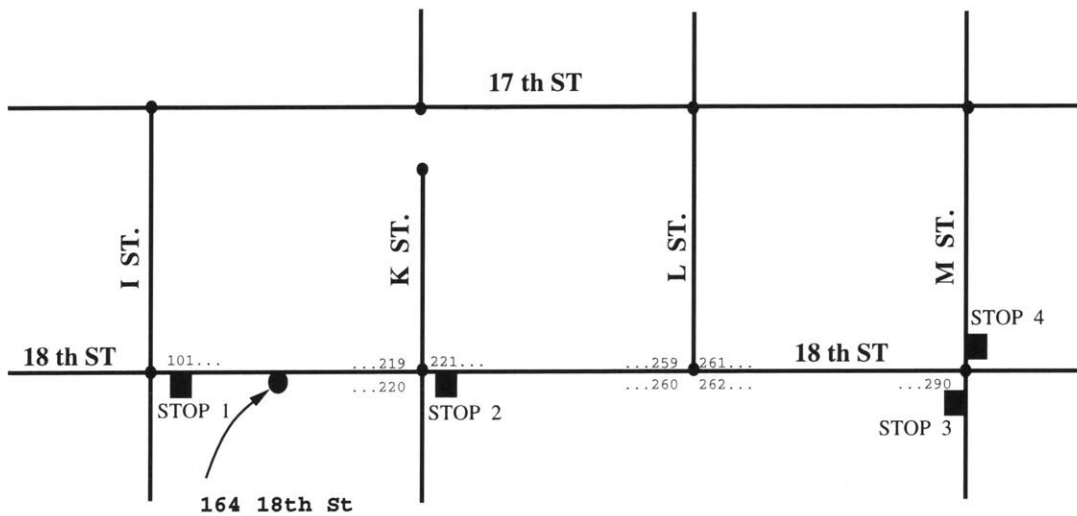
Figure 6.4 - Trip Planning: Locating Addresses and Finding Nearest Stops

6.2.2. Trip Planning - Locating Addresses and Nearest Stops, Figure 6.4:

One of the applications of GIS technology in the marketing department is the customer information system. In the previous chapter we discussed how a GIS can be used to determine the location of the origin and destination addresses of a caller and to find the nearest stops to each of the two addresses. The address matching capability of GIS tools can be used with TIGER files in order to locate the caller's address. For example, if the caller indicates that he is at 164 18th street (see Figure 6.4), this address can be highlighted on the screen to check the nearest stop. The resource allocation tools in many GIS can be used to determine the stop within walking distance from that address.

Complications can arise if more than one stop are within walking distance from an address and each stop is convenient for a specific type of travel. In other words, a bus stop as well as a train station might be close to a specific address. The bus stop might be convenient for local trips while the train station is convenient for express travel. Allocation algorithms can take care of such situations but the algorithms included with typical GIS packages may not.

TIGER files representation of street network files is very adequate for this type of application. The streets address range information is very useful for determining the geographic location of addresses and determining the position of the nearest stop to an address. The only limitation to using the TIGER files is that the segmentation of streets needs to be followed as it is. No merger of two links into one link or addition of missing links is recommended. Such alterations might result in introducing errors into the address ranges of the streets and entail a lot of manual work for their adjustment.

6.2.3. Trip Planning - Routing Component, Figure 6.5:

After identifying the nearest stops to the origin and destination addresses, two approaches can be used to determine the optimum path that needs to be followed between the two stops: (1) using the routing capabilities of GIS tools, or (2) using the relational database managers of GIS packages[39]. A subset of the initial street network file, which consists of street links that belong to transit routes, needs to be created first (see Figure 6.5). If the length attribute of links is the only function needed for calculating the shortest path between two nodes and if the topological representation of the network corresponds to its geometrical representation (i.e., at any node, movements in all directions are possible), the shortest path tools that are provided by GIS packages can be used. If, however, more sophisticated path length that account for transfer penalties and bus schedules are needed, the database side of GIS tools can be used to build tools that meet those requirements [Grayson, 93].

The GIS-provided shortest path algorithms that are used for calculating the optimum path, require the use of the node-link representation of the route network which makes TIGER a convenient and useful data file for operating such algorithms. Double encoding links and stops for overlapping routes may cause some problems for these algorithms and may confuse current commercial GIS packages that can't easily distinguish between a link in the street network file and the multiple routes that may utilize that link. In this case, overlapping routes need to be singly encoded. Similarly, different stops at different sides of an intersection need to be aggregated into one node.

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[39] For more details about the use of relational databases of GIS tools for finding shortest paths, refer to [Grayson, 1991].

NODE 11 = STOP 2

NODE 10 = STOP 1   NODE 36   NODE 42 = STOP 3
                                                    & STOP 4

                                                                    L42(2)

L10(1)   L11(1,2)   L13(1,2)   L1-(1,2)

                                                              L41(1)
        L21(2)
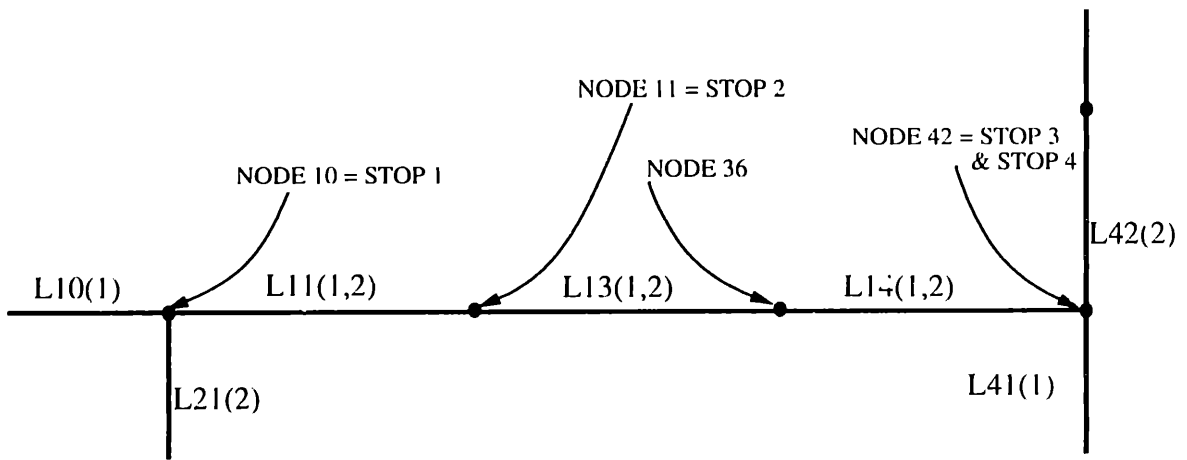
Figure 6.5 - Trip Planning: Routing Component

18 th ST   18 th ST   STOP 4

STOP 1   STOP 2
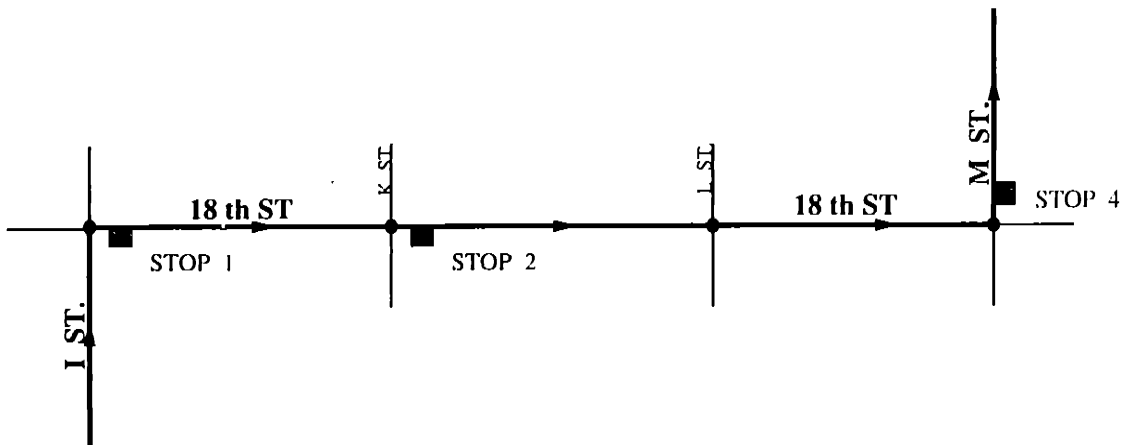
Figure 6.6 - Schedule Map of Route 2

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In Figure 6.5, for example, stop 3 (belonging to route 1) and stop 4 (belonging to route 2) are aggregated into one single node, node 42. These types of representation of multiple routes and stops clearly differ from the other representations required by the other applications discussed above.

In other words, in order to do the routing properly, the user needs to handle a number of special situations that will make the single encoding of street links inadequate and that may or may not be within the capability of a particular GIS package. Moreover, one or another of those limitations may cause the user to cut corners and complicate the data representation as compared to what might be needed in other cases or for other applications. Figures 6.7 and 6.8 clarify this idea.

FIGURE 6.7
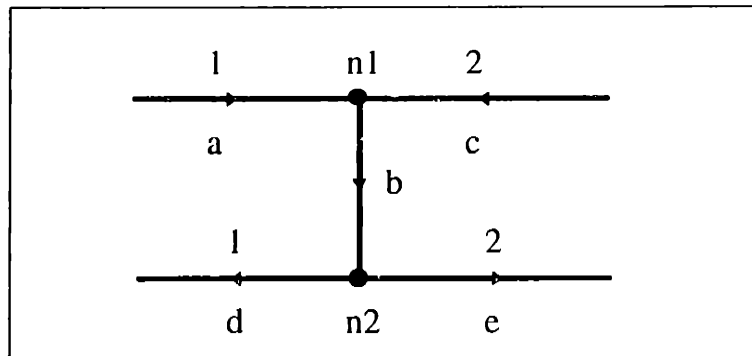
In this example links 'a', 'b' & 'd' belong to route 1, while links 'c', 'b' & 'e' belong to route 2. Link 'b' is common for both routes. A turntable can be used to set negative impedance at node n_1 for flows coming from link 'a' to link 'c' and vice versa in order to refrain the flow from going in the wrong direction. The flow on the 'b' link can be either the one coming from route 1 or route 2. The turntable at node n_2, however, can not be used to inform the program that only the flow coming from link 'a' can turn to link 'd' and only the flow coming from 'c' can turn to link 'e'. At n_2, the flow should

be allowed from 'b' to both 'd' and 'e'. As a result, flow coming from link 'a' can go to link 'e' and the one from link 'c' can go to link 'd'. As it might be the case that no stop exists at node n_2, using the routing algorithms of off-the-shelf GIS would hence generate wrong routes when a link belongs to multiple routes.

This problem can be resolved using the RDBMS of a GIS or by adding new spatial features to the existing TIGER file. Figure 6.8 represents one way of addressing this complexity. Two pseudo-nodes n1' and n2' and a link b' connecting them can be created in order to model the turn movements properly. In other words, shared arcs are duplicated in order to properly represent transit lines connectivity.

FIGURE 6.8
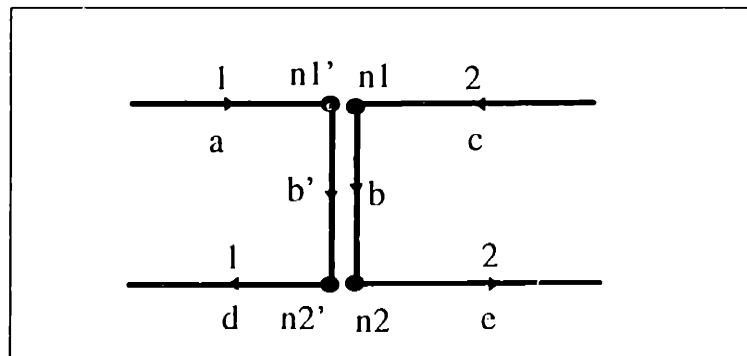
The modifications of TIGER topology to accommodate such complexities suffer from the following problems:

1. The modification has to be done manually or at least semi-automatically which means that it might take quite some time and effort to do it for all routes sharing arcs. Furthermore, it might be that several routes happen to be sharing some arcs which would result in the creation of several pseudo-nodes and links in order to properly represent connectivity. The creation of pseudo nodes and links can be

automated to some extent (as described later in Chapter 7) but the bookkeeping is, at best, a continuing headache.

2. The process of data update might also become very complicated. With a new release of TIGER, the generation of pseudo nodes and links has to be repeated. Since a revised TIGER can involve various topological changes, linking new and old pseudo nodes becomes a non-trivial conflation problem. This means that updates of TIGER file might create major problems to the organization especially when only one department has the authority to modify data. This problem jeopardizes the sustainability of applications and the timely integration of updates.

3. The complexity of such expanded networks can impact the computational speed of the routing algorithms. The connectivity between the pseudo nodes can become quite complex when more than 2 routes share common arcs and many 'real world' cases can involve 3 or 4 routes sharing common arcs. Doubling the number of links in a network is quite possible but the solution times could be increased by a factor of 4 or more.

The other approach to addressing this problem is the use of RDBMS tools. Grayson [1991] showed a way for using RDBMS to represent TIGER files including all the complex connectivity problems. He demonstrated also how the RDBMS can be used to compute shortest path between an origin and a destination. The price for implementing this approach on the database side of a GIS and overcoming the above problems was the speed of this operation. For example, it took several minutes to calculate a shortest path using the RDBMS of GIS on a network of 400 directed links and 125 nodes, whereas Arc/Info's internal routing algorithm could accomplish the same process almost instantaneously. The slowness was not due to the inefficiency of

RDBMS, but rather to the time to convert the network representation back and forth between the GIS and the RDBMS and to the additional complexity of the expanded network. However, Arc/Info's routing algorithms can not accommodate complex turn movement and connectivity problems without making hard-to-maintain changes to the underlying network while the RDBMS-based process can.

6.2.4. Schedule Maps, Figure 6.6:

Schedule maps are produced by scheduling departments (and in some agencies by planning departments) to describe the pathway of a certain route. Those maps, which are made for distribution to customers, show the layout of a route and the location of stops as well as all the turns, reference points, and key intersections along that route. Information related to schedule of buses, such as headways and expected running times, are also described on those maps. Schedule maps can be built using the TIGER street links file (if the TIGER file is suitably complete and accurate). Figure 6.6 shows a schedule map for route 2 with the actual locations of stops 1, 2 & 4, in addition to the cross-streets which are useful for visual reference. In many instances, schedule maps are distorted on purpose. Portions of a map are stretched or shrunk in order to make a whole route fit on one page. In such a case, the TIGER street network file might be used as a reference for determining the extent of distortion needed. Furthermore, these maps usually contain land mark and other reference information that are not available in TIGER. Therefore, TIGER files need to be supplemented with other local detailed maps that contain such information. The stretching and warping of these maps can not be done easily using GIS tools. Paint packages are more suitable for these operations.

6.3. Reasons for Complexity

Historically, the focus of the data processing industry was on the development of individual systems which produced specific information for their users. Dedicated applications and dedicated data files were designed to satisfy the information needs as they were recognized. The result of this approach was rather a narrow view of data, where each data structure is designed for a particular function or a unique task [Nolan, 1984].

The complexity of building sharable databases depends upon the type of data structures and is often aggravated by a lack of encoding standards and by the application-by-application approach to building databases that has tended to occur. Data sharing refers to the situation in which two or more application systems have access to, and use the same data file. It is the "act of transferring data from one party to another for different use. It involves (1) the transfer of meaning in the form of data representation and (2) the structure for the organization of these representation"[Von Sydow, 82]. Data sharing has long been an issue in transportation planning. What is new is the interest in sharing spatially referenced data where rich and varied possibilities exist for how to represent geometry and location especially when data standards are only beginning to develop.

By standards it is meant a set of standards rather than single standards. Such sets can include stops encoding and numbering standards, links and routes encoding and identification standards, etc. In a transit agency, it is hard to identify any standard adopted by any department for building databases even those not tied to spatial information. Inconsistencies in encoding schemes such as abbreviation patterns (e.g., street vs. st. or avenue vs. av.) and method for numbering stops do even exist within

the same application.

Furthermore, when file structures are designed to support individual systems, they are generally designed to suit only those particular systems and to make them run most efficiently. In other words, such a design focus means that the file organization is convenient for one specific application and the nature of road network and transit information is such that one scheme is unlikely to be best for all applications. Hence independent development of applications is quite likely to lead to incompatible data structures.

In general, the complexities of using GIS for transit applications can be divided into several aspects and attributed to several major reasons. These complexities can be classified as "data-related", "software-related", or "organizational."

6.3.1. Data-Related Complexities

6.3.1.1. Different Attribute Requirement
Different applications have different attribute requirements. It might be true that the spatial features of a route are common to many applications but the attributes that need to be attached to that route vary widely between these applications. For example, it is very essential to encode directionality of streets (one-way vs. two-way streets) and turn movements at intersections (nodes) for routing applications in order to correctly calculate the optimum path between two stops. The street width, the number of lanes, and the road condition, on the other hand, are of more importance for scheduling and route-analysis applications. Such data help in determining whether a route is wide enough to handle buses and, if so, the estimated travel speed on that route, for

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example.

6.3.1.2. Different Spatial Representations

One of the major factors adversely affecting the building of sharable databases is the difference in spatial representation required by each application. By spatial representation differences, it is meant the difference in terms of segmentation, scale, accuracy, and dimensionality. In the above examples, the problems related to differences in segmentation were clearly shown. It was clear that the segmentation required for the representation of ridership in the corridor analysis was different than the one needed for the routing or address matching applications. In the former case, the stop-to-stop segmentation was utilized whereas in the latter the intersection-to-intersection segmentation was needed (see Figures 6.3 and 6.4).

The issue of network representation is not simply a choice about what each application needs in terms of network segmentation or whether the data representation for one application is more suited than the representation for another. If this is the case, we would recognize that one size does not fit all needs and resolve to allow multiple representations to coexist. The real complexity issues relate to how easily can one transform one representation into another. The viability of a GIS at a transit agency is dependent not only on the capability to meet all the different representations needed by various applications, but also on the capacity to move from one representation into the other easily. This is especially important when data sharing activities are occurring in the agency.

Data sharing is "easier said than done." This is, in part, due to the fact that there are many sub-pieces of data that are potentially sharable and that it is difficult to isolate

these pieces. The question of data sharing is not an "all or nothing" question. It is not whether one can share everything or nothing. However, it is not obvious as to which parts need to be standardized and shared, and which parts are uniquely added on to a particular application. This becomes more evident when the agency gets into identifying what are the different datasets that are needed, which different sources they come from, which parts will stay constant, and which parts will change over time.

The scale required for each application, moreover, is not always the same for all representations. The TIGER file scale is convenient for most applications except for a few applications where more details than the centerline of a street are required. In chapter 3, we talked about one application whereby the real-estate department is interested in knowing the width of streets and the width of its right-of-ways in order to keep good track of the agency's properties and be able to determine the exact boundary of these properties. This interest is especially important as many public utility companies run their facilities within the right-of-way of the agency's lines. For this application, for instance, the scale of the TIGER file is not appropriate. More detailed maps are needed.

In addition to the scale issue, the 2-dimensional (2D) representation of the street network is not always convenient. Using the same example of the property management by the real-estate, 3-dimensional (3D) representation of some data is more adequate for some applications. For example, it would be useful to know the location of the fiber-optics cable that the phone company runs underneath the track of the rail line and its position with respect to the rail line tracks. 3D representations in such a case are more useful than 2D ones. Another example where 2D representations are not of great usefulness is the representation of complex intersections. Underpasses or overpasses are the source of confusion when complex intersections are represented

in 2D.

It is true that some of the 3D data can be added as attributes to the 2D representation in order to convey the same information. As a matter of fact, this is a part of the more general "attribute vs. spatial feature" problem. The lack of encoding standards, as discussed above, aggravates this problem. In the absence of these standards and in the face of limited budget constraints for application development, some of the spatial features (e.g., number of lanes, street width) are encoded as a spatial feature for some applications and as attributes for others. This inconsistency in encoding standards adds to the complexity of building sharable databases. Part of the major decisions that transit operators have to make is related specifically to this issue. In chapter 7 we elaborate more on this issue.

6.3.1.3. One-to-Many Problems

The third data-related factor that relates to the above complexities is the 'one-to-many' problems[40] associated with routes, stops, directionality of routes (inbound vs. outbound), and routes variations (AM route vs. PM route). Transit routes are dynamic in nature. They vary with time and with time-of-day. Unlike street networks, in a transit network routes can overlap on top of each other, share stops and links, and use the same links for inbound or outbound directions. These characteristics of transit routes cause a lot of one-to-many problems. As illustrated in Figure 6.1, route 1 and route 2, for example, share a set of links and have 2 common stops that belong to both of them. Encoding and building the needed databases for these routes can always create ambiguities related to issues such as which data belongs to which spatial feature. For example, the representation of the total number of passengers boarding or

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[40] A "one-to-many" problem is a term used in relational database management to indicate, for example, that one row in a table may be related to multiple rows in one or more other tables.

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alighting at a common bus stop can cause confusion about the number of passenger traveling on one route and stopping at that stop with the ones traveling on another route. Furthermore, when an inbound route shares the same links with the outbound one, stops on opposite sides of streets can exist. For some applications, such as routing, these stops need to be collapsed into the nearest node in the network. When several stops are collapsed into one node, connectivity between routes is made possible. As we saw earlier, routing algorithms might give wrong results while calculating shortest paths, as a result.

6.3.2. Software-Related Complexities

6.3.2.1. Transit Route Connectivity and Turn Movements

At intersections, most GIS packages cannot properly handle turn movements, connectivity, and transfers between buses. In Figures 6.7 and 6.8, we illustrated the problems related to network representation and to the handling of connectivity between routes. In a typical GIS, any two intersecting lines are connected by a node. Representing connectivity and turn movement at these nodes is quite complex and sometime is very expensive to be handled properly by a GIS.

In order to overcome the 2-D limitations, a lot of "baggage" needs to be added to the network representation which would greatly increase the size and the complexity of the data structure. For example, if information about the possible 16 turn movements at every intersection are encoded into a network, the machine storage and its processing speed have also to be augmented by an order of magnitude. The computational complexity of making the transportation algorithms work has to do with the number of links and nodes in a network. If the network representation is blown up

for the purpose of integrating turn movement information, than the transit network might become far beyond the scope of any machine to run the algorithms efficiently. Cutting corners to make things doable is part of the motivation for what needs to be done when trying to implement a GIS. In other words, the data representation is in part driven by performance considerations in running the algorithms. This is not something that will go away in the near future nor will it be easily resolved by new technologies. As a result, ad-hoc solutions, such as turntables, are implemented by most GIS packages to deal with part of these representation complexities. These solutions are usually not very suitable as illustrated in the next example. The algorithm performance degrades considerably with network complexity and the pseudo nodes and turntables can explode the network size.

Referring back to Figure 6.1, we see that stops 2 and 3 belong to route 1 only whereas stop 4 belongs to route 2. Figure 6.5 shows the representation of the same route network in order to facilitate routing operations: stops 3 and 4 are collapsed into node 42 while stop 2 is represented in node 11. Since stops 3 and 4 are on opposite corners of an intersection, it can be assumed that passenger can transfer from one route into the other at node 42. If no connectivity is allowed at node 42, a turn movement table is usually used to describe allowed turns on intersections. However, in this case and as illustrated in the previous chapter, the turn movement table can not tell the software that route 1 is allowed to turn right only while route 2 left since both routes are sharing links L11, L13, and L14.

The mishandling of connectivity is further illustrated in the following simple example: Assume a passenger is boarding route 2 and wishes to stop at the intersection of K St. and 18th St., i.e., at Stop 2. According to the network representation of Figure 6.5, this operation is feasible while in reality stop 2 does not belong to route 2 and passengers

can not stop at it. The passenger has to stop at either stop 1 or stop 3 and walk to stop 2. This shows that the network representation used by the GIS can not handle connectivity and transfer between buses properly. In other words, collapsing the spatial features that is convenient for the reasons discussed above becomes a problem here. Various added links and/or attributes can help address the problem but add considerable complexity and maintenance headache to the task.

6.3.2.2. Processing Speed and Modularity of GIS Software

The practicality of using GIS software packages for transit applications with metropolitan size networks of transit routes is related to the issue that applications begin to look more like "customized" rather than "off-the-shelf" applications and to the fact that many GIS (but not all) are not up to the task. The delays in processing large information databases for some GIS applications, render the "out of the box GIS" inefficient and impractical in handling complex operations, such as building a PIS. The performance penalties associated with using general purpose GIS tools in place of customized code is the major contributor to the delay in running time of GIS-based transit applications. For example, the system overhead associated with moving from one module to the other can be extremely time consuming and taxing to the performance of the software as compared with the time needed to run the underlying algorithms once the data and variables are properly set up.

Furthermore, the sequential processing of operations adds to the inefficiencies of current GIS software. In Arc/Info for example, no two processes can be run at the same time. Each module must be started and stopped sequentially. "Multi Threaded" programming capability will enable GIS software to be more efficient. Either the GIS software must be rewritten or the operating systems must enable some form of

parallelism or at least some efficiency in retaining and cross-referencing programming modules in memory for easy and fast re-use. As GIS technology becomes more unbundeled and modular, the need for improved software engineering of the operating system and application will also increase. The macro programming languages that most GIS have are not efficient at handling such issues. Together with advances in workstation technology, these changes in software design will make it much easier to build efficient tools for transit applications.

In order to make complex GIS transit applications more efficient, pre-processing of information needs to be done. Since the technology is not well developed to support on-the-fly calculations for real time applications, such as the PIS, pre-processing of information and storing results in adequate and accessible formats is one option for dealing with this issue. The obvious inconvenience of this operation are basically related to the need for extra storage disk space and to the process and frequency of updates. In the next chapter, we discuss the choices that transit operators have to make. The choice of which data to pre-process and which to compute on-the-fly is one of those important decisions that might affect the ways the complexities can be addressed in different applications.

6.3.2.3. Unsuitable Transportation Algorithms

Transit applications require highly sophisticated transportation algorithms that are not usually available in "off-the-shelf" GIS. The prototypes that we built identified some of these deficiencies in the GIS algorithms. The regular routing or shortest path algorithms are not necessarily adequate to transit applications where travel distance is not the only factor that needs to be incorporated into finding an optimal path between an origin and a destination. Travel time and transfer time are usually more valued in

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these applications. Furthermore, transfer from one stop into another is not only dependent on geographic proximity but also on schedules of buses that vary with time-of-day and day-of-week. Incorporating all these factors into path-finding is more complex than what shortest path algorithms, that GIS have, can do. External relational DBMS and programming language can be utilized to support either the generic GIS algorithms in incorporating time and schedule factors in path finding or to build more adequate external algorithms.

Another deficiency with the algorithms of "off-the-shelf" GIS is related to the "allocation of resources" algorithm that is used to assign resources (links) to centers (stops), i.e., to find which streets are the closet to which stop. In Arc/Info, for example, the allocation algorithm requires that centers should be always located at nodes. If TIGER files, which adopt the street intersection segmentation, are used for this operation, bus stops can therefore be created at street intersections only. In a city however, it might be true that most of the bus stops are located at street intersections, but still there are many stops located along some of the links. Splitting a segment to accommodate such a stop sounds like an easy solution but, as the previous discussion indicates, this may lead into significant complexities in the sharing and updating of network data.

Another deficiency with this algorithm can be illustrated in Figure 6.5. In Arc/Info when links are assigned to nodes, the whole arc must be assigned to a node or a center. No part of an arc can be assigned to one center while the other part to another center. Link L11 in Figure 6.5 has stop 1 at one of its nodes and stop 2 at the other node. When the assignment is made, link L11 is arbitrarily assigned to the one of the two stops while in fact half of it should be assigned to stop 1 and the other half to stop 2. It is true that this might be a minor problem but it elucidates the lack of flexibility in

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utilizing "out-of-the-box" GIS algorithms.

6.3.3. Organizational Complexities

By organizational complexities we refer to those complexities resulting from the way or the method adopted for implementing a GIS in a transit agency. In the next chapter we shall discuss at length the development and implementation strategies in a transit agency and the different impacts, benefits, and inconveniences of each strategy. However, we shall list some of these typical complexities here which generally obstruct the building of sharable and sustainable GIS databases and applications (which, in some ways, also pertain to the above "data-related" and "software-related" problems). Organizational complexities are related to factors like lack of standardization, difficulty of implementing standards, availability of technical expertise and right skills, structure of the organization (centralized versus decentralized), strategies for building applications (in-house vs. contracted out), and the like. In the next chapter we dwell more on these problems.

The lack of encoding standards within the agency is not the only source of inconsistencies. Inconsistencies can also arise from the use of different basemaps. The DLG[41] street network files produced by the USGS, for example, are not very consistent with the TIGER files. The DLG files have usually a better positional accuracy but lack the address information that TIGER has. The shape of the street lines also differ between the two. DLG files use more shape points to represent streets more than what TIGER does. If each of the DLG and TIGER files is used for building

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[41] DLG: Digital Line Graphs, Department of the Interior, US Geological Survey, National Cartographic Information Center, 507 National Center, Reston VA 22092.

the databases of different applications, matching these databases becomes extremely tedious, as a result. Unless encoding standards and strategies are well set for developing databases, these problems would remain hard to tackle. These problems include:

1. Use of different basemaps for building different transit applications: This is usually caused by the lack of coordination between application builders and which generally results in major data reconciliation and sharing problems.

2. Incompatibility in hardware and software acquisition: Different departments purchase their own GIS software and hardware that meet their immediate needs. However, when data need to be shared between different groups of user, major incompatibility problems usually arise.

3. Different standards within the agency: In many case standards are completely absent and users are free to build databases or application as they please. In some other cases, different standards that relate to naming conventions and unique ID, for example, are adopted by different users. Reconciling databases in these cases is very complex, as a result.

The implementation of standards in the organization is as complex as the setting of these standards. Historically, transit agencies have adopted the product-by-product approach for developing applications. Many of these products are usually contracted out for outside consultants to develop. The lack of a holistic view in the development of applications makes it very difficult to implement any set of standards. The need to change the organization view from product-by-product choices to a data flow view is one important aspect of the organizational complexities.
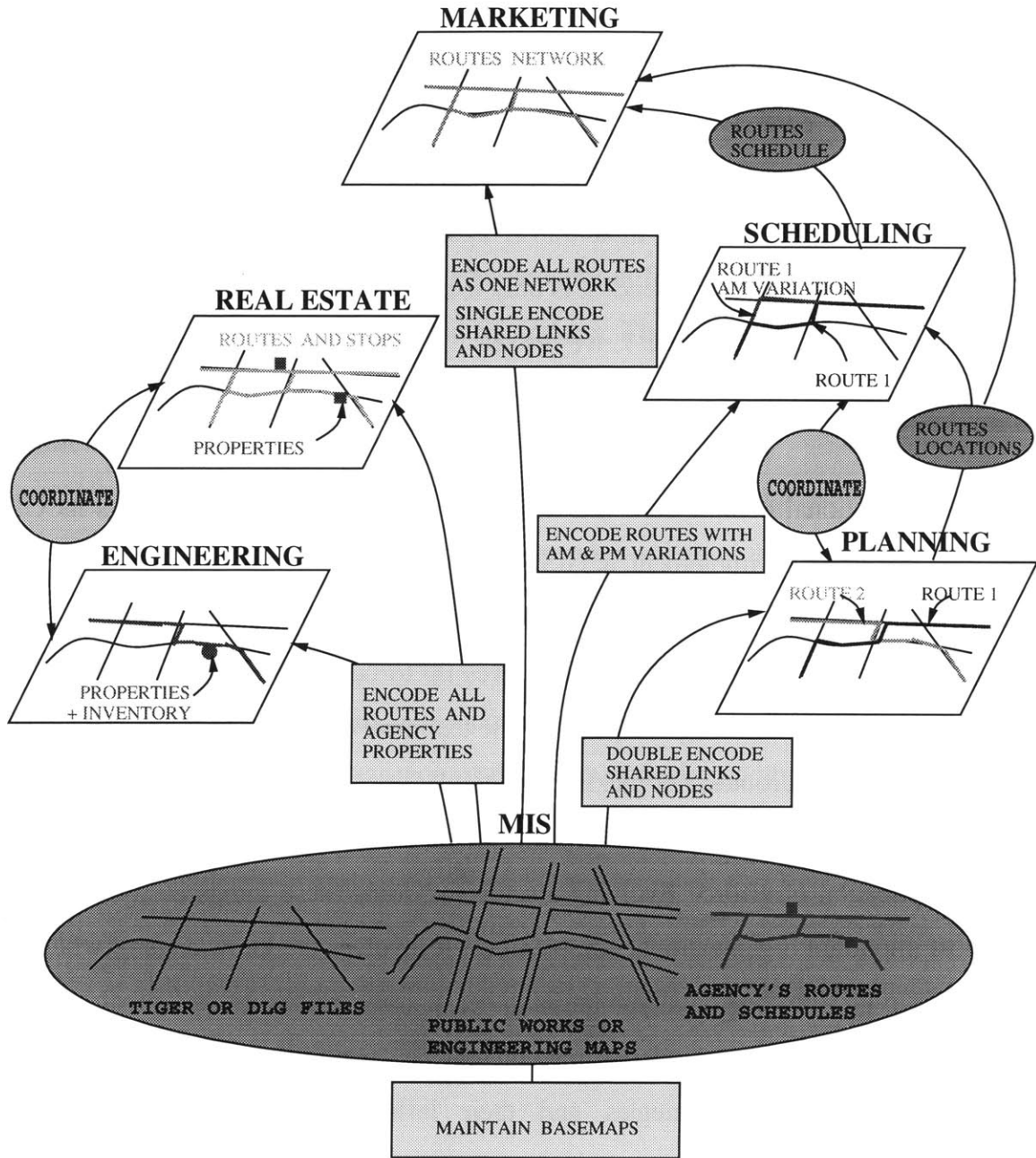
Figure 6.9 - Sample Data Pipeline In A Transit Agency

The following labels appear within the figure:

MARKETING
ROUTES NETWORK

REAL ESTATE
ROUTES AND STOPS
PROPERTIES

ENGINEERING
PROPERTIES + INVENTORY

COORDINATE

ROUTES SCHEDULE

SCHEDULING
ROUTE 1 AM VARIATION
ROUTE 1

ROUTES LOCATIONS

COORDINATE

PLANNING
ROUTE 2   ROUTE 1

ENCODE ALL ROUTES AS ONE NETWORK
SINGLE ENCODE SHARED LINKS AND NODES

ENCODE ROUTES WITH AM & PM VARIATIONS

ENCODE ALL ROUTES AND AGENCY PROPERTIES

DOUBLE ENCODE SHARED LINKS AND NODES

MIS
TIGER OR DLG FILES
PUBLIC WORKS OR ENGINEERING MAPS
AGENCY'S ROUTES AND SCHEDULES

MAINTAIN BASEMAPS

By "data flow" or "data pipeline" we refer to the process of propagation of data between applications and users and the additions / modifications to these data as they move between departments. As mentioned earlier, each application requires different representation of data. Data generated in one department of an agency is usually modified to suit the needs of other applications in other departments. Figure 6.9 shows one example of data pipeline in a transit agency. Note, that this pipeline is not necessarily the one we recommend. It is only used to illustrate what we mean by data flow or data pipeline. In chapter 7, we discuss examples of data pipelines that can be used to manage the implementation of a viable GIS in a transit agency.

Other organizational complexities are related to how a transit agency grows its GIS capacity. In order to implement a GIS in an organization and address all the of technical complexities associated with it, transit agencies need to be well equipped and prepared for that. They have to set themselves up to be able to make useful choices that serve both short and long term needs. The technical difficulties are not necessarily digitizing streets and routes, nor picking a particular encoding scheme, but the building of robust strategies and viable development paths that avoid expensive dead-ends or costly duplication of efforts. Evolving a setup for doing these things easily is one of the most important organizational complexities. It involves the knowledge of where to start, how to go from one data type into another, and what does it take to maintain the GIS capabilities over a period of time. In chapter 7, we discuss these issues and different organizational strategies and their influence on the success of the implementation of GIS.

6.4. Summary of Complexities

Addressing the complexities we have discussed depends by and large on the overall implementation strategy of GIS in the agency. For example, in order to propose an encoding schema of routes that is suitable for several transit applications, it is necessary to have the adequate infrastructure to support such schema. By infrastructure we refer to the organizational setting that would allow the establishment of standards, the adherence to these standards by different users, and the mechanisms for exchange of data and propagation of updates. The availability of any part of this infrastructure is dependent on the IT implementation and adoption strategy in the organization as a whole.

Our discussion of the complexities so far was more or less at the conceptual level. We have discussed bits and pieces of these complexities based on the three prototypes we built and our interviews and survey of transit operators. However, in order to get a handle on these complications it is necessary to summarize them in a fashion that would properly direct our discussion of the ways of dealing with each them. We shall first start by listing all the difficulties, then the GIS applications at transit agencies and finally cross tabulate one against the other.

The list of technical complexities that we have identified so far is the following:
1. Different Attribute Requirement
2. Different Spatial Representation
3. One-to-Many Problems
4. Route Connectivity and Turn Movements
5. Processing Speed and Modularity of GIS
6. Inappropriate Transportation Algorithms

Note that this is a compilation of the sort of typical complexities that might be encountered. Additional problems might be identified, for instance, while developing other GIS applications, but the value of this list is that it gives a framework that can be used to address similar complexities. Note also that not all these problems can be readily resolved. In the next chapter, we shall try to address each of them (as much as possible) and we shall see that some of these complexities might remain partially or completely unresolved.

In chapter 3 we described some of the important applications of GIS in transit agencies then in chapter 5 we discussed three GIS-based prototypes. The following is a list of the typical GIS applications in the different departments of an agency:

1. Corridor study
2. Ridership forecast applications
3. Production of schedule maps
4. Passenger information systems
5. Properties and facilities management
6. Crime analysis and police patrol dispatch

In order to get a better grasp of the GIS complexities, we shall now create a matrix that shows the way each of these problems gets exhibited for each application. Each of the above 6 complexities gets a different level of importance or a different way of manifestation depending on which application the GIS is being used for. Matrix 6.1 shows the relationship between difficulties and applications.

6.4.1. Rethinking the Notion of Basemaps

Matrix 6.1 shows that different applications need different network representations that can not be provided by a single basemap. Different basemaps need to be selected for building different applications. For example, TIGER files can be adopted for developing applications that involve routing analyses or address matching whereas local detailed maps can be used for developing applications that require highly accurate basemaps or that need to tap into local databases. TIGER street network files, for instance, are quite suitable for building ridership forecast models, passenger information systems, or police patrol dispatch. In addition to containing needed topological information for performing shortest path and routing applications, TIGER files provide the link to the demographic and socio-economic data that are needed for doing some of the ridership forecast applications, for example.

However, for some other applications, such as the properties and facilities management or the crime analysis, the level of detail of information and the scale of TIGER might not be very suitable. Local basemaps that can link to local data, such as land use or parcel level data, need to be used instead. Moreover, in some applications, such as the police dispatch, better geometry and more accuracy of address information are desired (more than the 75% accuracy of TIGER addresses). In some metropolitan areas, such as SANDAG, where centralized coordinated planning efforts are sufficient enough to generate street centerline from other sources that are better than TIGER, local files can be more useful to building such applications. In other words, TIGER files are suitable for building some applications while locally generated local street network files are more suitable for some other.

Matrix 6.1. Aspects of Complexities for Each Application					
Application Problem	Corridor Study	Ridership Forecast	Production of Maps	Passenger Information System	Properties and Facility Managem't	Crime Analysis and Dispatch
Different Attribute Requirement	Street width, number of lanes, speed limit are needed to examine bus maneuverability	Pointcheck, ride-check, and rider-ship survey data need to be used as attributes to segments	Street names and intersections are needed for maps (landmark infor-mation encoded as spatial feature)	Directionality of streets (1-way vs. 2-way st), turn movement are needed for routing and path finding	Maintenance information are attached as attributes to networks and routes	[same as Passenger Information Systems]
Different Spatial Rep-resentation	Double encode overlapping route Stops are repres-ented as offset of centerlines. Stop-to-stop segmen-tation needed.	Centerline repre-sentation used. In PRS, fixed-length segments are used to estimate rider-ship along routes. (Refer Chap. 5)	Schematic repre-sentation and distorted maps are needed. Land-mark information needed. Use of local maps	Routes need to maintain the same segmentation as street network file to preserve link between nodes that represent stop	Positional accura-cy of routes and stops is important. Higher scale is needed. Curb line representation of streets needed.	Patrol dispatch: same as PIS. Crime Analysis: same as properties and facilities management
One-to-Many Problems	If TIGER repre-sentation is used, 1 arc might corre-spond to multiple routes. Stop-to-stop segmentation does not corres-pond to TIGER's	N/A	TIGER segments might not have a one-to-one correspondence with local maps, if TIGER repre-sentation is used	Stops on different sides of streets intersection: one node corresponds to several stops	[same as Production of Maps]	[same as Production of Maps]
Route Connectivity and Turn Movements	Need to incorporate transfer data from ridecheck and pointcheck surveys	[same as Corridor Study]	Use special symbols on maps to indicate stops where connection to other routes is feasible.	Connectivity is dependent on schedules of bus. Complex data structure is needed.	N/A	TIGER topology is not enough to represent connec-tiovity and turn movements of transit routes.
Processing Speed and Modularity of GIS	N/A	Forecast models require several overlay and buffer operations Which make models very slow	N/A	PIS requires the use of address matching, alloca-tion, path-finding algorithm in different modules	N/A	[Same as Ridership Forecast]
Unsuitable Transport Algorithms	N/A	N/A	N/A	Need to incorporate bus schedules in shortest path algorithms	N/A	Need to incorporate turn movement and traffic delay information.

The choice of using TIGER as a basemap or not is in fact one of two choices. The other choice is whether the variations of TIGER are really different enough to be viewed as different basemaps. Earlier in this chapter we discussed the augmentations that need to be done to TIGER to make it suitable for routing applications. It was clear that needed additions to TIGER are doable but significant. The TIGER representation could be supplemented with needed information to make it suitable for routing applications but the amount of work for doing this task is quite considerable. In other

words, the regeneration of these topological augmentations when new versions of TIGER are made available is the real problem. Hence, the choices that transit operators need to focus on are related to the data flow and update mechanisms, and to the fact that a "basemap" need not be the "finest grain" detailed starting point.

Viewing a "basemap" as something that will change or evolve is an important complexity. The need to move between basemaps is also an important problem especially when data sharing efforts are occurring at a transit agency. When using a certain basemap to build a specific application, designers need to keep in mind that more accurate basemaps might later become available to them and the need to rebuild the application using the new basemaps will likely arise. In other words, the complexity associated with the need for different basemaps is also related to the need to conflate data from one basemap into the other. Conflating data from one network into another which has geometrical, topological, segmentation, scale, and one-to-many correspondence related differences is a very complex operation. The complexities related to the need for different basemaps are hence more related to conflation complexities. Conflation tools that are currently available are not sophisticated enough to handle all these complexities yet. Hence, the questions that transit operators need to ask when selecting a basemap are related to how easy is it to conflate data from one basemap into the other, what problems will the agency face when updated versions of the basemaps are released, and what technical expertise needs to be in place to handle the technical complexities associated with moving from one basemap into the other. As we will discuss further in Chapter 7, the key point is that it is presently impractical for most transit agencies to expect to move forward with GIS only after selecting/building the ideal basemap.

6.4.2. Rethinking the Representations of Routes and Stops

When encoding spatial data for a GIS application, many data and spatial features can be encoded either as a spatial feature or as attributes. One classical example is the width of a road. Roads can be represented by their centerline and their width can be attached as an attribute or they can be represented by their curb lines. In most of the transit applications, the centerline representation is more convenient than the curb line representation especially for applications that involve routing, path finding, or address matching operations. The curb line representation is generally used by the engineering and real estate management applications where details of routes and inventory information related to them are stored. In other words, roads need to be represented by their centerlines for routing applications and by their curb lines for inventory and engineering applications.

Good curb line basemaps can include a lot of information that are needed for TIGER-style centerline maps. By delineating block boundaries, information about the width of streets become readable in the curb line representation of streets. Block level address range information, for example, can also be deduced from these maps. However, since these maps and TIGER files come from different sources, the access they provide to polygon data is also different. Curb line maps, for instance, can provide a link to parcel level data while TIGER can allow the linkage to the census socio-economic and journey-to-work data.

On the other hand, different representations of routes and stops are needed to suit different applications. The segmentation of transit routes varies widely with each application. For example, the stop-to-stop segmentation is the most suitable for corridor analysis (where route segments are used to analyze ridership information), the

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intersection-to-intersection segmentation is needed for routing applications, whereas the attribute-based segmentation is needed for maintenance and inventory applications. In other words, no single representation suits all applications.

However, the important feature of this complexity is associated with managing the mismatch between the representations rather than handling any one mismatch per se. When sharing data, the procedures for moving from one network segmentation or representation into the other becomes more important. In other words, the complexity of building databases that satisfy all application needs is more related to the need to move from one data structure into the other easily (using adequate procedures and GIS tools, such as dynamic segmentation or conflation tools).

The segmentation issue can be addressed using the dynamic segmentation tools of GIS. But the real question is more about the mechanisms and the procedures that allow the use of unified route systems among all users and across all departments and applications. In order to transpose data from one representation into the other using the dynamic segmentation tools, a unified routing system needs to be first in place. All routes should have the same starting point and ending points, the same referencing schema of attributes along the routes, and the same naming conventions. Standardizing the encoding schema of routes hence becomes one of the aspects of the complexities associated with the need for different network representation.

6.4.3. Handling Connectivity and Turn Movements

The applications that are affected by the connectivity and turn movement complexities are the ones that involve routing or path finding in general. TIGER files are the

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network files that are usually used for these applications especially since most of the applications that involve the use of routing algorithms also involve the use of address matching algorithms (e.g. PIS or patrol dispatch). As mentioned earlier in this thesis, the geographic representation of street network files is not very adequate for representing the complex turn movements and routes connectivity at intersections especially in transit applications. More sophisticated representations are needed to model these turn movements and connectivity properly.

The connectivity and turn movement augmentation to TIGER files are not only complicated, but also not needed for all applications. Adding them to the basic file can end up in cluttering the basic route files. The important aspect of this problem is related to the need to add such augmentation when needed in a sensible fashion. The real issue is not whether they can be added or not. It is whether the procedure used for adding them is sustainable or whether they have to be always added from scratch. The point is basically managing these complexities sensibly. It is managing some process that attends to these complexities rather than "once for all" choice or solution. Some coordination in application development can work but also there is a need to manage the complexities well and it is unlikely that a product-by-product view of application development is able to handle these complexities acceptably.

Figures 6.7 and 6.8 showed how the network representation needed to be augmented in order to model connectivity properly. Pseudo-nodes and pseudo-links were added to the geometric representation of the network in order to deal with the connectivity problem when several routes share common arcs. Augmenting the network representation is a major aspect of the connectivity complexity. However, creating the tools that allow the regeneration of these augmentations when more accurate network files become available is more complex than the augmentation itself. In other words,

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the selection of robust strategies for managing the complexities are especially related to issues about handling future updates, reconciling the network after being augmented with other networks, building tools needed to recreate these augmentations and developing the technical expertise in-house for dealing with these issues.

6.4.4. Sequencing of Processes in the Data Pipeline

As the chapter has progressed we shifted the focus from identifying complexities and selecting network models to managing the flow of data processing steps needed to meet the varied needs of a suite of applications. One of the most important aspects of the implementation complexity is related to the sequencing of processes in the data pipeline. Understanding and designing the data flow and the responsibilities for adding to the data pipeline is the most complex issue. This complexity is related to the fact that each application has its own local optimum in terms of data representation and that no obvious schema can be implemented that allows the addition to the data pipeline without destabilizing the different applications optima[42].

In a transit agency, routes are usually designed and analyzed in the planning department. The scheduling department takes the route design from the planning department and sets the schedule of buses to run along that route. The marketing department takes the information from the planning and the scheduling departments and feed them into their passenger information system. The engineering and real estate department utilize the same information for maintaining these routes. The police department also utilizes these route configurations to conduct its crime analysis and to

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[42] By "local optimum," we refer to the data and data structure best suited for each application. The local optimum of an application is related to the representation of street network, routes, and stops that best suit that application and the polygon data that need to be associated with them.

feed it into their patrol dispatch systems.

This is probably the most simplistic way of describing how the data flow between the different departments of a transit agency. This process is usually more iterative. The route design, for example, goes through several iterations before getting finalized. Nevertheless, it is clear from this data flow that data representation can not be made to satisfy only one specific application since other departments need to utilize the same data for their own applications. Therefore, the complexity that arises is related to how to make the propagation from one data representation into the other easy and possible. In other words, the strategies for addressing complexities can be framed as selecting a sequence of processing steps to manage the evolution of various data sets and then debate their relative convenience and robustness.

6.5. Conclusions

In this chapter we first showed the type of difficulties that can be encountered when implementing a GIS at transit agencies. We also showed that there is a certain structure to viewing these complications that distinguishes between things that are complicated but manageable (such as pseudo nodes), ways of managing complexities (by focusing on the data pipeline), and sustainability of startup strategies (how easy to recreate pseudo nodes). This chapter went from the delineation of difficulties to identifying important issues in thinking them through. The purpose of this chapter was not just to understand the reason of the complexities or to make case by case choices for each of them, but rather to realize that "no one size fits all." Transit agencies can not get easy choices of "where to start" and "what to use" that address all of their GIS implementation problems. The problem is managing their way through the

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complexities as they grow an increasingly capable system over time.

The second main point in this chapter is related to the development path of GIS at the agency. The development path, instead of being understood as a baseline delivered by the MIS department that can be used to build all applications based on it, is rather a few usable starting points that are good anchors in the process of evolving that is not very "clean" but yet manageable. In other words, the development path is not really technical complexities and finding technical solutions to them. It is managing the complexities through a choice of robust strategies that may not have a single "once and for all" basemap as one starting point.

The natural data structure for each application looks simple and easy to implement. However, when trying to combine all these structures together and make one representation suit all applications, the real difficulties and design choices start to emerge. Some of these complexities might be easy to handle and some very hard. In chapter 7, we discuss some of the choices for managing some of these complexities.

In other words, when the local optimum of several applications is examined, similarity between these optima might be observed. The question that application developers face is whether it is possible and worthwhile to use technology, such as dynamic segmentation, conflation tools, and attribution to overcome the complexities of combining the data structures needed for different applications. These technologies might help in addressing some of these complexities but utilizing them to address all the complexities is very hard. Furthermore, not only are these technologies hard, they also change the nature of the work that application developers are doing. Instead of worrying only about which basemap to pick in order to do one application quickly or about which application to develop in-house and which one to contract out, application

developers must also worry about whether the right tools are available to allow the migration from one data structure into the other.

In the next chapter we discuss different implementation strategies of GIS in a transit agency. We describe how each strategy can influence building, sharing, and maintenance of databases. Next, we try to address the technical complexities of implementing GIS based on the different organizational implementation strategies and in light of new technological improvements in GIS and database management technologies. We also look at the developmental pathways of GIS in transit organizations. We will try to answer the following questions: Which choices do these organizations have to make about how to get started with GIS applications? What data to use? Which other agencies can they connect to? and what kind of short cuts can they make along the way to get going?

Chapter 7

Implementation Strategies For GIS

Handling the difficulties of building a sustainable GIS system in a transit agency can only be achieved by addressing the organizational setup and the database development strategies. In this chapter we describe three typical development strategies that are used to implement GIS capabilities at a transit agency. We compare the advantages and disadvantages of each strategy and talk about the impact of each of them on handling the GIS complexities. In the previous chapter we showed some of the technical difficulties that the implementation of GIS usually faces. In this chapter we look at different developmental pathways of GIS in the organization. We take the difficulties that we discussed in the previous chapter and describe the different choices transit agencies have in dealing with these difficulties and the problems they will run into depending upon how they make their choices. We then talk about the real pathways transit agencies can pick

from and which problems go along with each pathway. We then compare the different organizational structures and development strategies that transit agencies usually adopt and determine which of those strategies seem to work well in this case.

7.1. Introduction

To handle the complications discussed in Chapter 6, the database development strategies need to be addressed. The literature identifies multiple approaches for system development strategy that are adopted by different organizations[43]. Existing databases in many organizations suffer from design defects. Complexity of data is usually at the basis of these defects. The database design process is usually divided into two stages: (1) logical design stage and (2) physical design stage. The physical design stage is always preceded by the logical one. The logical design of a database deals with the organization of data and is independent of any hardware or software on which it is to be implemented. The physical design, on the other hand, is more related to the implementation strategy of a certain logical design in the most efficient manner on specific hardware or software.

The logical structure of a database usually reflects the agency data model to a great extent since databases are the means used for managing firms. As a result, a top-down view of the agency data model is conceived as the best approach for the logical stage of the design. Another approach to modeling databases, is to take multiple bottom-up views of many application designers and merge them to generate the schema. Since the

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[43] for more details about the system development literature, refer to [Cash, 88], [Synnott, 81, chapter 12], [Davis, 85], and [Head, 84, Chapter 3].

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top-down and the bottom-up approaches to database design can be both valid, a more comprehensive approach is to accommodate the two to generate what is known as the middle-out or loosely-coupled approach to the logical design of databases [Afif, 84].

7.2. Organization of Information Systems

According to Gunton [1989], the implementation strategy adopted by an organization can be differentiated in terms of two basic variables: (1) autonomy and (2) coupling. Gunton analyzed how a range of businesses organized their information systems effort and recognized that "autonomy" and "coupling" were essentially the two dimensions along which the perception of what is best for the business diverged. He defines autonomy as "how important it is that end-users should be free to work out new ways of processing information rather than handling it largely in pre-defined manner" whereas coupling as "how important it is that end-users should have immediate access to data on corporate files, rather than working, for example, with aggregated summaries produced weekly."

Gunton [1989] used these two variables as the axes of a 2x2 matrix and arrived at 4 categories of strategies for building information systems in businesses. In transit agencies these two variables can also be taken into consideration when organizing information systems in general or when building GIS capabilities especially when one is interested in examining the extents to which end-users should have access to data or the flexibility to create their own models. Like Gunton, we cross-tabulate these two variables to come up with the following four strategies for building GIS capabilities at transit agencies. As we shall see, there are many structures that suit different types of "businesses" and there are no "good" or "bad" strategies:

7.2.1. High Autonomy, High Coupling

This strategy applies to agencies that have mesh-like rather than hierarchical organizational structure. In these agencies, end-users have a lot of autonomy to create their own models, modify major databases, and generate new datasets based on the needs of their work. The high coupling can be translated into immediate access to databases by all end-users provided to them by very efficient networking capabilities which inter-link all departmental, central and desktop computers. In other words end-users in the different departments of the transit agency can create their own GIS databases and develop their own models. End-users in this case should have the technical expertise and the experience to change data sets according to their needs.

In this model, the mechanism for data update and data control is not very important. If no proper mechanisms are in place, proliferation of uncoordinated databases and models might occur and inexperienced users might create a major threat to the integrity and accuracy of data, and the operation of the whole system. This structure does not apply to many transit agencies. Transit agencies that are very advanced in terms of technology adoption and implementation might fit under this category. Agencies that have adopted a distributed database design and client/server architecture might belong to this group.

7.2.2. High Autonomy, Low Coupling

This is usually the case with agencies that have several satellite offices that are geographically dispersed. Each of these offices usually has a lot of autonomy to build its own databases without really coordinating or sharing a lot of data with the other offices. Data sharing within these organizations is not really important, rather the

utilization of general purpose tools or applications that are developed by other users for similar analysis is more important. The advantage of this model is that it is very flexible and it allows the end-users to solve their problems easily and promptly using their local expertise and to develop their own databases to suit their needs. Obviously, the disadvantage of this strategy is the explosion of many uncoordinated databases and the duplication of common data by the different users or satellite offices.

From the perspective of the US DOT, state level transportation planning takes this form. Likewise, this model is representative of the relationship between the different transit operators and the Federal Transit Authority (FTA). Each transit operator has the autonomy to create its own data without worrying about what other operators are creating. However, operators are generally interested in sharing tools and models that other agencies have adopted for running their operations. FTA usually provides such information and sometimes with needed tools.

7.2.3. Low Autonomy, High Coupling

Low autonomy is usually translated into centralized databases and high coupling, which, in this case, means efficient links between users and immediate access to databases via high-performance networking infrastructure. This is the typical organization of hierarchical agencies where users do not have much leeway to generate their own databases or develop their own models. Users are generally adequately served by a standard set of services. Security and data control, in this case, are centralized and hence more easily controlled. This schema is usually achieved by linking the different users to a central computer, a mainframe in general, where all of the data processing and application development would usually take place.

A few transit agencies belong to this model. Our survey (that we discussed in Chapter 4) shows that the Dallas Area Rapid Transit (DART) is one example of such agencies. Users do not have the freedom to create databases as they please. Databases are centrally controlled by the IS department. IS only supports databases and applications generated by its staff.

7.2.4. Low Autonomy, Low Coupling

This is the case where the IS department in the agency allows little freedom to develop users application and at the same time does not focus on providing connections among users. IS provides data and applications for each group of users to meet their needs. Data sharing in this case is not an important priority for the developers of systems, databases, or applications. This is more representative of small transit operators that have limited resources. Our survey of Chapter 4 was focused on large transit operators only. It did not cover small operators who are the most likely candidates to belong to this group.

Our survey shows that most of the transit operators in the US adopt a "high autonomy, low coupling" strategy. In most of these agencies, different departments have the autonomy to create their own databases and applications with no coordination or data sharing efforts with other departments. A few agencies might belong to the "high autonomy, high coupling" category. TRI-MET is probably one of these agencies. It reports the building of autonomous applications while sharing data among departments. As mentioned before, DART is the only agency covered in our survey that belongs to the "low autonomy, high coupling" category.

Traditionally, transit operators have adopted a centralized model that provides users with controlled access to centrally-maintained databases. Mainframe computers were used in most transit agencies for running independently the activities of different functions in the agency. However, this traditional model broke down because of the failure of the "central" to accommodate computer graphics and GIS fast enough. Our survey confirms this fact and shows that most transit operators are currently implementing stand alone GIS capacities that provide needed graphics capability and within affordable departmental budgets.

Finally, there are no universally good or bad coupling and autonomy strategies. Each of these strategies can be applied to different organizations. It all depends on the size of the agency and its capacity to setup IS locally. In other words, there are several ways of organizing work and the viability of each of these strategy depends on how the work is organized which type of "business" is the agency in.

7.3. Data Structure Development Strategy

The above classification describes a static view of organizational structure. We shall now categorize organizations in terms of how they develop and implement IS applications. In other words, the previous categorization looks at the organizational chart of an agency whereas the following one tries to understand how organizations work by examining the way in which they evolve applications. The following are three possible data structure development strategies that transit agencies usually adopt:

7.3.1. Top-Down Strategy

In this strategy, all databases would use or be derived from centrally maintained ones. For example, the IS department would be centrally in charge of maintaining and building the road and route databases and providing the data to each application and ensuring the possibility of matching these data among departments. In general, the IS department would also be the provider of 'turnkey' applications to each department where the IS would be responsible for the maintenance of those turnkey applications while the departments responsibilities would consist of only operating the applications and reporting updates and changes to IS. IS, being the key player in this game, can coordinate the propagation of updates and changes from its centrally maintained databases to the departmental ones.

The main advantage of this strategy is that it provides consistency between databases and ensures that departmental databases can be inter-matched. It makes standards for information system development and operation easier to enforce. IS departments, in general, can develop sufficient expertise to evaluate technologies and to function as a research unit for leading-edge projects that individual users would not be able to undertake. However, rigidity, slowness, and idealism are the major defects that plague this strategy. Since databases are centrally maintained, few "super users" of these databases are authorized to perform updates or changes. It is rather the IS job to conduct such changes and diffuse these changes into the many applications that benefit from these databases. This rigidity in updating data and propagating changes can cause great delays which might endanger the viability of this system. In other words, the top-down strategy can be too cumbersome to implement for all but a core set of "corporate" databases. It needs a lot of effort to make it work and the temptation to let the quality of the underlying databases deteriorate is high as needs change and the

updating delays drag on. In the GIS area, further problems might also occur since, in general, central systems use different hardware that have lagged in handling computer graphics and GIS tools.

7.3.2. Bottom-Up Strategy

The Bottom-up strategy can be simply defined as: 'every department is on its own' or 'system modeling as an afterthought'. Each department is responsible for developing the databases and applications that it needs. No coordination between departments is required and databases for each application can be built from scratch. This is generally the fastest way to start implementing a GIS in each department's activity (since so little 'standard' databases exist and since desktop computing has developed computer graphics capabilities and interfaces sooner than many mainframe systems). The rigidity and unresponsiveness of top-down information systems to users' needs make the acquisition of user-area hardware and user-function development of applications more attractive. Furthermore, having direct control over information is very attractive to users especially when their performance relies heavily on the systems they are using. However, there is a tendency to encourage duplication of data and efforts as a result of adopting this strategy. Since a large portion of the route and road databases needed for different applications have common representation or attributes, this strategy may cause in the long run additional expenses resulting from storage of duplicate data and from buying incompatible software and hardware. The major problem with this strategy, moreover, is the difficulty in managing, organizing, and updating the abundance of redundant data resulting from the miscoordination. Such strategies in general tend to lack critical mass and budget for designing and implementing a sustainable system and often result in the proliferation of internally

inconsistent datasets within the agency.

7.3.3. Loosely-Coupled Collaboration Strategy

The loosely-coupled collaboration strategy is a hybrid of both top-down and bottom-up strategies. The main element of this strategy that differentiates it from the other two is related to retaining many of the "top down" characteristics, such as the creation of coordination committees, implementation of "prior approval" and reconciliation strategies, provision of necessary training , and planning of GIS financing, while allowing some autonomy and "incoherent" GIS development by focusing on standardization and coordination of a limited "core" set of data related to route and stop information.

In one of the loosely-coupled strategies (one that we will recommend in the course of this chapter), a regional or an agency-wide committee develops the framework and the guidelines for building databases. This committee has basically two concerns: (1) a functional concern where data ownership, standardization, and common definitions are examined and (2) a technical concern where the physical aspects of the data including design, implementation, and maintenance are studied. These guidelines recommend the type and format of data to be used in the agency. The central staff in the agency focuses on key data and tools that can initiate a manageable 'data pipeline'. To avoid the problem of using incompatible "basemaps", the committee after reviewing the different applications requirements would select a set of key databases and basemaps as the basis for building other databases. The central staff committee sets the responsibility of each department and the relationship between departments as far as database building are concerned. Then each department assumes the responsibility for

the appropriate value-added to the data pipeline and for building its own applications. The maintenance of databases becomes a departmental responsibility but emphasis focuses on practical coordination and tool development that allows gradual and semi-automatic maintenance and improvement of data in the pipeline. The advantage of building these automated maintenance tools is the ability to cope with changes in the key datasets used to build the application databases. For example, the process of extracting bus routes from TIGER files can be automated (using GIS capabilities) in order to handle most modifications to routes and to cope with the new releases or updated versions of TIGER.

7.4. Choices Facing Transit Agencies To Get Started With GIS

We have so far reviewed the different implementation strategies and the different organizational structures of transit agencies. In Chapter 6, we discussed the different complexities that are facing the smooth implementation of GIS and we also talked about how the solutions to the complexities are influenced by the implementation strategy in place. However, we limited our discussion so far to the nature of the problems without really addressing them in detail. The questions that come to mind, as a result, are: Are these complexities solvable, and how? What should transit agencies do? Should they wait until these complexities are resolved or should they start on their own and face these problems as the GIS work progresses at the agency. We shall now discuss the different choices that transit agencies have regarding how to get started with GIS and how to grow their use of GIS effectively. Each of these choices has several facets that range from the "obvious" to the complex ones. The "obvious" choices relate to which application to start with, which data to use, which outside agencies to connect to, and what development must be handled by transit agencies.

The more complex choices include how to build a data pipeline that ensures the propagation from one data representation into the other easily, which tools to use or develop in order to facilitate data sharing, what procedures need to be created to make the GIS viable, and what technical expertise need to be in place. In the next section, we also describe the type of problems that transit agencies might encounter depending on the decisions they make.

7.4.1. Where to Start?

For agencies who have already acquired and implemented a GIS the question of where to start implementing a GIS in the agency might not be a real issue to them[44]. However, for agencies that are contemplating the use of GIS, they can make several choices as far as where to start using the GIS and in what fashion. We now look at some of the obvious choices. The more complex ones will be discussed later in this chapter.

7.4.1.1. Choice of Applications

To start implementing a GIS, an agency first needs to identify where GIS can be used. In Chapter 3 we discussed some of the important areas of application of GIS from which transit operators can pick start-up applications. Agencies have the choice between implementing an agency-wide GIS or dealing only with the immediate needs for GIS. In other words, it all depends on the available budget for GIS and the awareness of its benefits and potentials. Transit operators who are aware of the benefits of GIS and who have the budget to go ahead with it, (or are aware of other

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[44] Even so, many agencies "start" GIS more than once for different applications or restart an application with improved data or tools.

agencies that have utilized it successfully), might be interested in implementing an agency-wide GIS. On the other hand, transit operators who are still at the exploratory stage and lack the budget for major GIS investments, have the choice of testing its potentials on applications that are of immediate interest or need at the agency.

Implementing an agency-wide GIS has the advantage of addressing some of the GIS complexities (that we discussed in chapter 6) from the onset. Organizational complexities related to coordination between databases and adoption of standards, for example, can be handled early on when agency-wide GIS is implemented. GIS coordination committees can be established at early stages of implementation in order to enable a more holistic view of the GIS use and to face some of the organizational problems earlier on. Standards for creating databases and GIS applications, basemaps for building applications, and outside sources or agencies to collaborate with can be all decided, for instance, by the GIS committee to avoid many of the GIS implementation problems. Furthermore, the difficulties related to different applications' needs in terms of data representation and the ability to move from one data representation into the other, that we discussed in Chapter 6, can be dealt with more effectively as a result of the holistic view of GIS in the agency.

However, for GIS committees to become effective, the right organizational setup and mix of skills need to be in place first. If the agency uses a bottom-up approach for applications development, the establishment of such committees is not as easy as in top-down or loosely-coupled organizations. Moreover, it is harder to implement the recommendations of the GIS committees in such organizations. In other words, the choices that these agencies have are not free or independent of other organizational considerations. The organizational structure of the agency plays a major role in deciding which choices to make.

7.4.1.2. Choice of Software and Hardware

Choosing appropriate GIS software and hardware is not a straight forward task. Several factors go into the selection of software and hardware. These factors include compatibility between selected hardware and existing ones, the possibility of linking selected GIS packages with existing databases or customized systems in the agency, friendliness or ease-of-use of the selected GIS, and cost of hardware and software needed to run the GIS. We have discussed previously in this thesis the problems related to mismatch and incompatibility between different GIS hardware and software used for different applications or in different departments. The choice of hardware and software is also dependent on availability of funds allocated to GIS. Usually, when GIS is adopted for building prototype applications, affordable PC-based GIS are acquired. However, when the scope of GIS is wider than meeting the immediate narrow needs of an agency or testing the potentials of GIS, workstation-based GIS becomes more suitable[45].

The choice of suitable software and hardware can also impact the GIS implementation complexities. Selecting compatible software and hardware can eliminate some of the mismatch problems. In addition to having some of the advanced tools needed for building sophisticated transit models, such as dynamic segmentation and some conflation tools, workstation-based GIS packages can also provide the necessary link to relational database management systems (RDBMS) that are also needed for handling many of the data representation complexities. This link, for example, can help in overcoming some of the complexities related to one-to-many correspondence

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[45] The spectrum of machines and systems that can be used for implementing a GIS varies from the stand-alone, single-user PC for desktop GIS to the networked graphics workstations supporting client/server applications via operating systems such as UNIX with pre-emptive multi-tasking. In this thesis, by workstation we generally refer to the later.

problems, and transit connectivity and turn movement. The issue of how RDBMS can be used to handle these issues was discussed earlier in this thesis and we shall go back to it at the end of this chapter too. PC-based GIS are not yet as flexible and sophisticated as workstation-based ones. In spite of the fact that PCs are catching up with the workstations in terms of speed and processing power, few GIS vendors have added the needed sophistication to their PC-versions of GIS. Hence, when using PC-based GIS, the task of handling turn movement, connectivity, and one-to-many complexities, for example, becomes quite complicated.

The choice of software and hardware can, however, be viewed differently. Instead of looking into the capabilities of each software and hardware and investigate the kind of problems they can address, a more appropriate approach is to first design the data pipeline and the application development pathway in the agency, while keeping in mind the technological developments and what each software can deliver, and then make the choice of software and hardware that best permit the implementation of these strategies. In other words, the choice of hardware and software can be better decided once the major decisions about the implementation strategies are made.

7.4.1.3. Consultant Versus In-House GIS Development

The question of whether GIS should be developed completely in-house or using outside help, like that provided by consultants, is very important for decision-makers at transit agencies. When the time comes to start building GIS applications, the complexities that we describe in this thesis can derail in-house development efforts of inexperienced GIS users. In other words, many of the implementation problems can become more complex depending on the in-house availability of qualified personnel and the level of their technical expertise. Transit operators have a choice between

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developing their GIS applications in-house, relying on consultants to help them get started by building key applications for them, or a combination of both. Consultants can be very useful for helping the agency in making decisions related to software and hardware selection, building applications, and becoming aware of the latest technological developments and where other agencies stand in terms of GIS implementation and of handling GIS-related complexities. Of course, there is a "chicken and egg" problem in developing enough in-house understanding to select consultants effectively, guard against consultant biases, and get far enough on the learning curve to write effective contract specifications. User groups, pilot projects, and GIS conferences can help agencies get to "first base."

However, the product-by-product development strategy that transit operators have historically adopted is somewhat related to their heavy reliance on outside consultants and the lack of internally developed expertise. Generally, when consultants are invited into an agency, the main concern is to address one specific difficult problem or to build a complex application that runs in a turnkey fashion with little need for development of in-house expertise. As a result, independent applications and databases are created in different areas of the agency. In other words, the benefits that are derived from consultants become very limited. The real benefits are reaped when a holistic approach to building agency-wide databases and applications is adopted, which helps to better understand and design the data pipeline and the tools needed to generate viable pathway from one or more basemaps to needed application databases.

As mentioned earlier, all of the above decisions that transit operators can make are very dependent on the organizational structure of the agency. In a top-down organization, the IS department plays the role of the decision-maker and can hence decide on many of the alternatives the agency faces. However, in the bottom-up

organization the decision-makers are distributed across the different departments and the decisions made by a certain group, although perfectly meeting the immediate needs of that group, might not be consistent or coherent with the needs of the other departments. Furthermore, the distributed decision making in these organizations is the major cause of the product-by-product approach for application development in these agencies. Ideally, the top-down structure of an organization allows the adoption of a holistic view for database design. However, big budget commitments and a lot of internal expertise have to be centralized up-front which, in reality, cannot be marshaled by most transit agencies.

Finally, the question that transit agencies are left with is the extent to which they should rely on consultants. The use of consultants is also dependent on the general implementation strategy and the development pathway that the agency chooses. Nevertheless, as a general recommendation, transit agencies should continue to use consultants but their attention should shift to developing in-house maintenance skills, understanding the agency rights to data and models developed by consultants, and using generic tools and off-the-shelf databases when possible. In other words, agencies need to move in the direction of fewer proprietary "black box" applications.

7.4.2. Which Data to Use?

In chapter 6 we saw how different representations are needed for different transit applications and how no one basemap can suit all purposes. The questions that transit agencies face now are related to which data should they use in order to create the many network representations needed by the various applications, which processes and tools should they create to move from one data representation into the other, and

what sequencing in the data pipeline should they adopt to avoid as many of the complexities, discussed in Chapter 6, as possible. In Matrix 6.1, we saw that each application requires different attributes, spatial representation, scale, and segmentation. We also showed that standard street network files, such as TIGER, are useful for some applications whereas local network files might be more accurate for other applications. The question now becomes is it possible to create a schema that allows the generation of coordinated and coherent databases that satisfy the different application needs using several basemaps. This question will be addressed later in this chapter. We shall now focus on the more basic question of which data structure and databases must be selected first and which choices are available.

In chapter 3 we discussed the different applications of GIS in a transit agency and showed that each application requires different spatial and non-spatial attributes. For example, the routing applications require address information, the ridership application utilizes socio-economic and demographic information, whereas the corridor study needs socio-economic, environmental, and land use data. The key issue in selecting these databases is therefore to ensure that selected network data for each application can link to the proper geographic boundaries or attributes. The issue then becomes which network representation for roads and routes should an agency select to build applications and which attribute data can be associated with the selected network.

7.4.2.1. Selecting Network Data

At this point, it is clear that no single map suit; all purposes or all applications. The list of street network files that can be used as basemaps is quite long and includes standard off-the-shelf networks, locally generated maps (by other agencies), or in-house digitized ones. Of the standardized street network files, TIGER files are probably the

mostly used (and the most recommended). Our survey shows that TIGER files are used by 74% of the transit operators we covered (refer to Chapter 4). This can be attributed to the fact that TIGER files are essentially free of charge, suitable for several usages, and used by many outside agencies.

TIGER files were initially developed by the Bureau of Census for the census enumerators to use while collecting data. They can be used to represent the road network geometry and topology in order to create street network maps. Each row in the (first) TIGER file contains location and attribute information for a single street segment (i.e., the longitude and latitude of the intersection at each end of the street segment, and the street name and address ranges that identify addresses along each side of that street segment). TIGER files are therefore useful for matching addresses and geographically locating (by approximation) these addresses on the map. They come in a standard ASCII format and they are readable by most common GISs. TIGER files are available from the Bureau of Census by county. They are almost free of charge ($200 for the first county within a state and $25 for each additional county within that state).

The major defects of TIGER files are the lack of street attributes (except for road classification), little and sometime no street information outside of metropolitan statistical areas, positional accuracy (in some areas), and the many errors such as missing streets, missing address ranges, or wrong location of intersections. The TIGER address range information are generally 75% accurate[46]. Enhanced versions of TIGER can also be used as basemaps depending on the area and their availability. The most important enhanced versions of TIGER include ETAK files, GDT files, and Thomas

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[46] refer to Chapter 6 for what is meant by 75% accuracy.

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Brothers files. ETAK files have, in general, a better spatial accuracy and include some information about connectivity between links and are more suitable for routing applications. GDT files have more accurate address information especially for areas outside metropolitan statistical areas. They are very suitable for geocoding and address matching. Thomas Brother files are similar to ETAK and GDT files except that they are available for west coast states only (i.e., California, Arizona, Oregon, and Washington). These files are developed by private companies and hence are not free of charge. As a matter of fact, users pay a fee for the right to use the data but not to own them. This means that sharing these network data files with other agencies might create some legal problems that can significantly impact development paths and costs.

Note that agencies can use proprietary network files without unduly encumbering future development options if they distinguish in legal terms and in system design between ownership / licensing of the data and ownership / rights to data structure whereby they might replace proprietary data with new TIGER at a later date. Also, one can use TIGER files, but loose the rights to build other applications around them if the data structure and tools used to store and access them have limited capability, or proprietary elements.

TIGER files can be used to build many of the transit applications. Transit agencies have the choice of using them for all applications (although in many instances they might not be the most suitable), and /or complementing them with other local network files or with in-house digitized ones and with various levels of enhancements. The advantage of using TIGER files lies in the link they provide to the census socio-economic information, the topological information that are suitable for simple routing operations, and the address information needed for address matching operations. Matrix 7.1 shows how TIGER files can be used to build the various applications, the

deficiencies they have to meet the requirements of some applications, and the augmentations that make TIGER files suitable to these applications.

Matrix 7.1. Building Applications Using TIGER					
Application\Problem	Corridor Study	Ridership Forecast	Production of Maps	Passenger Information System	Properties and Facility Managem't	Crime Analysis and Dispatch
Linking to Area/Polygon Data	TIGER provides link to Census socio-economic data. Local networks are needed to link to land use & environmental data	TIGER provides link to Census socio-economic data.	TIGER adequate for driver maps while detailed local maps with landmark data are needed for system & schedule maps	N/A	Local maps that can be linked to assessor's parcel data and land use data are more suitable.	TIGER is suitable for patrol dispatch while local maps that link to parcel level data are needed for crime analysis.
Handling TIGER Segmentation	Stop-to-Stop segmentation is better than TIGER's intersection-based segmentation. Dynamic Segmentation can be used instead.	TIGER segmentation is not problematic. Fixed length segments, independent of any geographic segmentation, are usually preferred	TIGER segmentation is adequate for drivers maps. Schedule maps need to be generated from detailed local maps.	Intersection-to-intersection segmentation of TIGER is usable for building PIS applications.	Segmentation based on maintenance activities (such as cable age) are more suitable. Dynamic Segmentation can be used instead.	TIGER segmentation is adequate for dispatch and routing applications
Adequacy of TIGER Details	TIGER scale is quite adequate.	TIGER topology and scale are adequate for routing applications.	More detailed network showing landmark information and a larger scale is more adequate than TIGER	TIGER is adequate for extracting routes, address matching, routing and allocation applications.	[Same as Production of Maps]	TIGER is adequate for patrol dispatch while crime analysis requires higher scale network
Representing Stops and Routes	Double encoding of TIGER links or use of dynamic segmentation to create route structure and handle ridership data.	TIGER representation is adequate but also there is need to encode stops along TIGER segments.	Digitize or scan routes & stops. Schedule maps require creation of routes and stops with respect to landmark location	TIGER adequate for address-matching. Routes are extracted from TIGER. Stops are represented by TIGER nodes	Positional accuracy of routes and stops is important. Use local detailed maps for digitizing routes and stops	Patrol dispatch: same requirement as PIS. Crime Analysis: same as properties and facilities management
Transit route Connectivity and Turn Movements	Usually handled graphically: Routes and stops are double encoded on common links	TIGER topology needs to be augmented by either adding arcs or using RDBMS to represent turn movements properly	N/A	Handled on the RDBMS side. No alteration of network geometry is recommended to maintain link between road and route networks	N/A	[same as Ridership Forecast]
Updating TIGER	Altering TIGER may cause mismatch with future updates of TIGER	[same as Corridor Study]	N/A	Difficulty in maintaining correspondence between roads network & route network extracted from TIGER	N/A	[same as Corridor Study]

The suitability of TIGER files to build most of the above applications, especially those that involve address matching, path finding, and routing operations, is shown in

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Matrix 7.1. However, these files need to be augmented to meet the special transit data needs. For some of the above applications, furthermore, TIGER files are not detailed enough or do not allow the linkage to needed databases as other local networks might do. For these applications, such as production of maps or crime analysis, it would be more reasonable to utilize more detailed networks such as the ones generated by local MPOs that are usually based on aerial photos or ground survey, for example.

The issue of linkage between street network files and polygon/area data versus their positional accuracy is very important. It is assumed, generally, that the more accurate the network is, the more suitable it becomes. This is not always true. Increased positional accuracy can cause the loss of linkage between the network data and the attribute polygon data. For example, if transit routes are encoded using Global Positioning Systems (GPS), the positional accuracy of these routes might become very high. However, if the available socio-economic data are associated with census-generated boundaries, such as census tracts or block groups, the agency may be worse off using the GPS-generated networks than using TIGER files which are typically half a city block in urban areas. This is related to the loss of any convenient link between the spatial features in the two data sets. Therefore, the choice of network data files is not dependent on positional accuracy only. Linkage to polygon data might be more important in some cases.

On the other hand, TIGER topology and geometry need to be augmented to represent the special characteristics of transit routes and stops. Matrix 7.1 shows that for a corridor study, where ridership data are compared to demographic data in areas surrounding transit routes, the geometry of TIGER needs to be augmented by double encoding shared arcs between routes. Routing and path finding operations require some augmentation to the TIGER topology. Turn movements and connectivity

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information need to be stored in the database side of GIS in order to perform needed routing operations accurately. Refer to Chapter 6 for more details about the augmentation of TIGER files to satisfy the connectivity representation requirements.

7.4.2.2. Selection of Attribute Data

The choice of basemap network file is influenced to a large extent by the choice of attribute data. As mentioned before, the issue of ease of linkage between network data and attribute data is very important for building transit applications. We saw in Chapter 3 that many of the transit applications involve the analysis of transit routes with respect to the characteristics of their surroundings. It is therefore very important to have the correct spatial linkage between routes and the polygons (i.e., areal spatial features such as census block group) that contain information about their surroundings. The polygon data needed for building transit applications are quite varied. They include socio-economic data for corridor analysis, ridership forecast, and crime analysis; parcel level demographic and land use data for crime analysis; and environmental and land use data for corridor study.

The census' socio-economic data can be used for many of these analyses. These data can be used in conjunction with TIGER files since the boundaries which are used for collecting these data, i.e., census tracts, block groups and blocks, are generated from the same street centerlines of TIGER files. This allows carrying out analyses that involve buffering around transit routes and overlaying those buffers on top of polygons of socio-economic data, such as ridership forecast and route analysis.

Other polygon data are also needed for many of the above applications. Land use information, environmental data, (flood plain areas, hazardous sites, protected areas,

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soil type, etc.), traffic information, and parcel level data are some examples of data that are not provided by the Bureau of the Census. Most of these data are available through outside local agencies such as the local or regional planning office, the state department of transportation, the assessor's office, the local environmental protection agency, and the like. Each of these organizations usually has its own street centerline file or is using a standardized off-the-shelf street network file, such as TIGER. Transit agencies can borrow polygon data from these organizations. However, it would be more preferable if a street network representation of roads has been developed from these local polygon databases so that it can be used for building the transit applications that need street centerline data without generating many of the inconsistency and mismatch problems. We now discuss which application needs which data and what are the external sources of these data.

7.4.3. What External Data Sources Can Transit Applications Tap Into?

At this point, it is clear that the implementation of GIS techniques for handling all applications in a transit agency is too complex to be a practical short term goal. It is also clear that there is no single basemap that suits all applications' needs. One of the choices that transit agencies can make in order to reduce the amount of complexity, is to couple some of the transit agency departments with outside agencies that are performing related activities or applications. This might address the complexity of building individual applications but the difficulty in coordinating these applications might very well increase. Hence, coupling cannot be done without relying on internal coordination mechanisms or set of procedures that ensure a certain level of compatibility and coherence between the different applications within the agency. Alternatively, transit agencies can create most of their databases in-house using some

schema that overcomes many of the GIS complexities and lives with the rest of them. We shall describe this schema later but now we shall specify which application needs which data and where these data can come from.

Table 7.1. Database Development Strategies for Transit Applications				
Department	**Application**	**Needed Data**	**Data Sources**	**Action**
Service Planning	Corridor Study	Socio-Economic Data	Census Bureau	Borrow environmental data; use TIGER files; extract routes and stops from TIGER.; Use Dynamic Segmentation to represent routes and stops
		Environmental Data	Environmental agencies	
		Land use Data	MPO, RPO	
		Street Centerline Data	TIGER	
		Traffic data,	MPO, DOT	
		Ridecheck, Stopcheck	Transit Agency	
		Routes and Stops	Transit Agency	
	Ridership Forecast	Socio-Economic Data	Census Bureau	[Same as Ridership Forecast]
		Ridecheck, Pointcheck	Transit Agency	
		Ridership Survey Data	Transit Agency	
		Street Centerline Data	TIGER	
		Routes and Stops	Transit Agency	
	Production of Schedule Maps	Detailed Cadastral Maps	Local Cities and Counties	Digitize Routes and Stops on top of detailed Maps.
		Landmark Information	MPO	
		Routes and Stops	Transit Agency	
Marketing	Passenger Information Systems (PIS)	Street Centerline Network	TIGER	Use TIGER segmentation; Extract routes from TIGER; Augment the topology using the RDBMS of GIS.
		Address Ranges data	TIGER	
		Routes and Stops	Transit Agency	
		Schedule Information	Transit Agency	
Real Estate / Engineering	Properties and Facilities Management	Routes and Stops	Transit Agency	Digitize Routes and Stops on top of detailed Maps. Use Dynamic Segmentation to build routes and display maintenance data
		Facility Location	Transit Agency	
		Inventory data	Transit Agency	
		Cadastral Maps	Local Cities & Counties	
Police	Crime Analysis	Socio-Economic Data	Census Bureau	Change parcel level data into point data using address matching; Use TIGER files to build routes and Stops.
		Cadastral Maps	Local Cities & Counties	
		Street Centerline Network	TIGER	
		Routes and Stops	Transit Agency	
		Accidents/Crime Data	Transit Agency	
	Patrol Dispatch	Street Centerline Network	TIGER	[Same as Passenger Information Systems]
		Address Ranges data	TIGER	
		Routes and Stops	Transit Agency	
Scheduling	Production of Drivers Maps	Street Centerline Network	TIGER	Use TIGER files for extracting arcs and intersections names.
		Intersection Address	TIGER	
		Routes and Stops	Transit Agency	

First, it is necessary to determine which databases are transit-specific and which

applications are not. Applications that do not rely on any transit specific databases and that are related to outside applications can be coupled with those agencies or departments. Transit-specific databases are those databases which are related to transit facilities, stored only by transit agencies, and needed for building GIS transit applications. By examining the list of GIS applications that we described in Chapter 3 and in later chapters of this thesis, we can determine which of these applications is transit-specific and which is not.

In Table 7.1 we list all the applications that can potentially benefit from GIS, the data needed for building each of these applications, the sources of each of the data component, and the way to build each application. The production of schedule maps application and the properties and facilities management application both need highly detailed street maps, such as the local cadastral maps. These maps are usually maintained by the local cities and counties. Tax maps that are available through the assessor's office, also contain some of the needed information.

Table 7.1 shows that needed data for each application can come from different sources. Each application requires a set of data that is maintained by outside agencies. Furthermore, the same data can also come from different sources. The detailed land use maps that are needed for map production activities and inventory systems, for example, can come from local cities and counties via the planning or assessor's office. Similarly, detailed city maps can come from different sources and with different levels of accuracy. For instance, coarse land use maps can be developed from aerial photos or satellite imageries. The accuracy and level of detail of land use maps based on each of these data collection and map creation schema vary widely and these coarse land use maps are less precise than cadastral maps developed from surveyed parcel data and tax assessment records. The difference between the coarse and the local land use maps

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is also related to the link each of them can provide. Coarse maps usually have useful land use categories and sufficient spatial accuracy that allow to link them to comparatively low scale maps (such as TIGER), but lack the tie to employment / job locations and land use specific data that can only be developed from parcel or address-based databases. On the other hand, high resolution local land use maps might tend to be inconsistent with TIGER files and hard to link to the socio-economic census data.

Furthermore, local databases that come from different sources and that have different data than TIGER are evolving in various states of disarray. These data can be used to build TIGER-like files that can allow some but not all of the complexities we discussed before to take care of themselves. For example, if the local polygon data are used to build TIGER-like files, the level of details that these maps provide would far exceed the ones provided by TIGER and would help in addressing some of the complexities related to linking transit routes to detailed land use and polygon data. However, using these data would also be complex as they would tend to provide more data (e.g. entrance ramps, U-turn lanes, etc.) than what is really needed. In other words, there is no single "right" outside source where transit agencies can get their information from, and identification of the most suitable and convenient source is not always easy.

7.4.4. Which Outside Agencies Are Useful Collaborators?

Should transit agencies develop their GIS capabilities in isolation of the outside world or should they connect to outside agencies (that are often well ahead of transit agencies in terms of GIS use and development)? This is one of the most important questions that transit operators have to address. In this thesis we tried to show how a transit

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agency can develop, implement, and maintain in-house GIS capabilities without really relying on any outside agency. We adopted this approach in order to be consistent with current practices of most transit operators in the US. However, due to nature of the complexities that we described in the previous chapter, we came to realize that such an approach is not necessarily the most appropriate. Linking to outside agencies for some of their basemaps and data is another alternative that transit agencies also need to examine. Coupling transit departments with outside agencies conducting similar studies or using similar databases might be a good starting point for dealing with these complexities.

This alternative is now taken more seriously as a result of the new technological advances. Recent technological developments in networking and distributed databases are enabling such coupling and making it more feasible. In Chapter 2, we discussed these technological advents and their impact on making distributed data more accessible to remote users. Many organizations that are concerned with regional planning and that need data from several sources, have started coupling with the different agencies that are storing and maintaining needed regional data. Transit operators can also link up with these organizations instead of focusing on building all their applications and databases in-house. However, the complexities of utilizing outside data for building transit applications might considerably increase. This is especially true, since transit agencies, in this case, have no say or control over the structure of data generated and maintained by outside agencies.

We shall now discuss which department or application can connect to which outside agency that might be using similar data or performing related analysis.

7.4.4.1. State Department of Transportation (DOT)

The state DOT is one important outside source to couple with. State DOTs have some applications that are basically very similar to ones in transit agencies. The DOTs usually are more advanced than transit operators in terms of technology adoption in general and GIS use in particular. This has to do with the fact that DOTs usually have more funds and resources to experiment with new technologies than transit operators do in general.

State DOTs maintain large highway inventory databases and conduct maintenance activities that are similar to the ones conducted by transit agencies. One major concern of DOTs is keeping track of the conditions of their highways. Large inventory databases and systems are built for this purpose using TIGER-like files in some cases, or locally digitized files in other cases. GIS-based sophisticated linear referencing schema for identifying spatial objects along highways are utilized. Many DOTs have used the dynamic segmentation capability of GIS to build these models. Transit operators, especially the engineering and maintenance departments, can link up with DOTs to get needed highway data from them and to copy their ways of implementing GIS to build inventory maintenance databases and systems.

Similarly, the corridor study that transit operators conduct is comparable to the corridor study done by DOTs. In a corridor study, transit operators examine the impact of building new rail line while the DOTs assess the impact of building new roads or highways. They both involve examining the environmental impact, affected population, and impacted habitats. These analyses involve the use and integration of land use data, socio-economic data, and environmental data together. Many DOT's have built these databases or acquired them from outside agencies. Transit operator can link up with the DOTs in order to either borrow data from them or copy their

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implementation procedures for utilizing outside databases.

DOTs also use road centerline network files that can be shared with transit agencies. Many DOTs have digitized their own street centerline files from aerial photos and the positional accuracy of these networks is usually higher than the standardized off-the-shelf centerline networks, such as TIGER or DLG. For example, Delaware DOT had started an initiative for digitizing all its road centerline with a 1:2,000 scale accuracy. Such files, however, do not provide any linkage to polygon data. Future AVL (automatic vehicle location) applications that some transit agencies have started to develop can probably benefit from the high positional accuracy of these files.

7.4.4.2. Metropolitan or Regional Planning Organizations

SANDAG (the San Diego Association of Governments) is one of the best examples of regional planning agencies that have extensive GIS involvement coordinated with detailed GIS databases developed locally for municipal purposes. Parrott and Stutz [1991] describe how GIS at SANDAG is used for building urban GIS applications. SANDAG is a regional planning agency, with quasi-governmental functions, encompassing the County of San Diego in the southwestern corner of California as well as 18 cities located therein.

SANDAG's database consists of general plans, census data, DIME files[47], land use data, Traffic Analysis Zones (TAZ), flood areas, slope maps, airport noise contours, future freeways, and other geographical boundary areas of all the 18 cities. All these information are maintained within a GIS. The typical planning applications that these

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[47] DIME is an acronym for Dual Independent Map Encoding, which refers to geographic base files that were created by the US Bureau of Census in order to conduct the 1970 census of population and housing. DIME files are the predecessors of TIGER files. They utilize a flat file structure containing point, line, and area information entirely within one record [Huxhold, 1991].

databases are utilized for are related to infrastructure planning, siting facilities, finding land for development, emergency planning, and crime analysis. These applications involve overlay, routing, allocation, and geo-referencing operations that can be performed efficiently by the GIS.

SANDAG has created a "multi-level nested system in which the census tract is the basis of the hierarchy of spatial units. There are four levels of aggregation and the boundaries at one level do not cross over the other. Smaller subdivisions and larger aggregations are created from the census tract system. The Traffic Analysis Zones (TAZ) are the smallest areas of reference. Geographical aggregations of census tracts form the larger Sub-Regional Areas (SRA) and Major Statistical Areas (MSA). Thus there are 759 TAZs, 380 census tracts, 41 SRAs and 7 MSAs covering the San Diego region in a nested system" [Parrott, 1991]. In addition to these different layers of data aggregation, SANDAG is building a link to the Regional Urban Information System (RUIS) detailed parcel level data that the city of San Diego maintains. This will enable the integration of TAZ and environmental data with detailed parcel level data.

Many similar regional planning offices exist in different metropolitan areas of the US. Some of them might not be as advanced as SANDAG in terms of building integrated GIS capabilities, but most of them have assembled large databases that are useful for many of the transit planning activities. Transit agencies can take advantage of organizations like SANDAG to tap into their databases in order to perform some of the transit analysis that is related to the ones carried out by these agencies.

7.4.4.3. Environmental Agencies

In the corridor studies several criteria are taken into consideration when designing new

rail lines. Environmental factors such as wetland, protected areas, and parks are among these criteria. State or local environmental organizations usually collect information about such areas and in many cases GIS is used for that purpose. Cities like Mesa (AZ), San Bernardino (CA), San Diego (CA), Colorado Springs (CO), Orange County (FL), St. Paul (MN), Cincinnati (OH), and Pittsburg (PA) are using GIS for collecting environmental data and performing environmental applications [Huxhold, 1991]. Transit agencies can link up with such local environmental agencies or other organizations performing environmental applications to borrow needed data such as wetland, flood plain areas, and protected areas.

It might be true that transit operators do not perform such operations quite often since rarely are transit rail lines extended or newly built. However, with the new environmental concerns, and the influence of the different environmental advocacy groups, the minor alterations to any rail line need to be environmentally sound. This means that environmental impact analyses need to be conducted even for minor modification to rail lines. This necessitates the use of the above data that can be borrowed from local environmental agencies.

7.4.4.4. Police 911 Service

Similarly the police department of transit agencies can connect to the police 911 service. After some false starts, 911 standardization efforts have settled on TIGER-style street network encoding. The 911 service usually contains information about streets addresses, landmarks, and other important reference points that are used for performing routing operations. In San Bernardino, California, for example the Sheriff's department is utilizing a GIS system to create a 911 service system. Many other cities have also used GIS to create safety and police service systems, such as Los

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Angeles (CA), San Diego (CA), Denver County (CO), St. Paul (MN), St. Louis (MO), Newark (NJ), New York City (NY), and Milwaukee (WI) [Huxhold, 1991]. The range of applications that these cities have developed vary from crime analysis, central dispatch, to handicapped-special requirements.

The police department of transit agencies can coordinate with other police departments outside the agency to utilize their 911 services in order to conduct some of the crime analysis and patrol dispatch activities. Alternatively, the transit police department can borrow the databases from the outside police and customize them to suit their specific needs such as adding to the system the bus routes and the transit stops that might not be integrated in outside systems.

Local databases that transit agencies can connect to vary in terms of accuracy and level of detail. For example, using SANDAG and the city of San Diego (that has developed RUIS) as two local sources of information, one can get an idea about how local data can vary in terms of scale and accuracy. SANDAG is an example of the well-developed regional planning organization that has built an extensive information system. RUIS is an example of an agency organized that over a period of years has developed the system and staff needed to build coordinated, parcel-level detailed data that can connect to the MPO usefully. The difference between the databases of SANDAG and RUIS vary in terms of aggregation and usefulness to different GIS applications. SANDAG's databases tend to be coarser than the RUIS databases. SANDAG's databases are generally built using 1:24,000 scale maps while the RUIS databases are built from much higher resolution maps and are hence more positionally accurate. SANDAG's databases, however, have the capability to link to TIGER census data whereas RUIS databases have links to parcel level address-based information. The census information that SANDAG's databases can link to are useful for building

"corridor analysis" type of databases whereas the parcel level databases of RUIS tend to be more useful for building "crime analysis" type of information. In other words, local databases that can be used for transit applications can come from different sources and can also be of different level of detail and accuracy, but each can be useful for different type of analysis. The choice of the these databases is hence not a straight forward task.

After describing which outside agencies are conducting similar activities or are utilizing databases that are useful to transit applications, we now discuss one strategy for implementing GIS capabilities in which transit agencies build their transit-specific databases in-house.

7.5. Schema for building Transit Data Structure

We now propose one strategy for building coherent and sustainable transit databases. In this strategy, we propose a schema for coordinating the creation of databases and applications, the propagation of data between applications, and the role that each user and department plays in terms of contributing to the data pipeline. This schema is designed to address the complexities related to the lack of a single representation that suits all applications and to the transformation of data from one representation into the other to enable data sharing. In our proposed strategy, most of the complexities are addressed in some fashion or another but some of them will not be resolved completely. Nevertheless, transit agencies can live with those partly resolved complexities.

We first start by assuming that the organizational complexities that are related to

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mismatch in software and hardware are resolved. We assume that in the agency, all the departments and users are adopting technologies that can communicate with each other in some reliable fashion to exchange boundary file and attribute information. These assumptions are not unrealistic. They belong to the set of simple choices that transit agencies can make. They can be easily implemented once the right organizational setup is in place and necessary funds are made available.

To handle the problem of data coordination and mismatch in routes and stops encoding methods, we first examine who should be creating or modifying routes and stops, and how the data propagate through the agency. In general, the planning department is the one in charge of proposing the layout of transit routes, changing the characteristics of these routes, and deciding on the location of bus stops. Once the planning department designs the route, the scheduling department assigns the necessary resources for operating that route and plans its schedule. The other departments take the layout information, plus the schedule information set by the scheduling department, and integrate them into their different databases.

In our data pipeline design, we propose that the department that performs the route planning activity (or incidentally any outside agency performing the route planning activity for the transit operator) be in charge of introducing and initiating data into the pipeline in a standardized and systematic fashion. Since new routes and stops originate from the planning department, it is the most practical to have the planning department responsible for creating and modifying the route and stop data structure. In agencies where planning activities are performed in other departments, the department in charge of designing new routes can be in charge of initiating changes in the data pipeline. The important issue in our strategy is that this department needs to be responsible for creating what we call a "foundation database" of routes and stops that other

applications or departments can utilize to generate their own routes and stops in the representation that best suits their individual needs. This strategy requires some standardization of a naming convention for all routes and stops.

In this schema all applications build upon core set of information from the "foundation database." As we shall see, the problem with mismatch in data representation can be dealt with using this schema while ensuring needed consistency and some uniqueness among all applications. In other words, since key elements of all applications utilize the same "foundation database," the incoherence among applications that utilize data from different sources can be minimized and complications introduced by data maintenance and updates can be considerably reduced.

7.5.1. Description of the "Foundation Database"

The structure of the "foundation database" (of routes and stops) is very simple. It basically consists of textual description of routes and stops. Figure 7.1 provides an example of a "foundation database." No graphical component for this database is needed. There are several reasons for focusing on building routes and identifying stops independently of their geographic representation by utilizing their verbal description:

1. the limited positional accuracy that is incapable of allowing the precise overlay of several layers of information that come from different sources;

2. the many representation complexities related to difference in segmentation, scale, and topology of routes used by different applications; and

3. transit services are usually provided in urban areas where street names are well defined.

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Using different GIS tools, each application area should be able to generate its own graphical component, with the representation that suits it best, from these textual descriptions.

FIGURE 7.1: Example of Textual Description of Routes

Route Metadata Table

Route #	Direction	Time of Day	Time of Week	Effective Date	Expiration Date	Comments
10-i-p-w	Inbound	Peak	Weekday	5/20/93	3/5/95	Connecting Down Town with Navy Yard..
10-o-p-e	Outbound	Peak	Weekend	5/20/93	3/5/95	
47-i-o-w	Inbound	Off-peak	Weekday	4/13/86	8/12/94	Serving the Medical Complex Area...

Route Table

Route #	Segment	Turn Direction	Intersection / Turn Address	Alias Addresses
10-i-p-w	0000	Starting Point	125 City Point Ct.	
10-i-p-w	10	Right-1	City Point Ct / E 1st St.	
10-i-p-w	20	Straight	E 1st St. / Broadway	E 1st St / Route 1 North
10-i-p-w	30	Left-1	Broadway / Dorchester St.	
:	:	:	: :	
10-i-p-w	9999	Ending Point	Tremont St. / Cambridge St.	
10-o-p-e	310	Right-2	Broadway / E 1st St.	
:	:			
47-i-o-w	10	Left-1	Massachusetts Av / Market St.	Route 9 Sth / Market St

Stop Table

Stop #	Route #	Intersection Address	Order #	Location	Name	Nearest Address
1045	10-i-p-w	E 1st St. / Broadway	10		Start Pt. of 10-i-p-w	
:	:	: :				
1066	10-i-p-w	Broadway / Dorchester St.	120	Before	Staples Stores	215 Broadway St.
:	:	: :				
2156	47-i-o-w	Broadway / Dorchester St.	80	After	Staples Stores	215 Broadway St.
:	:	: :				
2297	47-i-o-w	Market St / Cambridge St.	370		End Pt of 47-i-o-w	

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The textual description of routes consists of detailed description of street names and stop locations that a route follows together with all the turn movement information at intersections. A relational model for storing the verbal description of routes and stops is recommended. Figure 7.1 shows an example of a core relational model for storing route and stop representations. A "stop table," a "route table," and a "metadata table" are the basic three tables that constitute the "foundation database." Each route is given a unique ID. The route ID is composed of the route number, its direction, its time of day, and its time of week. The metadata table contains all information about each route including the date it became effective, its expiration date, and any other comments needed for describing it.

The "route table" contains information about the segments that the route is composed of, the name of the intersections that it follows, the turn movements that it makes, and the alias names of the streets that it uses. It is advisable to include all the intersections that the route crosses. It helps in resolving future ambiguities. However, it is imperative to include all the intersections where the route makes a turn or where the name of the street along the path changes. As we shall see later, the intersection addresses will be address matched against the street network files and the shortest path algorithm will be used to select the arcs between intersections. If all intersections are included, it becomes easier for the shortest path algorithm to select the arcs that belong to the route. Nevertheless, if the route follows a straight line path, where no turn ambiguities might happen, including only intersections where turns are occurring or street names are changing would be sufficient. In other words, the person encoding routes should use his/her own judgment to include as many intersections as needed in order to avoid any future ambiguities but not to clutter the route description with redundant data.

Each transit route usually consists of two directions (inbound and outbound) and varies with time of day (peak and off-peak) and day of week (weekday and weekend). Each of these variations of a route is encoded as a separate route with all the descriptions of the streets and the turn movements that it makes. Sometime streets might have several names or aliases, such as federal route number and local street name. All names and aliases need to be included in the "foundation database."

Please note that in Figure 7.1, we focused on core relational tables that can be expanded or linked to other tables to handle one-to-many relations and the like (such as additional alias names for streets). Variations in the details of the foundation database might also occur depending upon encoding practices in the agency and what tends to work for the geometry and particulars of the city. Furthermore, there is a trade-off between how rigorous the relational data model is at handling all aspects and details of encoding routes and stops and its level of complexity. In other words, the relational data model can be made quite comprehensive to include every single possibility or to represent every single detail of a route in order to handle a limited number of exceptions. Alternatively, simpler models can be created that handle almost all of the cases but require manual intervention for some few exceptions. The trade-off is therefore between how much manual work is needed and how complex the relational model can become.

Stops are also assigned unique IDs. The "stop table" in Figure 7.1 shows that each stop is also associated with the route that it belongs to. A sequence number (order#) and a location description (location) are assigned to each stop to indicate its location with respect to an intersection. For instance, a stop can be located at any four corners of an intersection. Since the address of an intersection is used to locate the stop, the "order#" and the "location" items are needed to indicate on which corner the stop is. The

sequence of the "order#" item shows the direction of the route and hence eliminates the corners to the left of the street. The "location" item contains information (before or after) about the position of the stop with respect to the intersection. If the stop, for example, is before the intersection, the "location" item is assigned a "before" value.

In many instances overlapping routes share common segments and have common stops. In order to distinguish between these stops, each of them is assigned a different ID, although they are located at the same location. This method makes the encoding schema more systematized. However, a separate correspondence table (that we did not include in Figure 7.1) can be created to show which stops are located at the same geographic locations but belong to different routes. The usefulness of this table is also in resolving any ambiguities or confusion that users might face. However, the creation of these correspondence tables might require some visual and manual interventions.

In order to automate the geometry generation and the relation to routes, a mechanism for storing one or more facts about each stop needs to be provided. Figure 7.1 shows that at each stop, intersection street names, landmark name, and nearest address are attached. The street names can be used by the address matching capabilities of GIS software to determine the location of stops. The name of a close landmark makes it easier for users to identify stop locations. In many instances, the location of a stop falls in the middle of an arc. In this case, the nearest address to that stop can be address matched to determine the location of the stop. Please note, there is no need to have an entry in every column, if the location of a stop can be identified from one or two column entries. The planning department needs to set some naming conventions for routes and stops to ensure that all applications built on top of the "foundation database" are consistent. For example, standardized spelling of street names will make it much easier for GIS address matching software to identify and cross reference

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streets.

The advantage of using the verbal description of routes and stops is related to simplicity, ease of use, and availability of data in similar format. Some form of textual description of routes is already utilized by many agencies. Standardizing the way of encoding verbal descriptions is important to allow the automation of software modules to read the textual data and transform them into geographical objects. The textual description, is a simple way of standardizing the description of spatial objects without having to tie them to any X-Y coordinates.[48] It addresses many of the complexities of linking spatial objects to different coordinate systems and the capability of moving from one geographic representation into the other. We shall elaborate on the advantages of this schema as we go through the different ways of building different applications.

To build the different geographic representations of routes and stops needed by other applications, we propose the use of TIGER-like files. By TIGER-like files we do not mean TIGER per se, rather we refer to any street centerline network file that utilizes the intersection-to-intersection segmentation, contains address information, and provides a good link to socio-economic data. For instance, agencies who have developed street network databases that are based on TIGER or that are more accurate than TIGER in-house, can utilize these files instead. Our choice of TIGER files is also related to the affordability and availability of these files for all metropolitan areas in the US. Please note, in the rest of this chapter, by TIGER-like we refer to any street network file that has the characteristics of TIGER network files.

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[48] If a transit agency has GPS tools and has located each stop with high precisions, then it would be useful to include the X-Y coordinates for all stops (and beginning and end points of a route) in a relational table that can be linked to the stop table. However, the precise GPS locations may not be sufficient to locate stops on a basemap that could be less accurate (with 100 meter errors), for example.

The other major component of the "foundation database" is the creation of GIS-based semi-automated tools for the generation of routes from the verbal description, the conversion of geographic routes into textual description, and the augmentation of topological representation of the TIGER-like network files. Figure 7.2 shows the different components of the "foundation database" and illustrates one way of using it to build the different GIS models. Three automation tools are created: (1) route extraction tools, (2) topology augmentation tools, and (3) route conversion tools.

The "route extraction tools" are semi-automated programs that use the address matching and path finding capabilities of many GIS tools to extract routes from a TIGER-like files using the textual description of these routes. The addresses of intersections along the route are matched against the TIGER-like files and the shortest path between them is calculated. At complex intersections, or when a street name intersection does not match, manual interventions are needed to indicate to the software which arc belongs to the route. These routes are then stored into separate files and saved using a route data structure. Such programs allow the regeneration of routes in a comparatively quick and easy fashion every time a modification to the route alignment is made. (Refer to Grayson [1993] for details of programs for doing this operation.[49])

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[49] In Chapter 2, we reviewed the research in the field of GIS in Transit and cited the work of T. Grayson [1991 and 1993] whereby the idea of automating geometry building from textual description was first used.
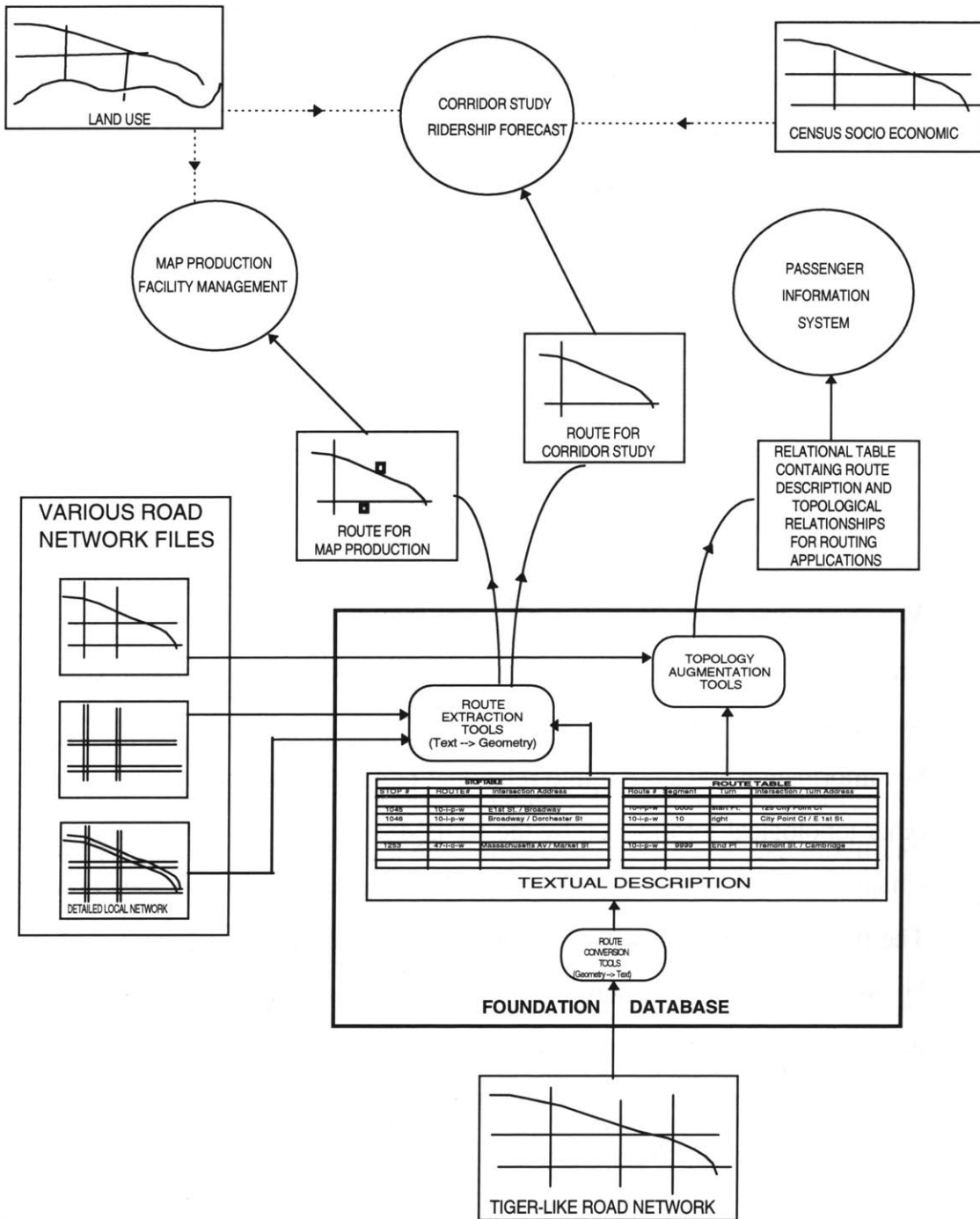
FIGURE 7.2: Use of "Foundation Database" For Building GIS Applications

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The "route conversion tools" are basically responsible for performing the opposite operation of the "route extraction tools." The "route conversion tools" start with a geographic representation of a transit route and change it into textual description. This is a very useful tool for converting existing databases that are built on top of TIGER-like files into the recommended textual format. Furthermore, these tools are very useful for creating and designing new routes. When new routes are created, it is easier to start with a digital map, such as the TIGER-like network files, and select the arcs that the route should follow. Once the alignment and path of the route is finalized, these tools can be used to convert the routes into textual files that are usable by other applications.

The "topology augmentation tools" are semi-automated tools that can be used to supplement the route topology with additional information related to connectivity and turn movements that transit routes can make. These tools also utilize the schedule of bus information and store it into relational tables that can be used in conjunction with other topological information by the RDBMS to carry out path-finding operations. In Chapter 6, we discussed two alternatives for augmenting the topology of transit routes. The first alternative consists of modifying the geometric representation of the network by using pseudo-nodes and links. The second alternatives consists of saving turn movement, connectivity, and transfer information at route intersections into relational data models that allow the utilization of the RDBMS to perform the routing operations. The "topology augmentation tools" are based on the later alternative.

In addition to the above automation tools, in this strategy we also rely on the dynamic segmentation tools of GIS packages to address the complexities associated with need for different representations of routes. We also adopt the route data structure for

encoding routes and for referencing objects and stops along theses routes. The "route table" includes information about the starting and ending points of routes that will be used to set the base point for each route. Stops will also be encoded as point data along these routes. The GIS software can be used to address match the location of a stop and then compute its offset from the base point. We shall see in the next sections how the foundation database, the automation tools, and the dynamic segmentation tools are utilized for building the databases for each application.

7.5.2. Building Databases for Corridor Study

Table 7.1 shows the different data needed for conducting a corridor study. In a corridor study, routes are examined to check how well they are performing within the overall system. Modification to route characteristics or creation of new routes are usually proposed at the end of these studies. These changes have to be evaluated with respect to the socio-economic conditions of the area (to assess the number and the background of people affected by these changes) and to land use or environmental data (to check the environmental impact of these modifications, for example).

TICER-like files can be used for building the routes and stops from the "foundation database." Existing routes or proposed ones can be extracted from TIGER-like files using the textual description of these routes and stops stored in the "foundation database" and the "route extraction tools." Once these arcs are extracted, they would ideally be stored as route objects in a GIS so that the attributes along these routes can be represented and referenced independently of the underlying segmentation. Stops along these routes can be represented as points

with associated attribjtes or "events" along these routes.

These routes can be used in conjunction with the socio-economic data files of the census bureau to study the impact of proposed changes on population and riders. As for utilizing these routes with local land use maps (that don't coincide exactly with TIGER files geometry), the positional accuracy of TIGER files, in general, is acceptable as compared to the accuracy of land use maps. In other words, if land use maps are transformed to the same projection and unit systems as the TIGER files, the overlay of the routes (built on top of TIGER) with the transformed land use map would generally yield accurate enough results. In other words, the typical half block error in urban area settings would not greatly affect typical corridor studies. The buffer width utilized to represent the walking distance is believed to vary from 1/4 to 3/4 of a mile. The positional accuracy error is therefore less important than the approximation of walking distance error. Nevertheless, if the overlay is not accurate enough, the textual description of the routes could be used to select corresponding block and street segments in the detailed land use map.

The elements of the "foundation database" can support a variety of applications using convenient tools. For instance, one of the problems with data representation in a corridor study is related to routes sharing common arcs. To display ridership information along routes, a band with a width corresponding to the ridership value along each segment of the route is often used. Common arcs, as a result, have to be double digitized to properly represent ridership along each individual route. Since the textual route data structure is the starting point, the GIS augmentation tools can be utilized to generate and draw each route by using different colors and showing each band with a different shading scheme (thereby allowing the viewing of different bands on top of each other). Alternatively, the routes can be drawn with

an offset from the arcs beneath them to distinguish between overlapping routes.

7.5.3. Building Databases for Ridership Forecast

In ridership forecast applications, ridership along new routes is examined. The planning department can utilize TIGER files to check proposed routes and if a route fulfills its need, the planning department will store the detailed textual description of that route in the "foundation database" for other users and applications to build upon. Programs, that utilize TIGER files, can be developed to convert a newly created route into a standardized textual description of that route. The "route conversion tools" module of Figure 7.2 represents such models that start with the geometric representation of a route and convert it into textual description that can be added to the "foundation database."

In Chapter 5, we showed an example of GIS-based Period Route Segment (PRS) ridership forecast models. The centerline representation of TIGER files was quite adequate for building the PRS forecast model. The convenience of TIGER files is also related to their link to the socio-economic data provided by the census bureau. To build a ridership forecast model, arcs can be first displayed on the screen then extracted manually from the main TIGER street network files and saved into a route data structure. The GIS will then be used to segment the route into fixed length segments and to create buffers around each segment in order to estimate the production and attraction factors along the different segments of that route. (Refer to Chapter 5 for more details about the usage and adequacy of TIGER-like files for building PRS ridership forecast models.)

7.5.4. Production of Schedule Maps

Schedule maps are usually produced to help prospective riders learn about the path that each route follows, the stops that it makes, and the schedule of buses operating along that route. A unique aspect of these maps is that they usually contain a lot of landmark information to let the riders associate the route with familiar references or spots. They also must fit onto one page which means that these maps are usually distorted on purpose.

TIGER files contain address information that can be used to indicate the names of streets and intersections along the path that the route follows but lack other landmark information. More detailed maps are usually used for creating schedule maps. In our schema we propose that local detailed maps, such as the "tax maps" or commercially supported street maps, are used as backdrop maps for supplementing the TIGER information. Routes and stops can be first extracted from TIGER files using the textual information in the "foundation database" and the "route extraction tools" (refer to Figure 7.2). Local street maps, tax maps, and the like need also to be scanned in order to be used as an image backdrop in conjunction with the TIGER-based routes. These routes can then be transformed to match the tax maps which enables the addition of needed land mark information to them. Stretching and distorting these maps (if they do not fit on one page) can be done last. What needs to be emphasized in this application is that routes, stops, and local road maps need to be used as the starting point and that "paint packages," such as Canvas® and Photoshop® are more suited for this type of applications than GIS unless very sophisticated GIS packages with sophisticated cartographic tools and/or paint packages capability are in place.

In this schema, a reasonable amount of manual work still needs to be done. However, the advantage of this approach is that the route naming and the stop numbering is consistent with the rest of the applications in the various departments and easily identified from the route and stop databases and maps. Furthermore, the production of transit schedule maps is usually done quarterly, which means that the recreation of these maps is not a very frequent operation and the amount of manual work can hence be very tolerable.

7.5.5. Passenger Information Systems (PIS)

In Chapter 5 we described how a PIS can be built using a GIS. The prototype we developed proved that GIS tools can be utilized to replicate most of the functions of customized PISs. We utilized TIGER files to build our prototype. As we showed, a PIS requires two sets of networks: (1) a street network file that is used to locate addresses of callers and to determine the nearest stop to these addresses, and (2) a route network file that is used to determine the path between the origin and destination stops of the caller. Both networks can be derived from TIGER-like files.

TIGER-like files contain address information that can be used to perform the address matching operations in order to locate on a map the origin and the destination of the callers. They can also be used to allocate street arcs to bus stops and to find the nearest stops to origin and destination locations. The route network can be extracted from the TIGER network by using the description of routes and stops in the "foundation database" and the "route extraction tools." The topological relationships needed for performing transit path finding algorithms are

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not available in the TIGER representation of transit routes. We discussed this problem at length before in this thesis and we proposed augmenting the topological relationships of TIGER-based transit routes by storing connectivity, transfer, and schedule information using a relational data model. In Figure 7.2, the "topology augmentation tools" module represents a set of programs that can be used to encode connectivity, transfer, and turn movement information about transit route networks in a manner that can automatically be linked to route descriptions in the "foundation database" so that revising routes would not loose all association with the added topology.

To clarify how this might be done, let's take a closer look at the steps that would be involved. In the previous section we talked about the data pipeline in the agency and how the planning department should be the care-taker of the "foundation database." In the pipeline of data flow between departments, the planning department first designs the routes and then passes them over to the scheduling department for allocating resources and scheduling bus runs. This might be an interactive process until the final design of a route is reached. Once this phase is achieved, the final route design can be turned over to the marketing department for encoding the topological relationships, connectivity and turn movements for each route. This information can also be stored in the "foundation database" for other applications to use.

The augmentation of the topological relationship of each route is a totally manual work. However, the "topology augmentation tools" can store the results of these relationships in textual format that can be automatically loaded by the RDBMS (to use in path finding operations). When a route is modified, for example, these text files permit the automatic regeneration of the relational tables that contain the

topological relationships between all routes. In other words, the marketing department (or the department responsible for the PIS) should create textual tables that contain information about turn movements, schedules, and connectivity between routes, and should also write programs for loading into the RDBMS the topological relationships between routes from these text files. Such a procedure ensures that modifications or updates to routes are automatically integrated into the PIS without the need to hand check every turn condition to see with which intersection in the new base it must be related. Grayson [1993] described some of these relational tables that are needed for storing the topological relationships between transit routes and the RDBMS-based programs for computing optimal paths. However, these augmentation tables are quite complex and a risk to clutter up the textual description might very prominent.

7.5.6. Property and Facility Management Systems

In the property and facility management systems, detailed street maps and parcel level data are needed to perform some of the desired queries. In chapter 3 we described the importance of the positional accuracy of transit routes for determining the spatial relationship between transit routes and their right-of-way, and the parcels abutting these routes. The real-estate department, for instance, is interested in knowing the exact boundary of the agency's right-of-way, the condition of all facilities owned by the agency, and all the information related to parcels that are owned by the agency or falling within the right-of-way of its lines. The engineering department, on the other hand, is interested in keeping track of all its maintenance records of all transit lines and facilities. Detailed data such as the cadastral maps and tax maps are needed for these applications (refer to Chapter 3).

TIGER-like files are not capable of providing the positional accuracy that the detailed local maps have. Similarly, the census polygon information is not as disaggregate as the assessor's office maps. For this application, the real-estate department can acquire the detailed databases and digitize routes and stops on top of these maps. This activity is similar to the map production activity where detailed databases need also to be acquired. The only difference is that the route data structure needs to be adopted when digitizing these routes. In other words, once the digitization of the routes from the detailed tax maps is done, these routes need to be converted into "route" features described in terms of street names and connections (i.e., the textual description) without any dependence upon specific geographic coordinates and segmentation. This allows the engineering and maintenance department to utilize these routes for building the necessary maintenance/inventory system. As local maps become more standardized, the textual description of routes and stops can also be used to extract highly accurate routes instead of digitizing them.

7.5.7. Patrol Dispatch

The patrol dispatch application can basically utilize the same databases and GIS procedures as the Passenger Information System (PIS). The patrol dispatch application involves the use of a street network file that contains address ranges for converting address information into point locations and the finding of the optimal path between a patrol car and the location of an incident. One of the differences between this application and the PIS, is that the PIS path finding algorithms are more complex as they need to incorporate route connectivity and

route schedule information whereas the dispatch application focuses on road connectivity and, for example, one-way street information. Another difference between the two applications is that the network utilized in this path finding is different. In the PIS, the network consists only of arcs that belong to routes and of transit lines, whereas in the patrol dispatch it consists of all the street network arcs in the area.

The route connectivity complexities are not valid for this application (since patrol cars use the road network and not necessarily the transit route network) but additional information about one-way streets and intersection delays need to be incorporated. Some of the improved versions of TIGER, such as ETAK for example, include some of this information. Alternatively, some GISs such as Arc/Info allow the creation of turn movement tables at each intersection to incorporate delay and one-way information. The difficulty in encoding all these information for all intersections in a metropolitan area is not only related to the time it takes, but also to the question of how to handle future versions or updates of TIGER.

The Bureau of Census is considering standardizing a unique identification of each arc and intersection of TIGER 2,000 (their next release). When such standards are implemented, the information stored in a turn movement table can be more easily transposed between different versions of TIGER. Until such standards are implemented, the turn movement information including the census-id for each arc can be stored in relational databases which would allow the update of these tables. This operation is not very trivial. Until the time when TIGER becomes more standardized, and due to the cost of maintaining such a network totally in-house, coordinating with the local 911 police service in the area is likely to be more

economical and practical. Police and other local public works agencies are more logical repository for improved TIGER-like road network data. Transit operators should focus on what it takes to keep in sink with their improved road networks and concentrate on the internal development and maintenance of only the routes and stops.

7.5.8. Summary of Data Pipeline in the Proposed Strategy

We have so far described many of the components of the data pipeline. We shall now recapitulate and summarize the different aspects of the data flow associated with our strategy. We shall describe the responsibilities of each department toward the foundation database and its automation tools and the procedures for integration of updates.

As mentioned earlier, the "initiator" of the data pipeline is the planning department (or any other department or outside agency that is in charge of designing transit routes). The responsibilities of the planning department consist of creating the textual descriptions of routes and stops, standardizing the naming conventions, and building the extraction tools. These extraction tools can be used by each department to extract the routes from the foundation database. Each department can modify these tools in order to make them more suitable to its applications' needs.

The scheduling department needs to contribute the scheduling information to the "foundation database." In some agencies, the planning department is also in charge of scheduling activities. In such agencies the planning department adds the

schedule information. These information are also stored in relational models in order to allow RDBMS to compute complex transit routing and path finding algorithms.

The department that is in charge of maintaining the PIS or the one that conducts routing applications on transit routes is in charge of augmenting the network topology of routes. The marketing department is usually the one that conducts these applications. The topological augmentation, as we mentioned earlier is basically done on the database side and not the geometry side. Relational data models that describe the complex turn movements, connectivity and transfer information need to be created. Augmentation tools that allow the applying of topological augmentation information onto new networks are also created by the marketing department.

All departments and users should have access to the automation tools. They can use these tools to create the databases with the representations that best suit their own applications. However, only limited number of experienced users have the authorization to modify the "foundation database." In general, the responsibility of integrating updates or alterations to routes and stops into the foundation database is restricted to the planning department. Alternatively, few experienced users in other departments can perform such operations but only according to the encoding standards set by the planning department. Procedures for dissemination of information about updates should also be in place to inform different users of changes. Similarly, the responsibility of schedule information and network augmentation are limited to the scheduling and marketing departments, respectively.

The sequencing of information in the data pipeline starts at the planning department. The planning department after finalizing a route design with the scheduling department, adds the route and stop textual description into the "foundation database." The scheduling department follows by adding the schedule information. All users and applications, agency-wide, can have read-access to the "foundation database" to build their own applications. The same sequence can also be implemented for integrating updates into the "foundation database."

7.5.9. Needed Technical Skills

To properly manage the strategy we propose, adequate technical skills need to be created at the agency. Consultants can also be used to help create or design part of the data pipeline or to help in building the foundation database and its automation tools. However, the use of consultants should not be to build turn-key systems that are not coherent with the proposed strategy. In other words, if consultants are invited into the agency, the scope of their work should be tied to helping in building the components of the data pipeline. Stand alone, customized systems are not recommended if they do not explicitly tie into agency-wide verbal description of routes.

In house, the technical expertise should also be grown. Obviously, GIS expertise is useful at all levels in the data pipeline. "Foundation database" developers and end-users should all be familiar with the technical capacities of their GIS packages. Furthermore, the database management skills are especially necessary for the viability of the strategy. In our strategy, we rely heavily on RDBMS to address many of the complexities of GIS implementation. The "foundation database"

stores all route and stop information in relational models. The augmentation of route topology is also achieved using the RDBMS. Even the models for computing complex routing algorithms utilize the engine and the algorithms of the RDBMS. In other words, the RDBMS skills are very crucial for the success of the implementation of our strategy

It is clear that the RDBMS skills needed for each of these tasks vary widely. Using the RDBMS to build path finding algorithms requires advanced knowledge of database management tools. Consultants can be hired to build such models (especially since the advanced expertise in RDBMS are needed for a limited number of tasks only). However, for building and maintaining the rest of the relational databases and models, users need to know enough RDBMS to understand "one-to-many" relationships and be able to evolve these relationships into relational tables and use SQL (Structured Query Language) to perform needed analysis. In other words, programming with 4GL (Fourth Generation Language) or using advanced RDBMS structures to build advanced automation tools can be contracted out. However, in order to convey to the contractor what is really needed, sufficient RDBMS skills need to be grown in-house. Furthermore, transit agency staff need to play a key role in building the relational model of the textual description of routes and need to understand what does it mean to link them to geometry in order to communicate their needs properly to contractors. Note that building geometry from text requires more tools than some desktop GISs or RDBMS tools have (though most GIS packages are adding them).

7.5.10. Evaluation of Proposed Strategy

We first start by briefly restating the important characteristics and advantages of the proposed strategy and then discuss the impracticalities, disadvantages, and assumptions needed to make it work. This strategy is characterized by the following three cornerstone elements: (1) standardization of description of transit-unique spatial features, namely routes and stops, (2) the automation of the link between one textual route description and one or more GIS basemaps and other data, and (3) the isolation of the "foundation database" from added attribute data. This strategy addressed the issue of inconsistencies between databases caused by the different naming schemes adopted by different departments or different application developers. Basing transit route elements of all applications on data that can be developed from the "foundation database" eliminates key discrepancies between different applications agency-wide.

The other important aspect of this strategy is the automation of the link to the GIS databases. The "route extraction tools," the "route conversion tools," and the "topology augmentation tools" are created to automate the link between the geographical, topological, and textual descriptions of routes and stops. Geographic features can be regenerated from textual descriptions in a semi-automated fashion, newly created routes can be added to the textual description files, and the topological relationships between routes can be used by RDBMS to compute complex path-finding algorithms.

The reliance on textual description of spatial objects makes the creation of these routes and stops independent of the specific geometry of any basemap. In our strategy we recommended the use of TIGER files for building the different databases. However, when more accurate street centerline network files with address information become

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available, the process of shifting into the more accurate basemap is simplified. The same textual description of routes and stops stored in the "foundation databas?" can be applied against the more accurate new road network to regenerate the graphical representation of these objects. In other words, this strategy allows the users to create the databases that best suit their applications without worrying about what will happen when updated versions of the network they are using or more accurate networks become available.

However, the schema we are proposing for handling the GIS complexities is not free of impracticalities or loose assumptions. These deficiencies are related to the difficulty in maintaining correct alias files, verbally describing topological relationships, accurately representing stops along arcs, and properly implementing linear referencing schemes. The verbal description of routes and stops that we based our strategy on has its advantages (that we described above) and also has its inconveniences:

1. *Stability of Street Names*: We are assuming in our strategy that street names are stable and do not change over time. This assumption might be true for most of the time, but cases do exist where street names have been changed or modified as a result of constructing extensions to roads or bypasses. In these cases, applying the old textual description of routes onto new network for extracting routes might yield wrong results. Manual check of route alignments is always needed as a result. Furthermore, we are assuming that street names exist for all roads in urban areas. A few exceptions do also exist where street segments in some small cities have no names or are not well recorded.

2. *Difficulty in Verbally Describing Routes*: In our schema, we propose the textual description of routes and stops for encoding transit routes. However, at complex

intersections where elevated highways overlap with surface or depressed ones and where each of these highways belong to different routes and has a different name, TIGER-like files usually fail to capture the complex relationships between such structures and the textual description of such relationships is also quite confusing. The use of several road maps to distinguish which arc belongs to which route and sometime site visits might be needed to resolve these ambiguities. This difficulty is not limited to the time when such routes are being converted into textual description and entered into the foundation database, but also to the time when these descriptions are used to extract routes from new network files which might also lack sufficient road attributes and street names.

3. *Difficulty in Creating Alias Files*: We proposed to resolve the problem of having multiple names to certain road or highway sections by adding an "alias address" item to the route table in the "foundation database" (refer to Figure 7.1). However, the knowledge of whether an alias name to a certain street exists or not is not simple. A set of maps that come from different sources need to be checked in order to learn about different alias names. Failure to capture all possible alias names is very likely. Furthermore, an alias name may apply to only a portion of a street (e.g. route # alias) which will complicate the construction of accurate correspondance tables between aliases.

4. *Difficulty in Augmenting Topological Relationships*: The proposed augmentation of topological relationships of TIGER-like files in order to make them useful for transit path-finding algorithms is quite a complex process. Verbally describing the topological relationships, turn movements, transfer, and connectivity information at complex intersections is more difficult than what it looks like. The complex database design of these topological relationships can be handled by outside

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consultants. However, encoding these relationships needs to be done in-house. When modifications to route alignments are conducted, new topological relationships are created and they may concern not just the modified route but also all routes connecting to it. The regeneration of these information is not a very straight forward process.

5. *Inaccuracy in Representing Stops Along Routes*: In our strategy, we proposed that stops are represented by the name of the street intersection where they are located and by the nearest address if they happen to fall in the middle of an arc. In the later case, the representation of stops might not very positionally accurate. In some cases, the nearest address might be a little far away from where the actual bus location is. For instance, at shopping malls or at big centers, the whole compound might be given a single address. A "One Plaza Mall" address might represent a whole block, for example, and locating a stop at such an address might correspond to many possible places.

6. *Inaccuracy in Linear Referencing Schema*: In order to handle the segmentation complexity, we proposed to standardize on a textual description of routes plus routines that would allow one to use any one of several basemaps to extract arcs that belong to these routes and the employment of the route data structure and the dynamic segmentation capabilities of many GISs for referencing objects and data along these routes. When moving from one network into a more accurate one, and if the same linear referencing schema and offset values are utilized, the location of objects along routes might be inaccurately represented. In the "base point offset" schema for representing objects that most dynamic segmentation tools use, the location of objects along a route is measured as an offset from a base point. When routes are regenerated from more accurate files (that might contain more shape

points, for example), the old offset values become wrong. Applying the old values on the new routes would hence yield wrong results. Calibration tools do exist for re-calibrating data offsets when such cases happen, but these tools stretch or shrink attribute location linearly based on the change in total route length which does not also yield accurate results.

For this strategy to thrive, the appropriate organizational setup needs to be in place. As we saw, this strategy allows each individual user to generate his own data representation based on the description of routes and stops in the "foundation database." At the same time, a certain degree of control is needed to ensure that users are developing their applications based on the guidelines of our strategy. The top-down strategy will no doubt provide the needed control but lacks the flexibility that allows each user or group to develop their own databases and integrate data updates on time. The bottom-up approach, on the other hand, provides the users with too much autonomy which makes it hard to enforce the guidelines that application developers should follow. The loosely-coupled approach for building applications is probably the most adequate environment for implementing the proposed strategy. It minimizes the amount of standards and procedures that must be agreed to at early date. It also allows the creation of committees for coordinating the additions to the "foundation database," controlling the development of applications, and ensuring the adherence to the general framework and guidelines of the strategy by all users.

Finally, in our strategy we recognize the need for some loose ends and customized fixes in order to make the strategy work. These loose-ends and fixes are related to the fact that there is no one strategy that can be applied to all transit agencies. The detailed implementation of any strategy are dependent upon several local factors that include local skill, availability of agency and local data, current extent of GIS use,

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sophistication in technology implementation, and availability of needed funds. Furthermore, our strategy did not discuss in detail database design issues since no one database design can also be applied to all agencies. The detailed design usually requires the knowledge of every aspect and encoding scheme of each database currently in use for all applications in a transit agency. However, the strategy we proposed can be used as an example of the ways to manage the GIS development and implementation specifics can hence be deduced from the general framework set by our strategy.

In the next section we address the issue of software related complexities and how the advances in technology can have an impact on improving these problems. In the last section of this chapter, we address the organizational issues and discuss which implementation strategy is the most recommended.

7.6. Addressing GIS Software-Related Complexities

The major software-related complexities are associated with the limited ability of GIS tools to handle multiple representation of spatial objects, the software design of many GIS, and the generic network algorithms of GIS. The issue of handling multiple network representations was discussed at length. The use of textual description for representing routes, the augmentation of network topology, and the adoption of dynamic segmentation are some of the major elements of the strategy to deal with this complexity. We shall now focus our discussion on the ways of handling the software design problems and the adequacy of generic GIS software algorithms.[50]

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[50] Please note, as we mentioned earlier, we used one particular software package, Arc/Info®, to develop all of our prototypes. Arc/Info is illustrative of more capable GISs in which complex applications can be built. Nevertheless, in our discussion we try to remain generic and package independent as much as possible when referring to GIS problems in general.

7.6.1. Processing Speed and Modularity of GIS

The PIS and the ridership forecast prototypes that we built show that current GIS are slow at processing complex queries needed by transit applications. The major limitations of both models is their lack of speed. For example, the time required by the PIS prototype to determine one route between a pair of origin and destination addresses is almost 40 seconds on a typical 1991-generation UNIX workstation (DECstation 3100). This is quite slow for this type of applications where instantaneous results are usually desired. Similarly, the ridership forecast model required 70 minutes for the complete analysis of a realigned route on a similar workstation. Such times prevent the analysis of alternative routes from being the highly interactive and exploratory endeavor that was envisioned.

Table 7.2 - Running Time Per Operation (Workstation Version)											
OPERATION	RUNNING TIME [seconds]										
Observation #	1	2	3	4	5	6	7	8	9	10	AV
Loading INFO Module	3	4	3	3	5	3	4	3	5	3	3.6
Creating INFO File	2	1	1	1	1	2	1	1	1	1	1.2
Cleaning Old Matching File	5	6	5	5	5	4	4	4	4	4	4.6
* Address-Matching	6	6	7	6	7	5	6	6	7	5	6.1
Loading Arcplot Module	10	6	11	9	10	10	10	11	4	4	8.5
* Finding Nearest Stop	3	2	3	3	3	3	2	3	2	2	2.6
Loading ROUTE Module	10	4	10	10	9	9	9	9	5	5	8.0
* Calculating Optimal Path	7	8	8	7	8	8	7	7	9	7	7.6
TOTAL RUNNING TIME	46	37	48	44	48	44	43	44	37	31	42
* Basic operations of the prototype											

However, by breaking down the running time for these operations into actual computing time versus overhead time, the causes of slowness become more clear. Usually, the bulk of the time is spent on overhead operations that are caused by the modularity and the inefficiency of macro languages adopted by GISs in general. Table 7.2 shows, for example, the running time in a PIS for each of the operations involved in determining a path between an origin and a destination address.

The total running time varied from 31 to 48 seconds. This is due to the fact that (a limited number of) other users' processes were running simultaneously and affected whether needed code was already in RAM (or swapped out) and whether RAM could accommodate all the required processes of Arc/Info. Note that the most variation in operation time is in loading modules (e.g., between 4 and 11 seconds for loading Arcplot) which is dependent on availability of free swap space and memory. The macro involved many overhead operations such as loading modules into the memory, killing old files, and moving from one module to another. These operations consume more than 60% of the total running time of the program.

Furthermore, the prototypes were both built using Arc/Info's AML macro language without any restructuring of basemaps and datasets to speed up the types of computations needed for these analyses. Implementing the PIS and the ridership forecast models at this upper level of programming results in significant system overhead delays as the various modules and tools of Arc/Info are invoked to call each computational and graphical function.

Trends in technology and GIS software development show that these deficiencies can be handled in the future in the following fashion:

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1. *More Efficient Macro Language:* The macro languages of GISs is one of the significant factors affecting the slow performance of the GIS-built models. For instance, three modules of Arc/Info need to be used in the GIS-based PIS and the results of operations in one module need to carried over as input for other operations in other modules. The macro language used by Arc/Info does not allow the setting of the results of any operation as variables, but rather the results need to be written into a file in order to be read by other operations. The writing and reading of files involves the opening and the closing of these files before and after every operation which delays the running of the programs. In other words, a major contributor to the low efficiency of models built on top of Arc/Info is the fact that the macro language cannot call functions (except for a few commands on the workstation version), pass parameter values, and return results in the style of most high level programming languages (without having to store the results in files). In the prototype we built, the Arcplot module, for example, was used not for plotting or displaying the network, but for setting the output of operations in the INFO module as variables to be used in other modules without the need for writing the results into files. The reason for using Arcplot is simply that it is the only module where the right command for selecting fields from a table in INFO and directly setting them as variables exists[51]. However, the number of operations that can assign their results directly to variables is very limited.

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[51] In fact there are some other indirect and complicated ways for selecting fields from a table and setting them as variables, such as going into INFO, creating a "sub-macro" inside INFO which assigns a field to a variable when run outside INFO, quitting INFO, and running it at the ARC level. Interestingly enough, the performance of this macro varied significantly between platforms. When run on a IBM RT 120 workstation, this macro was extremely slow (200 seconds) since loading INFO into the memory of the machine consumed 30 seconds on the average. The same macro however, had a good performance on DECstation 3100. The average running time of the whole macro was around 30 seconds. This illustrates the variation in terms of efficiency of programs between platforms.

While different GIS packages offer different internal programming capabilities, most tend to focus on implementing macro languages that offer ways to package sequencing of menu choices or commands rather than full fledged programming languages with efficient access to in-memory data structures and geometry manipulation tools[52].

Future developments in GIS and language architecture can address some of these limitations. It is beyond the scope of this thesis to research these issues but it is worth noting three such developments: (1) restructuring GIS software using inter-process communication tools to allow efficient client/server separation of back-end (server) geometry processing and front-end (client) desktop mapping and user interface tools, (2) the evolution of object-oriented internal programming languages, such as the ones in SmallWorld or ESRI's ArcView, and (3) the improvement and widespread adoption of OLE, ODBC, opendoc, and other general purpose client/server tools that are increasingly being utilized by GIS developers.

2. *Parallel Processing:* The sequential processing of operations is another limitation in the software design of current GIS packages. As GIS software adopts "Multi-threaded" programming capabilities and other parallel processing techniques, GIS software will become more efficient. Parallelism in operating systems is the current trend in the development of future technologies. However, major re-writes of GIS software are needed to support the use of such methods.

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[52] An example of an exception is SmallWorld® which uses as its internal macro language a C++ like object-oriented programming language with numerous spatial operators as pre-defined procedures.

3. *Unbundling of GIS Software:* In the future GIS technology will become more unbundled and modular. This will allow the easy integration of external tools with generic GIS tools to address the more specialized problems in a more effective fashion. Off-the-shelf GIS algorithms are usually "generic" and sometime are not suitable for specialized transit applications. The unbundling of GIS tools would allow the use of efficient external engines to address complex computational problems. Together with advances in workstation technology, these changes will make it much easier to build efficient tools for transit applications.

4. *Improved Spatial Indexing Strategies:* Augmenting or repackaging foundation data to facilitate task specific performance for spatial operations is part of what GIS tools offer and the techniques (indexing methods, quad-tree models, wavelet based compression schema, etc.) are constantly being improved. In order to make operations like address-matching efficient on large scale networks, indexing by street name, street type, address prefix, and suffix of all records can be done. In applications where address matching type of operations are performed on large networks, creating such indices would help improve the performance of GIS tools.

5. *Improved Processing Speed:* Technological advances in hardware already enable current (1994-generation) UNIX workstations to be 2 or 3 times faster than the ones used for building our prototypes. In the next several years, such improvements are likely to provide an order of magnitude improvement in performance for the types of transit applications we have considered.

Improvements in software engineering and computer science are gradually allowing GIS tools, functionality, and data representations to be repackaged in ways that are more modular, efficient, and conducive to parallel processing and

client-server architectures. Hence, these changes and a continued improvement in processing speed can combine to provide a hundred-fold increase in overall speed in the near future while enabling the modeling and mapping tools to be distributed more easily to the transit planner's desktop.

7.6.2. Inappropriateness of Standard GIS algorithms to Transit Applications

As discussed in chapter 6, standard GIS algorithms, such as the shortest path and resource allocation, are not entirely appropriate to be used on networks with travel times that are schedule-dependent and stochastic. This inadequacy, coupled with the inefficiency described above, support adopting one of two options: (1) the customization of these algorithms to make them useful for transit applications, or (2) the use of the database side of the GIS to provide for the functionalities that are lacking on the geographic side of current GIS.

The customization of standard algorithms is one alternative for computing efficient shortest paths. Efficient codes which use more adequate and sophisticated algorithms than the standard ones can be written outside the GIS. These codes can access the databases used by the GIS to calculate shortest paths and output the path results in a form readable by the GIS. This approach, it might be argued, runs against the purpose of using GIS in transit applications since it suggests the use of customized algorithms in order to solve problems initially associated with the use of customized systems, such as the PIS. However, general purpose GIS cannot be equipped with algorithms for all types of applications and the sophistication of typical GIS algorithms is far less than what some commercial routing packages use. Moreover, such coupling is possible in ways that are not cumbersome and retain the capacity and licensing freedom to use

the GIS tools to maintain and edit the underlying databases.

The second option suggested for handling the inefficiency and the inappropriateness of standard shortest path tools used by GIS is the use of the database side of the GIS. "Relational Data Base Management Systems (RDBMS) permit the use of the GIS's geographic database with other data sources not automatically recognized by GIS systems and other application-specific customizations,... and permit the building of network analysis tools" [Grayson, 1991]. Shortest path tools, for example, can be built on the database side of GIS and can be sophisticated enough to account for all the time variations in schedules. The execution times of such algorithms are quite high, but with sensible indexing, and the use of powerful workstations and multi processing, the performance of such algorithms is well worth considering.

7.7. Conclusions: Which Implementation Strategy To Recommend?

The next choice that transit agencies are facing is related to the selection of implementation strategies. Early in this chapter we discussed the benefits and the disadvantages of each of three implementation strategies; i.e., bottom-up, top-down, and loosely-coupled strategy. It is clear at this stage in this thesis that some of these strategies are more suitable than others.

In general, in the bottom-up structured organizations, users have the freedom to create databases that best meets the needs of each individual application without really worrying about other usage of the developed database or GIS model by other groups or really worrying about the viability of applications. In other words, each complexity for each application can be addressed in the simplest and easiest way. Such an approach

has many defects:

1. *Thousand Flower Bloom*: It is true that each application can work properly when databases are customized to meet its immediate needs. However, this approach results in a multitude of applications that will mushroom in each department and that have inconsistent and impossible to coordinate databases. This also has the disadvantage of duplicating large databases, consuming storage space, and duplicating encoding and programming efforts.

2. *Viability of Independent GIS Applications:* Living with the above disadvantages might make sense as long as the GIS is providing users with their needs and as long as it is improving their net efficiency. Immediately after implementing a certain application, the GIS-based applications might be able to improve the efficiency or effectiveness of end-users. In the long run, however, as more and more applications are developed, inconsistencies in route description and delays in propagating changes among all applications will bog the system down and raise questions about its integrity and efficiency. For most large transit operations, these headaches will be significant and not easily resolved (such issues are analogous to the corporate pressure to develop enterprise-wide multi-user databases systems in most large firms).

The top-down implementation strategy, solves part of these complexities. Because of the centralized approach to problem-solving, the technical problems related to coherence between databases, ways of encoding data efficiently, and mechanisms for data update and propagation, can be handled properly in top-down oriented organizations. However, such a structure is too idealistic and its implementation usually faces many practical deficiencies. The major defects of such an

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implementation strategy are the following:

1. *Rigidity:* The cost of restricting data creation, application development, data maintenance, and data propagation to the IS department would result in many layers of "bureaucracy" that render the whole operation very rigid. Since the IS is the only department allowed to conduct modifications to databases and basemaps, users' requests for data modification might be very delayed which might reflect negatively on users and increase their levels of frustration with the technology.

2. *Inadequate Tools:* When IS is customizing applications and building turn key systems for end users, those applications and systems might not always meet the exact needs of these users. This is related to the fact that applications and technology are constantly changing as people discover what can be done with GIS technologies and reorganize their tasks to accommodate the new changes. Central planning cannot keep up well enough to meet all expectations.

3. *Client / Server Trends:* The general trends of IS departments is toward end-users empowerment and client/server applications development. The top-down GIS implementation strategy encourages centralization which basically contradicts the overall client/server trend in the organization. Distributed computing and distributed databases trends that are occurring at all levels of information infrastructure development in transit organizations will sooner or later make GIS follow.

The loosely-coupled collaboration strategy is the most recommended one. In our discussion we showed that somewhere in between the two worlds of top-down and bottom-up a happy medium exists. In order to implement the strategy, we proposed in

this chapter, a certain level of coordination and structure for database building is needed. A more coordinated bottom-up or a loose top-down strategy is recommended. This is what we believe the loosely-coupled collaboration strategy can provide.

In our strategy a certain level of coordination is needed for building databases using the "foundation database." Users can create their own models that are based on this database which best suit their application needs. This ensures a desirable level of coherence and consistency between the different models. Furthermore, since these models are generally created using semi-automated tools that read their information from the "foundation database," this approach allows for the on-time integration of updates into the different applications.

In the proposed strategy, we relied a lot on TIGER-like street centerline files for building the route and stop basemaps needed to implement different transit applications. In many metropolitan areas, planners are trying to get the Bureau of Census to make the TIGER 2000 be the local map for them to use rather than using partly ancient or partly revised local maps. If TIGER 2000 is tightly linked and consistent with detailed local maps, many of the complexities related to digitizing local maps will go away. For example, instead of digitizing routes and stops on top of local files, the textual description can used to extract the routes from the detailed local maps (that are consistent with TIGER). Nevertheless, the need for using textual description of routes and stops, the standardization that supports the textual descriptions, and the creation of extraction tool would still persist.

The loose part in our loosely-coupled strategy is that there is still some duplicate digitizing taking place and that different departments might be doing things differently. This is expected to continue until such times as the local basemaps become

coincidental enough at the metropolitan level with TIGER-like street centerline files suitable for routing algorithms. As time goes along, there will be more efforts to conflate or augment some of the local basemaps and TIGER files. Once these efforts succeed, especially at the metropolitan level, tying into these databases would make some of the problems related to difference in segmentation, scale, and geometric representation that we discussed above fade away. On the other hand, due to the different network representation needs of different applications, multiple geometric representation of routes and stops will exist in parallel for a long time to come.

In the meantime, rather than waiting for this these efforts to succeed, our proposed strategy allows agencies to move along a GIS development path while building the sort of standardization that would make it increasingly easier for those agencies to give up their old network files once the more accurate one become available. Nowadays, many transit agencies are contracting out pieces of the start-up process with the assumption that the cost they are paying for initiating GIS at the agency is only a one shot deal with a low maintenance cost. However, in reality contracting out the start-up of GIS is proving to be more expensive than anticipated because not only there is a need to change a few routes every year or correct a few errors, but over time, agencies will realize that better basemaps are needed and many of the applications have to be redone completely.

Chapter 8

Conclusions

The major goal of this thesis was to identify and describe viable strategies for building, managing, and implementing GIS capabilities at transit agencies. The preceding chapters described:

- the motivation for this thesis and the research questions;

- the literature that serves as the foundation for this work;

- the applications of GIS in transit agencies;

- a survey that investigates the current use and implementation of GIS by the largest US transit operators;

- "what does it take" to build transit applications using GIS;

- the complexities of implementing GIS capabilities; and

- the development pathways to address these complexities;

In this chapter, we conclude by first summarizing the findings of the research and then describing the impact of GIS technologies on making transit agencies more integrated into regional information infrastructures. We finish this thesis by making a set of recommendations and discussing future research in this field.

8.1. Summary of Findings

The thesis has focused on the following research questions:

1.   What are the areas of integration of GIS in transit agencies?

2.   What are the complexities related to database design, system design, and data flow that are affecting the implementation of GIS?

3.   How are GIS technologies, regional information infrastructure, and transit planning processes changing and evolving over time?

4.   What are the different implementation strategies that can be adopted in a transit agency for the efficient and effective implementation of GIS technologies?

5.   What are the viable developmental pathways that transit agencies can follow for the implementation of GIS? How can advances in information technology help in addressing some of the implementation complexities and in shaping the transit planning process in the near future?

8.1.1. Question 1: Areas of Integration of GIS in Transit Agencies

In Chapter 3 we discussed at length the areas of integration of GIS technologies and the benefits that can be derived from implementing GIS in transit agencies. In Chapter 4, we also described the results of a survey of the largest transit operators

in the US and we showed the areas where transit operators have already started using GIS. Transit applications are perceived to benefit from GIS in several different ways. The graphical component of GIS allows the visualization of spatial objects which helps in better understanding the spatial relationships between geo-referenced objects. GIS tools have the potential to automate much of the manual analysis conducted by transit planners such as overlaying several data layers. Automation usually yields narrow efficiencies, however it allows the redefinition and reorganization of some basic work in ways that were not possible without automation. The benefits of GIS can hence be translated into improved and innovative planning processes. Finally, the link to spatially referenced outside data is another potential benefit that transit applications can derive from GIS.

The areas of integration and the benefits of GIS in the different departments of a transit agency can be summarized as follows:

1. *Service Planning Department:* Corridor study and route analysis are two applications that can benefit from GIS. GIS can be used to automate many of the manual overlay processes conducted in these applications. Mapping applications were also identified as areas where GIS might have an important impact in the planning department.

2. *Marketing and Ridership Department:* The passenger information system (PIS) is the main identified area for potential application of GIS in a marketing department. GIS can be used to replicate the usually expensive, turn-key PIS systems in a more flexible environment. It allows the addition of new features to the customized PIS to overcome some of its deficiencies. The graphical component of GIS can be used to add a visual component to the customized

PIS in order to visualize the results of queries and maintain the PIS geographic databases. (Refer to chapter 5 for more details).

3. *Real Estate Department / Engineering Department:* The applications in these two departments that can benefit from GIS are the ones that involve the use of spatial data and geo-referencing. These applications include property and facility management, maintenance of inventory data, and production of maps. The GIS can potentially enhance these applications by basically automating most of their processes.

4. *Police Department:* Safety and security analysis and emergency response are the two areas of potential use of GIS in the police department. The overlay, address matching, and the path finding capabilities of GIS can be used to create emergency response systems and perform crime analysis operations. (Refer to Chapter 3 for more details)

8.1.2. Question 2: Complexities Affecting the Implementation of GIS

In Chapter 3 we described the potential use of GIS in the different departments of a transit agency without going into the complexities and the meaning of using a GIS for each application. In chapter 5 we studied these issues in more detail. We built three GIS-based prototypes to illustrate the type of complexities that are faced while implementing a GIS and to understand the "what does it take" to build transit applications using general purpose GIS tools and data that could fit into a coherent agency-wide GIS strategy. In chapter 6, we then summarized and categorized these complexities. These problems can be classified as follows:

8.1.2.1. Data-Related Problems

Different applications require different attributes and different spatial representations. The spatial features of a route might be common to many applications but the attributes that need to be attached to that route and the way the routes are represented vary widely between these applications. In chapter 6 we explained how the data required for routing applications differ from the ones for mapping applications, for example. We also showed the importance of the issues related to network representation in terms of building sharable, maintainable and viable databases. The important aspect of these complexities, furthermore, is related to the procedures that allow the movement from one data representation into the other when data sharing is desired within an agency. The following is a list of these data-related complexities that were covered in detail in chapters 5, 6, and 7:

1. Different network segmentation: (one-to-many or many-to-many relationships; routes vs. segments)
2. Different network topology: (overpasses and underpasses; connectivity)
3. Different geometric representation: (road width vs. centerline)
4. Different schema for encoding Stops: (stops vs. nodes, handling transfers and delays)
5. Conflation related problems: (different network geometry, missing arcs, scale)

8.1.2.2. Software-Related Complexities

GIS packages, in general, are general purpose software. As a result, the network algorithms that they have are generally generic and non-customized to transportation applications. In this thesis we showed how special attention need to be paid to

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represent connectivity and turn movements in order to make off-the-shelf GIS algorithms suitable to transportation applications. We also discussed how the software design of GIS packages, and the performance penalties associated with using general purpose GIS tools in place of customized code need to be addressed in order to make GIS-based transit applications efficient and fast enough to handle metropolitan size networks of transit routes for real-time applications such as PIS.

8.1.2.3. Organizational Complexities

By organizational complexities we mean complexities resulting from the GIS implementation strategy in a transit agency. Some of these organizational problems that obstruct the building of sharable and sustainable GIS databases and applications are related to:

1. the lack of encoding standards within the agency;
2. the difficulty in enforcing the use of standards;
3. incompatibility in hardware and software acquisition between users and departments;
4. availability of right technical expertise;
5. structure of the organization (centralized vs. decentralized); and
6. strategies for building applications (in-house vs. contracted out).

In Chapter 7 we discussed three GIS implementation strategies and explained how the approach to addressing the above problems depends largely on the overall structure and implementation strategy of the organization.

8.1.3. Question 3: Evolution of GIS, Information Technology, and Transit Planning

As we have shown in this thesis, there are many complex problems that are obstructing the use and implementation of GIS in transit applications. At the same time, the GIS technology and information technology are also evolving rapidly and in a fashion that might help in addressing these complexities. Likewise, recent trends in development of regional information infrastructure are suggesting and enabling the more integrated approaches to transportation / land use planning. The third research question of this thesis, focused on the ways GIS technologies and the transit planning process are evolving for the purpose of exploring, at a later stage in the thesis, the question of how these evolutions would help in addressing the GIS complexities. In other words, the third research question is limited to investigating the recent trends in transit planning and information technology development whereas the last question of this thesis is more concerned with the pathways that transit operators can follow and the choices they can make in order to implement a viable and sustainable GIS. The last question also deals with the impact of technology on the transit planning process and on integrating transit agencies into the regional information infrastructure.

The 'Literature Review' chapter discussed the issues raised in research question 3. Question 3 investigates the changes in transit planning processes over time and the recent trends in information technology developments. The Technological developments that might impact the use and implementation of GIS in the near future and eventually help in creating the integrated land use /transportation model can be summarized as follows:

1. *Hardware developments:* recent trends in hardware developments show that future technology will basically continue to become more affordable and much faster. This helps in processing complex operations on large databases needed for building efficient transit models. Parallel processing, multi-processing, and 64-bit computing technologies are the recent manifestations of these technological developments. These developments are capable of overcoming many of the GIS complexities especially those related to slowness and efficiency of GIS-based transportation models. (Refer to Chapter 5 for more details on these models).

2. *System Architecture:* Recently, distributed computers and networking have made certain forms of distributed computing more and more practical. The most important of the system architecture developments is probably the move into client/server models and distributed database management technologies. These developments are responsible for making the data sharing and the distribution of databases more feasible. The benefits of these developments are basically related to cost saving, scalability, and robustness of systems and to inter-operability with desktop applications.

3. *Software Development:* The most significant trend in software development is related to object-orientation and parallel processing. Parallel processing, in addition to being implemented at the hardware level, it is also being implemented at the operating system and application levels through the use of, for example, multi-threaded programming. Similarly, object oriented programming technologies are impacting the operating system, the programming language, the applications, and the database management tools. The parallel processing techniques can speed up time consuming spatial

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queries and the object oriented approaches facilitate the handling of complex data structures that are typical of GIS applications and, more importantly, help allow multiple representation of spatial features to be used in the particular applications that best suit them.

As for the transportation / transit planning process, we described in chapter 2, how this process and its focus have changed over the years. We described how it evolved from being only highway-focused in the 50's to paying more attention to transit issues in the 70's and 80's; and how in the 90's its scope broadened enough to address environmental concerns (Clean Air Act), land use planning issues (ISTEA), and social concerns (American with Disability Act). To meet all these requirements which necessitate the coordination of multi-agency objectives, we also talked about how a regional transportation planning infrastructure needs to be created and how GIS technology can be one of the fundamental foundations of such transportation planning infrastructure.

8.1.4. Question 4: GIS Implementation Strategies

In order to tie spatially referenced data and tools (i.e., GiS) into the backbone of the regional information infrastructure, the complexities related to the use and implementation of GIS in transit agencies need to be addressed. Addressing these complexities cannot be done in isolation of the overall implementation strategy and the structure of the organization. Question 4 of this research concerned the different implementation strategies that can be adopted at the agency and their influence on the approaches for resolving the GIS implementation problems. In Chapter 7, we addressed this issue at length.

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Based on the literature and our survey of the largest transit operators in the US, three basic implementation strategies were identified. These strategies consisted of: (1) *bottom-up strategy* where each department in the transit agency is responsible for developing its own databases and applications and where no coordination is required; (2) *top-down strategy* where all databases are derived from centrally maintained ones and where the IS, and not the users, have the authority to create users' databases and applications; and (3) *loosely-coupled collaboration strategy* which essentially is a hybrid of both top-down and bottom-up strategies. In the loosely-coupled strategy, many elements of the top-down strategy (such as the creation of coordination committees and the implementation of "prior approval" and reconciliation strategies) are retained while allowing some autonomy and "loose" GIS development. This is achieved by agreeing on standardizing a limited, transit-specific, core set of data, which are related to transit routes and stops, and which are not tied to any specific geometry. (Refer to Chapter 7 for more details about these strategies).

In order to address the complexities of implementation of GIS, we created a matrix that tabulates the GIS complexities versus the different applications of GIS. The purpose of that matrix was to show how these complexities get manifested for each application. That matrix helped us realize the following:

1. No single basemap can be utilized to suit all transit applications in a transit agency. Some applications required more detailed street network files than others. TIGER files are generally suitable for routing and path finding applications while detailed local network files are more suitable for mapping and inventory applications.

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2. Different network representations are needed for different applications. The segmentation of TIGER files, for instance, is not suitable for building all GIS applications in the agency. Utilizing the dynamic segmentation capability of GIS tools can help in resolving parts of this problem. Furthermore, the natural data structure for each application might look easy to implement, but when trying to combine all these structures together and make one representation suit all applications, the real difficulties and design choices start to emerge. Some of these complexities might be easy to handle and some very hard.

3. Technical difficulties are not necessarily related to making the "right" initial choices for digitizing routes, labeling segments, or picking any particular data encoding scheme. The difficulties are rather related to managing the complexities and building a developmental pathway that serves the multiple representation needs by having the appropriate additions to it over time. The development path at the agency should not be understood as a baseline delivered by the IS department that can be used to build all applications based on it. It is rather a few usable starting points that are good anchors in the process of evolving an increasingly capable system over time. It is managing the complexities through a choice of robust strategies that may not have a single "once and for all" basemap, for example, as one starting point.

4. Dynamic segmentation, attribution, and the utilization of pseudo-nodes are a sequence of technical strategies to manage the mismatch between the different data representations. They are examples of compute-on-the-fly strategies that allow real-time generation of new topology and spatial relationships to solve specific needs and to get around the differences in what is ideal for each

application in terms of data representation.

5. Off-the-shelf GIS network analysis algorithms are not sufficiently rich to handle many aspects of transit routing and modeling. Customization of these models or the utilization of the relational database management tools of GIS are needed to perform complex transit routing and path finding applications. Augmentation of network topology is also needed to incorporate complex connectivity, turn movement, and schedule transit data.

Addressing these complexities is by and large influenced by the implementation strategy in the agency. We examined how each of the three implementation strategies, discussed above, can affect the viability of solutions to the GIS problems in general. We concluded that the bottom-up approach is susceptible to many problems especially since it encourages the creation of uncoordinated and inconsistent applications. This, in the long run, will create major update and maintenance problems and the cost of redeveloping applications will make the GIS look like an inefficient and non-sustainable set of tools.

In the top-down strategy, the centralized approach to data and application creation and maintenance can resolve many of the problems related to data inconsistency and duplication. However, such an approach can result in many deficiencies that usually translate into rigidity and lack of flexibility of the system, inadequacy of tools created by the IS department to meet individual users' needs, and the inefficiency of GIS as a planning tool (caused by the overhead cost and delays in keeping the system up-to-date and able to accommodate user needs).

The loosely-coupled collaboration approach was the most suitable strategy for

building maintainable and viable GIS databases and applications. The fact that different applications require different representations and that no single basemap suites all applications are clear indications for the need for multiple versions and for major flexibility in building databases and applications. However, in order to avoid the duplication of work and the creation of inconsistent and uncoordinated databases, a certain degree of control needs also to be available. In chapter 7, we described a schema for generating sustainable individual GIS application databases from a "foundation database" that provides users with lots of autonomy while requiring some degrees of coordination. The loosely-coupled strategy can provide the best environment for such a strategy to succeed.

8.1.5. Question 5: Viable Developmental Pathways for GIS

The last question of this thesis deals with the different choices that transit agencies can make in terms of implementing GIS capabilities and the implications of each of these decisions on dealing with the GIS complexities. This question discusses the different decisions that transit operators can make in terms of how to get started, which data to use, what other outside agencies to connect with, and what shortcuts they have to make in order to ensure a viable developmental pathway for GIS in the agency. In chapter 7 we discussed these issues at length and described one developmental strategy that can be adopted in order to handle many of the GIS complexities, described earlier in this thesis.

8.1.5.1. How To Get Started?
The choices that transit agencies face have several facets that vary from the very straight forward to the really complex ones. The first choice that transit agencies

face is where to get started and how. These choices are related to identifying applications for the implementation of GIS, deciding whether to develop those applications in-house or to rely on outside consultants for assistance, and choosing the convenient platform and software for running GIS. These "initial" choices are also associated with the more complex choices of data structure design, the capacity to move from one data representation into the other, and the availability of the adequate tools and the right skills for the maintenance and viability of the GIS applications. Nevertheless, once these complex decisions are made the "initial" choices become easy and simple to handle. For example, the choice of hardware and software becomes obvious once the data pipeline is designed and needed computing capabilities are set. The less complex choices that transit agencies face are:

1. *Development Strategy*: Agencies have the choice between implementing an agency-wide GIS or dealing only with few immediate applications of GIS. Implementing an agency-wide GIS has the advantage of addressing some of the GIS complexities from the onset. Complexities related to coordination between databases and adoption of standards, different application needs in terms of data representation, and the ability to move from one data representation into the other can be dealt with more effectively as a result of the holistic view of GIS in the agency. However, the organizational structure of the agency plays a major role in deciding which choices to make. In bottom-up organizations, it is harder to implement agency-wide GIS than in loosely-coupled or top-down agencies.

2. *Hardware and Software*: The choice of hardware and software is also dependent on availability of funds allocated to GIS. Usually, when GIS is adopted for building prototype applications, affordable PC-based GIS are acquired. However,

when the scope of GIS is wider than meeting the immediate narrow needs of an agency or testing the potentials of GIS, workstation-based GIS becomes more suitable. In addition to having some of the advanced tools needed for building sophisticated transit models, such as dynamic segmentation and some conflation tools, workstation-based GIS packages can also provide the necessary link to relational database management systems (RDBMS) that are also needed for handling many of the data representation complexities. PC-based GIS are not yet as flexible and sophisticated as workstation-based ones. In spite of the fact that PCs are catching up with the workstations in terms of speed and processing power, few GIS vendors have added the needed sophistication to their PC-versions of GIS. Hence, when using PC-based GIS, the task of handling complexities such as turn movement, connectivity, and one-to-many, for example, becomes quite complicated.

3. *Use of Consultants*: Transit operators have the choice between developing their GIS applications in-house, relying on consultants to help them get started by building key applications for them, or a combination of both. Consultants can be very useful for helping the agency in making decisions related to software and hardware selection, building applications, and becoming aware of latest technological developments. However, the product-by-product development strategy that transit operators have historically adopted is somewhat related to their heavy reliance on outside consultants and the lack of internally developed expertise. Transit agencies can derive more benefits when a holistic approach to building agency-wide databases and applications is adopted. A holistic view helps to better design the data pipeline and the tools needed to generate the right pathway from one or more basemaps to needed application databases. Finally, while transit agencies can continue to rely on consultants, their efforts should focus on

developing in-house maintenance skills, requiring consultants to use generic tools, and moving away from proprietary "black box" applications.

8.1.5.2. Which Data To Use?

The choices that transit agencies have are related to which data should they use in order to create the many network representations needed by the various applications, which processes and tools should they create to move from one data representation into the other, and what sequencing in the data pipeline should they adopt to avoid as many of the implementation complexities as possible. Some of the basic decisions associated with these complex choices are related to picking the adequate data structure and databases that would cause the least problems. The key issue in selecting these databases is to ensure that selected network data for each application can link to the proper geographic boundaries or attributes. The issue then becomes which network representation for roads and routes should an agency select to build applications and which attribute data can be associated with the selected network:

1. *Use of TIGER-like files to build many of the transit applications.* Transit agencies have the choice of using TIGER-like files for building all applications or complementing them with other local network files or with in-house digitized ones. The advantage of using TIGER-like files lies in the link they provide to the census socio-economic information, their topological information that are suitable for simple routing operations, and the address information they contain that is needed for address matching operations. However, TIGER-like files are not detailed enough or do not allow the linkage to other needed databases. For some applications, it would be more reasonable to utilize more detailed maps such as the ones generated by cities, counties, local MPOs, or assessor's office. The topology

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and geometry of TIGER-like files need also to be augmented to represent the special characteristics of transit routes and stops. Routing and path finding operations require some augmentation to the topology of TIGER-like files. Turn movements and connectivity information need to be stored in the database side of GIS in order to perform complex transit routing operations accurately.

2. *Adding Transit Attributes vs. Changing Geometry*: The augmentation of transit network representation to represent complex transit connectivity can be basically done by either changing the geometry of the network file or by adding needed attributes to this file. The route network representation can be augmented by either modifying the geometry of the network (by adding pseudo nodes and extra links) or by creating relational tables to store the complex connectivity information. The former choice might be easier to represent simple route connections but bogs down with multiple routes sharing common arcs and making complex connections. Furthermore, the modification of the basic geometry of the network files might create update problems with newer versions of the file and reconciliation problems with other applications built on top of that file. The Use of the RDBMS to augment the topological representation of transit networks is more recommended. It provides the flexibility needed to encode complex connectivity information and preserves the geometry of initial network and hence the link to other applications or newer versions of the network file.

8.1.5.3. Which Outside Agencies Are Useful Data Sources?
Through consultants or in-house staff, transit agencies can develop, implement, and maintain in-house GIS capabilities without really relying on any outside agency. However, several outside agencies, who are generally well ahead of transit operators in

terms of GIS use and development, are conducting similar studies or using similar databases. Coupling transit departments with those outside agencies is one alternative for dealing with the GIS complexities. Recent technological advances in networking and distributed databases are also enabling such coupling. Transit operators can take advantage of these technological developments to link up with outside organizations instead of focusing on building all their applications and databases in-house. However, since transit agencies have no control over the structure of data generated and maintained by outside agencies, the complexities of utilizing outside data for building coherent and sustainable transit applications might increase significantly. Outside agencies conducting similar activities include:

1. State Departments of Transportation (DOTs)
2. Metropolitan or Regional Planning Organizations (MPOs and RPOs)
3. Local Cities and Counties (that have developed parcel level GIS layers and/or road netwoks).
4. Environmental Agencies
5. Police 911 Services

In Chapter 7 we discussed at length the commonalties between the applications developed by each of these organizations and the different departments of a transit agency. We also identified the applications at a transit agency that can benefit from coupling with outside agencies. However, in order to maintain the consistency between the different applications and the different departments of an agency when such coupling occurs, transit agencies need to set a schema for handling propagation of these data among the different applications and the migration to updated versions of the external maps.

Next, we describe an example of a schema that allows the propagation from one data representation into the other while maintaining a significant level of coherence and consistency between these applications. Similar schema or more sophisticated ones need to be implemented if the agency elects to link up with outside agencies and share data with them.

8.1.5.4. Schema for Building Transit Data Structure

In Chapter 7, we proposed one strategy for building coherent and sustainable transit databases. In this strategy, we propose a schema for coordinating the creation of databases and applications, the propagation of data among applications, and the role that each user and department plays in terms of contributing to the data pipeline. This schema is designed to address the complexities related to the lack of a single representation that suits all applications and to the transformation of data from one representation into the other to enable data sharing. The following are the major components of this strategy:

1. The planning department is responsible for creating and modifying the route and stop data structure and for maintaining what we call a "foundation database." The planning department (probably, in coordination with the IS department) also sets the naming conventions for all routes and stops. This allows the standardization of a naming convention and the dealing with part of the mismatch in data representation problem. Other departments can utilize this database to generate their own routes and stops in the representation that best suits their individual applications. Other departments can also add to this database information that they utilized to generate their routes that other users might also be interested in using.

2. The structure of the "foundation database" consists of textual description of routes and stops. No graphical component to this database is needed. Since the positional accuracy of different network and geographic data is limited, and since each application requires different schema for representing spatial objects, and given that streets names are well defined in urban areas where transit services are generally provided, utilizing the textual description of routes as the structure of the "foundation database" is the most practical solution. The textual description of routes consists of detailed description of street names and stop locations that a route follows with all the turn movement information at intersections. Sometimes streets might have several names or aliases, such as federal route number and local street name. Relational tables can be used to handle these aliases. Stops are given unique ids and are associated with the routes they belong to. Stops can be described as street intersections when they happen to be situated at intersections or as addresses when located somewhere along a segment.

3. Each transit route usually consists of two directions (inbound and outbound) and varies with time of day (peak and off-peak) and day of week (weekday and weekend). Each of these variations of a route is encoded as a separate route with all the descriptions of the streets and the turn movements that it makes and of all stops that belong to it. A relational model is recommended for storing the different verbal descriptions of routes and stops.

4. The other major component of the "foundation database" is the creation of GIS-based semi-automated tools for the generation of routes from the verbal description (route extraction tools), the conversion of geographic routes into textual description (route conversion tools), and the augmentation of topological representation of the TIGER-like network files (route augmentation tools).

5. Using the semi-automated tools, each department should be able to generate its own graphical components of the data, with the representation that best suits its applications, from the textual descriptions of the "foundation database." These tools allow the re-extraction of routes in a comparatively quick and easy fashion when modifications to route alignments are made or when more accurate basemaps become available.

6. TIGER-like files are used to build the different representations of routes and stops needed by most applications. By TIGER-like files we refer to any street centerline network file that utilizes the intersection-to-intersection segmentation, contains address information, and provides an easy link to socio-economic data.

7. In applications where detailed street maps are needed, local detailed maps, such as the "tax maps," cadastral maps, or local road maps are used as backdrop maps for supplementing the TIGER-like files information. Routes and stops are first extracted from TIGER-like files using the textual information in the "foundation database." Local maps need also to be scanned in, in order to be used in conjunction with the TIGER-based routes. These routes can then be transformed to match the local maps so that needed land mark information can be approximately located on the composite maps.

8. The use of a data structure that allows the representation and referencing of attributes along routes independently of the underlying segmentation is recommended to build all transit routes and stops. Some GIS packages have implemented such a data structure. Arc/Info, for example, names it "route feature." In order to create segment free transit route networks that are capable

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of addressing the complexities related to difference in segmentation between applications' needs, arcs are extracted from TIGER-like files and stored as "route" objects in the GIS.

9. Reliance on the Dynamic Segmentation capabilities of GIS to represent attributes along transit routes. Dynamic Segmentation is used to reference line or point attribute data along transit routes using the "base point" linear referencing methods. In other words, transit route attribute data are referenced as offsets from a base point that is located at the beginning of a route. Stops can be represented as point attributes or "events" along routes too. Dynamic segmentation tools are recommended for building route inventory and maintenance applications.

10. Employment of relational data models and RDBMS to handle one-to-many problems, augment topology of TIGER-like files, and perform some of the complex path-finding operations. When the correspondence between spatial objects is identifiable, RDBMS can be used to establish the correspondence between the attributes associated with these objects. Since the topological relationships needed for performing transit path-finding algorithms are not available in the TIGER representation of transit routes, the topology of transit routes based on TIGER-like files are augmented, by using a relational data model, to store connectivity, transfer, and schedule information. The RDBMS can also be used to conduct path-finding operations that off-the-shelf GIS network algorithms are unable to perform, such as when schedule data and transfer information need to be incorporated into finding a path.

In Chapter 7, we discussed the advantages and disadvantages of the above schema.

In short, the advantages are related to simplicity and ease of implementation of strategy, consistency between applications, ease of integration of updates into existing databases and applications, and the ability of applications to propagate from one basemap into a more accurate one. The defects of this schema, however, are related to the following difficulties and inaccuracies: difficulty in verbally describing routes, creating street names alias files, and augmenting topological relationships of routes; and inaccuracy in representing stops along routes, in the linear referencing schema, and in assuming that street names are very stable.

8.2. Conclusions

The natural questions that follow our above discussion are: What should transit agencies do? Which implementation strategy should they follow? Which pathway should they follow in order to move from their current strategy into the recommended one. Certainly, there are no single answers to all these questions since the answers are related to many factors dependent on the particularity and characteristics of each organization. These factors include the budget allocated for GIS, management attitude towards GIS, in-house technical expertise, and the current level of use of GIS and standardized databases at the agency.

Out of the three development strategies, the loosely-coupled strategy is the most recommended. However, to successfully implement this strategy, special efforts need to be made especially if ventures for using GIS have already started in the agency. Re-designing the whole structure of the data pipeline finds great resistance in general as it might involve rebuilding databases and large investments in terms of time and resources. In this thesis, we discussed one viable strategy that provides a lot of

autonomy to users while maintaining a desirable level of consistency between databases and applications. Transit operators can follow that strategy to implement GIS or customize their own strategy that addresses the complexities we discussed. Nevertheless, to make this strategy or any other strategy work, the following must be taken into consideration:

1. There is no single ideal choice for basemaps, data encoding, and ways for sequencing the data pipeline. In other words, if TIGER files are chosen as the basemap for building other databases, it does not mean that other basemaps are of no use for all applications. The important issue is that the selection of key databases or basemaps must be made in order to constrain or limit the divergence of inconsistencies between application databases. Furthermore, the pathway from one or more basemaps to needed applications databases must be explicit, sustainable, and cost effective.

2. There is no single data structure that can be recommended for all agencies. Specific strategy depends upon local situation and information infrastructure in the agency. In general, the details of a strategy depend largely on what is already in place. Some of the factors which are unique for each agency and must be considered include the internal political structure and the existing data structure. The existing data structure, tools, and personnel qualification influence to a great extent the specifics of a strategy. Moreover, the willingness of departments to collaborate and coordinate is a major factor that determines the shape of a strategy to be adopted.

3. Standardization of encoding schemes is the first step to be made. The encoding of streets, routes, and stops must be standardized by understanding the sources and flow of existing data and by building maintainable look-up tables for

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cross-referencing alternative names and characteristics between departments. The flow of data between departments is an important factor that needs to be considered in order to determine what attributes need to be created, at which level in the pipeline and by who. If GIS efforts have already started in an agency, examination of the defects of current GIS databases helps in avoiding the flaws previously encountered and in developing databases that meet the requirements at each level of the data pipeline.

4. Adopt a set of basemaps for building databases for departmental applications. TIGER-like road networks can be used as a starting point for building these databases, but it should be assumed that the segmentation and the positional accuracy of most links are likely to change. In fact, with every new release of TIGER, the segmentation of streets are changed which makes it very necessary not to build databases dependent on these segmentations or positional accuracy in order to avoid being stuck to one version and unable to take advantage of the updated data in the new releases.

5. The focus at the early stages of defining the strategy should be on the identification of a data pipeline that has a set of basemaps, data tables and processing steps and which contains simple components that are practical to maintain and re-combine. If several basemaps are identified as the foundation for building other databases, attention must be made in order to provide consistencies between databases that are being built down the road.

6. Promoting departmental control over application development as each department builds the infrastructure to use and maintains its end of the pipeline is very essential for avoiding rigidity and ensuring the viability of the proposed strategy.

8.2.1. Examples of Likely Components

Finally, examples of specific components of a well designed 'loosely-coupled' strategy are offered. The following details are very valuable for building sharable and maintainable databases. These recommendations are found to be very useful for getting started with GIS and surmounting some of the data inconsistency, updated versions of key datasets, and cross referencing of data problems.

1. Appointment of a GIS coordinator in the agency at the early stages is very useful for ensuring the desired level of coordination needed in the loosely-coupled strategy. The GIS coordinator's responsibilities will increase over time as the GIS use evolves in the agency. His/her role can be expanded later on to establish the GIS coordination committee at the agency.

2. To properly implement the GIS at the agency, it is necessary to increase the GIS awareness among all users and managers. GIS Workshops, lectures, conferences need to be attended by as many people as possible in the agency to make them aware of the benefits of GIS.

3. Consultants can be relied upon for designing complex databases that go beyond the capability of the agency. However, consultants need to follow the general development pathway in the agency by building applications that use standardized tools and databases as much as possible, and by avoiding the creation of "black box" proprietary systems.

4. It is recommended that efforts are spent early on to set up a "strategic plan" for the development of applications and databases by prioritizing applications at the agency based on their need and usefulness and on the availability of funds over the years. Consultants can be hired to design this plan and on extent to which departments are willing and able to grow it effectively. The design of the data pipeline needs to be the first stage in the strategic plan.

5. The acquisition of GIS software and hardware should not be the first step in the implementation process. A user needs' assessment is recommended first, followed by the design of databases and data pipeline. Based on the requirements of these designs, the acquisition of software and hardware can be then made.

6. The "corridor study" type of applications is the most recommended to start implementing GIS at a transit agency. These applications can use TIGER-like files that are generally affordable (or free) and that have links to needed socio-economic data. The ease of implementation of this type of applications and their usefulness make them recommendable to initiate GIS modeling efforts at an agency. Nevertheless, databases for this application need to be designed in accordance with the guidelines we described in this thesis

7. It is very useful to generate a list of 'standard' spellings and abbreviations for all streets and routes. Including aliases in cross-reference tables but developing a plan whereby no new data are entered into the tables unless they use the standard spelling, is very helpful to avoid inconsistency problems.

8. Developing unique and standardized ID numbers for streets, routes, and stops is very essential for providing the link between databases developed in different

departments or at different levels in the data pipeline.

9. Fixing TIGER files by adding links or splitting segments where needed is not a very good approach for handling the TIGER deficiencies. Modifying the TIGER basemap results in loosing the link between the 'official' TIGER that is being used by others (even outside the agency) and the database being built. Consider, for example, the task of building bus routes from the TIGER street network files. The verbal description of a route in many instances might not correspond to the TIGER representation of the streets (i.e. links might be missing or wrongly connected at intersections). In such cases, it is advisable to extract the links that match the verbal description from the TIGER into a separate file and then make the needed corrections. Alternatively, leaving the original TIGER file unchanged and building an address-matching utility that utilizes the verbal description of a route to pull relevant TIGER links into a new route map and then editing the file on screen with the TIGER map in the background is considered a better approach.

10. Using relational database management tools for cross-referencing individual bus stops with 'pseudo-stops' that are aggregated for routing applications is found to be the best alternative for handling all the one-to-many problems related to multiple stops and shared links.

8.2.2. Questions to Keep Asking

In order to ensure the sustainability of the system, the following questions should be asked while building databases:

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1. When a street segment changes or any part of the basemap or the key datasets is changed, how much of the rest must be rebuilt or changed? For example, if a link in the TIGER basemap is split into two or its geometry is modified, how should these changes propagate into the databases that are being built on top of TIGER? Should the whole database be built again or is there a way of incorporating these changes into the databases without the need for rebuilding them again?

2. As a follow up to the above questions, database developer should check whether these changes can be automated and whether or not they are labor intensive. For example, when changes occur to TIGER or when new versions are released, the developer should think of the tools and means for automating the rebuilding of the databases which avoid any labor intensive work.

3. Another question that needs to be asked is what can be computed on-the-fly and what should be pre-processed. Developers need to know what data need to be always stored and what needs to be computed on-the-fly or as needed, especially that some of these data are common to many applications. For example, the TIGER street files can be used to create the census tracts, the block group, and the block boundary files which might occupy a lot of space. The developer should know whether these files are always used or whether it is more cost efficient to derive them from the TIGER street files on as needed basis. The importance of this issue emanates from the fact that the manageability of databases becomes extremely strenuous when duplicate and redundant data are developed and stored for each application while they can be generated when needed. Dynamic segmentation is an example of a compute-on-the-fly technique that has become common in transportation planning.

Finally, in the course of our research we also made several observations that transit operators need to be aware of. These observations include:

1. *Transit agencies are very unconnected to the GIS community and they need to connect.* In our survey we have observed that rarely a transit organization discussed how they can fit into the regional information infrastructure or how can they connect to outside agencies. Historically, transit agencies are known for being "behind" in terms of technology adoption or coordination with other agencies. Transit agencies need to coordinate more with outside agencies in order to first catch up with the technological developments and second to benefit from other people's experience, databases, and models.

2. In this thesis we argued that the loosely-coupled collaboration strategy is the most recommended for viable implementation of GIS at transit agencies. Nevertheless, we understand that implementing such a strategy is very complex especially when GIS it still at its infancy stage. It is very hard for transit operators to understand the issues we discussed in this thesis unless they start building applications themselves and start facing the many complexities we talked about. We therefore believe that the implementation has to go through several stages. GIS start-ups will always follow the bottom-up approach until the deficiency of the model are realized. The reaction to the uncoordinated GIS efforts caused by the bottom-up approach is expected to be translated into the other extreme of centralization of all GIS efforts. The loosely-coupled approach will not be put in place until the rigidity and unresponsiveness of the top-down approach are conceived.

8.3. How Can US Transit Operators Benefit From This Research?

We used our survey to check how each group of agencies can benefit from our research. We have divided the US transit operators into three categories related to their capacity to benefiting from the proposed strategy:

1. *"Voyeur" Agencies*: This category of agencies basically consists of all agencies that are interested in using GIS but have not yet started, and that are appeased by watching others move into the technology to learn from their experience. 25% of the agencies we surveyed fit under this category. The value of our research to these agencies is in getting aware of the type of problems they might face once they start using GIS. This thesis can serve as a "guidebook" for the "do's" and the "do not's" for the implementation of GIS. It can support them in knowing how to use beneficially the help of outside consultants, where to get data from, where other agencies are in terms of using GIS, and how to get started. In other words, this thesis can help these agencies in getting conscious of the fact that building viable GIS systems is a complex but doable task if certain notions and concepts are considered early on in the implementation process.

   For these Agencies to get started, they need to do the following:

   - Appoint a GIS coordinator
   - Increase GIS awareness
   - Identify one area for testing a pilot application
   - Design the database for that application based on our recommended strategy
   - Acquire needed software and hardware based on available funds and needed

GIS and computing capabilities.

- Acquire needed data

- Build application

- Use it both to explain GIS to others and to surface out complexities and staff willing to work on them inside.

2. *"Novice" Agencies*: Agencies that have started using GIS but for limited purposes only belong to this category. Our survey shows that around 25% of all agencies (that responded to our questionnaire) are using GIS for a single application in the agency and that the majority of these agencies are using it for conducting ridership analysis only. This research can help these agencies realize that the many promised benefits of using GIS and the ability to keep applications up to date are more complicated to realize than building one set of databases and performing one type of analysis. Once the GIS expands into the rest of the agency, the problems of regenerating and sharing databases will certainly emerge. This thesis can serve several purposes. It can first show the "novice" agencies what other areas of application of GIS exist and cautions them about the approaches of building sustainable systems. This research shows these agencies what are the pitfalls to avoid, what expertise are needed and how to go about building agency-wide databases. In other words, this thesis can send a message to those agencies that their current GIS endeavors might not be working in the future unless the issues we discussed in this thesis are well understood.

For these agencies to move on, the following is recommended:

- Check what happens when an updated version of the database used for the GIS application is released. If significant portions of the database need to be re-checked and re-done or if the checking requires significant human judgment and time, this means that the database structure will soon be problematic. Redesigning the database to allow the systematic update of data is needed.

- Check whether the data structure utilized by the one application they have can be used for any other applications they are contemplating to implement. If the data can not be shared, attention must be paid to the database design. It is easier at this stage to redesign one database than to continue with the uncoordinated database design until reaching the crisis stage.

- Look for a consultant if in-house expertise are not sufficient for designing the data pipeline. A detailed database design and data pipeline are needed at this stage if the will to move on with GIS exists.

- Check whether the hardware and software already acquired are suitable enough to your needs or not.

- Check with other agencies about their experience with GIS

3. *"Ripened" Agencies*: Our survey shows that around 11 transit operators (50%) are using GIS for more than a single application. However, most of these agencies did not focus on maintenance and coordination issues yet. These agencies belong to a category that we name "ripened" agencies. Out of these agencies, probably the most "ripened" ones are these agencies that started some data sharing efforts and that are aware of the complexities of building multi-application databases, such as Dallas Area Rapid Transit (DART), New Jersey Transit, New York City Transit, and Tri-County Metropolitan Transportation

District of Oregon (TRI-MET). The value of this research to these agencies is in helping them realize the nature of the difficulties they are facing and showing them means for managing these complexities. This thesis provides these agencies with a list of issues that they should be concerned with to ensure the viability and sustainability of their systems. Some of these agencies are well advanced in terms of using GIS and their sunk cost is large enough for them to reconsider any of the choices they have made. However, this thesis can direct them to the issues they need to reconsider in the future when implementing a new application or when re-evaluating their current systems.

The same questions that were asked by the "novice" agencies can be asked by the "ripped" ones. Additional questions include:

- Check whether each application is built independently in the agency. If this is the case it simply means that GIS might not be very viable at the agency.
- Check whether a data pipeline design exists in the agency or not. If no data pipeline exists, immediate efforts need to be made to create one.
- Check whether any standards are set in the agency or not. If none are in place, standardization of databases and tools are needed to ensure the viability of GIS.

8.4. Impact of Technology and GIS on The Transit Planning Process

In this thesis we investigated the ways of building and managing sustainable GIS capabilities at transit agencies. Future research can build on this thesis to examine how information technology and GIS can help transit agencies become more integrated into regional transportation planning efforts and how would such

integration affect the transportation planning process. This thesis investigates how to make GIS work within the agency first in order to make transit agencies technically able to join and benefit from regional planning efforts. In this section, we discuss the potential use of spatially referenced data and tools, such as GIS, for building integrated land use / transportation planning systems once transit agencies are now capable of sustaining internal GIS capabilities. In other words, in this thesis we focused on building GIS capabilities at transit agencies only. However, as metropolitan regions evolve, the use of GIS is becoming increasingly wider which makes it helpful to examine how the development of GIS at transit agencies fits into the regional planning efforts and how can transit agencies benefit from being part of these efforts. We first summarize the historical review of the impact of information technology (IT) on the transportation planning process that we covered in Chapter 2, then discuss the potential impact of GIS on this process.

8.4.1. Impact of Technological Developments on Transportation Planning

As discussed in Chapter 2, the transportation planning process in the US has undergone several changes. Its focus over the past few decades was partly dependent on institutional and organization environment and partly on technological developments. In the 50's and the 60's the centrality of the transportation planning process can be attributed to the institutional environment whereby the federal government was undertaking the construction of the interstate highways and where centrality was almost a necessity for coordinating between the different states and allocating the interstate highway funds among the states. Centrality was also driven in part by the development in information technology. Back then, mainframe computers were developed and used for transportation

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planning for the first time. Travel demand forecast models, such as the four-step or UTP model, were the important transportation planning applications run on these computers. Mainframe computers were tremendously expensive and hence available in central government offices only. As a result, transportation planning and modeling were conducted in these central offices and the planning process in turn became very centralized.

In the 70's, under the pressure of environmental groups, the transportation planning focus of providing new highways to meet the demand for travel shifted towards transit solutions within the comprehensive planning process. In the early 70's, state DOTs started acquiring their own mainframe computers to conduct their local transportation modeling using the Urban Transportation Planning (UTP) model that was provided to them by the federal government. The centralized process continued but the evaluation criteria of transportation systems started to change. Transit and bus demand, in addition to highway demand, started to be included in travel demand forecasts. Building new highways for the purpose of improving mobility was no longer the only measure utilized in transportation models. Transportation models started to include social, economic, and environmental factors along with traditional system costs and benefits for evaluating measures for meeting travel demand.

In the early 80's transportation modeling became less and less centralized. Transportation planning focused on small area improvements and on enhancing the capacity, safety, and efficiency of existing infrastructure. The introduction of desktop computing and the availability of the more sophisticated versions of the UTP model allowed this shift in planning to focus on small area improvements. Personal Computers (PC) enabled the use of a host of new tools for transportation planning and

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project evaluation which replaced the regional models with site impact analysis and corridor studies. PC-based transportation models became more sophisticated and were capable of modeling detailed intersections and the effect of local transit services, for example. In other words, the process changed from being regional to becoming more localized requiring less coordination by the central government.

In the late 80's, the local improvements were recognized as incapable alone of resolving the larger area transportation problem. Consequently, the demand management concept was introduced (such as rideshare programs and high occupancy vehicles) accompanied by a return to larger metropolitan area focus with a special concern related to larger scale policy issues. Such policies, however, were not very easy to formulate and implement at the regional scale especially when the transportation planning process was still conducted in isolation of land use, zoning, environmental, or other planning policies. The isolation of the transportation planning process had a lot to do with the lack of the appropriate regional information infrastructure for the exchange and sharing of the various regional information.

Currently the focus on building integrated land use / transportation planning models is getting stronger. Traditional travel demand models, such as UTP 4-step model, are conceived as non-practical and inaccurate. These models are expected to incorporate innovations to cope with the new federal planning requirements and the local fiscal austerity. Recent federal legislations, such as the American with Disability Act (ADA), the Clean Air Act (CAA), and especially the Intermodal Surface Transportation Efficiency Act (ISTEA), are driving the need for more comprehensive transportation planning processes whereby environmental, land use, and social factors need to be fully integrated into the transportation planning process.

8.4.2. Potential of GIS to Build Integrated Land Use Transportation Systems

The need for more comprehensive and coordinated regional transportation planning motivates the interest in an improved transportation planning infrastructure. GIS tools can play a major role in providing the needed infrastructure. This is related to the database management and data integration capabilities of GIS. More and more detailed data are coming on line. Future transportation modeling techniques can benefit from the availability of detailed data to improve current transportation processes. Address information, block-level socio-economic information, census information, and high resolution satellite images are some examples of these data that can be integrated into future models. The volume of these data and the need to use them together necessitate the use of tools, such as GIS, that are capable of managing large amounts of spatial information and of integrating different data from different sources and with different internal structures.

As mentioned earlier, the need for the more comprehensive transportation planning process is especially driven by the ADA, CAA, and ISTEA legislations. The way each of these acts is driving the comprehensive transportation planning process and how transit agencies are concerned with each act follow:

1. *American with Disability Act (ADA)*: In short, the ADA requires the provision of adequate mobility and accessibility to all disabled people. Transit agencies are, for example, concerned with providing paratransit services to elderly and disabled people, equipping their buses with special wheel-chair lifts, ensuring that stops and shelters are accessible by disabled people, and the like. Looking at the accessibility requirement, for example, transit agencies need to have access to detailed engineering maps of the roads (that the city usually

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maintains) in order to check the condition of the sidewalks and the existence of ramps near the location of the bus stops while designing routes and locating stops. Similarly, when the city is redesigning its sidewalks, it needs to know where the transit agency is locating its stops in order to make their designs more coherent with the transit needs. The city, for example, can take the textual description of stops that the transit agency maintains, and match them with their detailed maps (using the "intersection address," the "order #," and the "location" items) to locate exactly where bus stops are and design their ramps accordingly. The standardization of spatially referenced data and tools can allow such data sharing to occur.

2. *Clean Air Act (CAA):* According to the CAA, cities are mandated to reach a certain "attainment" level of emission and pollution within different timeframes. Reducing emissions can be generally achieved by reducing the number of car trips in the whole system. The reduction of trips can be accomplished using a combination of demand management policies (such as gas taxation, HOV lane, parking pricing, etc.), land use and zoning regulations (that allow high residential densities next to employment locations, for example), and improvement to the level of service of public transport (to attract car drivers). Complicated models that can assess the impact of each of these components on trip reduction are needed. The data utilized by these models are quite varied and come from several sources. They include land use and zoning, environmental data, traffic volumes, demographic, socio-economic, transit data, etc. An integrated information infrastructure that has access to all these data is not often in place. Unless a form of standardization of spatial data is adopted, using all these information together is awkward and expensive. Obviously, for these policies to work, all concerned parties need also to

cooperate. The Transit agency can make its "foundation database" accessible to other agencies to utilize and incorporate into their models.

3. *Intermodal Surface Transportation Efficiency Act (ISTEA)*: One of the ISTEA objectives is to make the different transportation modes more coherent with each other. The Federal government realized that since each transportation mode is managed by an independent agency, low coordination between these agencies might be happening. ISTEA requires that transportation modes need to be designed in a more global fashion that optimizes the total mobility in the whole transportation system. Like the Clean Air Act, sophisticated models that require the use of data coming from different sources, including transit agencies, need also to be built. The optimization of multi-agency objectives requires the development of regional information infrastructure that can integrate different data. Transit agencies can participate effectively in the comprehensive planning efforts by providing access to their standardized textual databases that other agencies can tap into and integrate with their own databases.

In this thesis, we showed how GIS can play the role of data integrator within the transit agency. Extrapolating from this role, the standardization of spatially referenced data (that then allows easy spatial interpretation of data via GIS technologies) has the potential to become tne backbone for building the regional transportation land use system. We showed how different data representations needed by different applications or caused by the variety of data sources can be overcome and how the migration from one data representation into the other can be done using some of the GIS tools and RDBMS. Regional systems are expected to encounter similar problems but at a very magnified scale. However, the schema

for handling such complexities that we discussed in this thesis can be utilized as a framework within which solutions to the regional integrated system (that do not necessarily use the textual description of spatial objects) can be devised.

The recent developments in GIS technologies are also providing the capability of utilizing GIS as the backbone for regional information infrastructure. Integrating spatial databases that have different geographic representation and reconciling them with each other are some of the major problems facing the development of regional information system. Future conflation tools might allow the integration of such spatial data. Furthermore, the full-fledged relational database management tools that recent GISs have will allow the linkage between databases with different representations. (We have discussed this idea thoroughly in this thesis so far.)

Finally, developments in computer technologies are making the building of regional information infrastructure more feasible. The high speed processing machines are allowing the development of sophisticated models that utilize large number of data sets, to meet the new federal requirements. The building of integrated models that are mandated by the clean air act for example, requires the use of transportation models in conjunction with detailed demographic, land use, and environmental data. These models can become quite sophisticated and require a lot of processing power in order to become useful and practical for planning purposes. Furthermore, the databases used by these models are usually distributed across different agencies and the need to tap into these geographically distributed databases can now be met by the recent developments in distributed databases management tools (that we described in Chapter 2). The client server computer architectures can also support the distribution of databases and the proper management of databases distributed over a network of computers. All these

technological developments have great potentials to overcome many of the barriers that are obstructing the creation of regional information infrastructure.

8.5. Future Research

The previous discussion shows that building regional integrated transportation land use systems is a complex but potentially useful process. In this thesis we addressed the internal implementation problems within transit agencies that are obstructing the efficient use of GIS in building transit applications. We have discussed the strategies for building and maintaining GIS databases in a transit agency and how to overcome the internal problems that can jeopardize the viability of GIS inside the agency. However, in our discussion, we focused our attention on the general framework and guidelines that need to be followed. We did not go in detail into the design of the data structure for each application, rather we focused on the tools to use and the questions to ask when designing these data.

In the above discussion, we also touched upon some of the issues related to creating regional integrated transportation systems and discussed the potential of utilizing GIS for that purpose. However, the creation of a regional integrated system has major problems related to coordination among agencies. In other words, the integration of databases that are generated in different agencies into a large system or the use of distributed computing and databases architecture for that purpose, are more complex than the issues we discussed in this thesis. Future research can focus on the complexities of dealing with inter-agency data models and application development and at the inter agency data sharing and coordination efforts that are needed for building the regional integrated systems.

Future research can also examine how information technology and GIS can help transit agencies become more integrated into regional transportation planning efforts and how would that affect the transportation planning process. The impact of information technology on the transportation planning process need to be investigated given that technology is now enabling the creation of regional information infrastructures and given that GIS and IT would allow transit agencies to become active participants in the regional planning efforts and regional databases.

Finally, we envision an expanded marketing role that transit agencies can play in the future. The evolution of the transit databases along the lines we described in this thesis and the advances in information technology will enable many uses of transit routing and scheduling databases by external parties. Part of the marketing strategy of transit agencies ought to be fostering such use. Significant advertising and convenience can be generated by enabling other private sector services and other regional planning agencies to easily incorporate transit data into the services they provide. For example, the trip planning service that transit agencies provide can be offered by external parties as a service that users can do on their own. Transit agencies can facilitate this service by standardizing the way routes, stops, and other transit-specific data are represented and allowing others to integrate them into their tools. Future research can explore different ways of going down that route by looking at some of the data structures that can be most usable for others and that fit well with the development of future technologies.

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APPENDIX 1

**Questionnaire Used To Survey GIS Use By
The Largest 30 Transit Operators in the US**

COMPUTER RESOURCE LABORATORIES, MIT
Questionnaire

The purpose of this questionnaire is to investigate the use of digital data and some of the organizational arrangements relating to data sharing and data maintenance strategies at your agency. Please fill out anf return in self-addressed stamped envelope.

DEPARTMENT/ DATA	PLANNING	SCHEDULING	MARKETING	ENGIN'G	COMMENTS
1. TYPES OF DIGITAL DATA:	(Check Box if Digital Data Are Used in a Department; Use "?" if unknown.)				
Road Network					
Routes & Stop Locations					
Ridership					
Demographics					
Other (Specify) (e.g. AVL, APC)					
2. ENCODING OF ROUTES	(D for Done; U for Underway; P for Planned; NA for Not Applicable)				
Digitization (Inhouse)					
TIGER / DIME Files					
Consultant Generated					
Other Source (Specify)					
3. GIS/CAD SOFTWARE	(List the Packages Currently Used by Each Department)				
GIS					
CAD					
Other (Specify)					

DEPARTMENT/ DATA	PLANNING	SCHEDULING	MARKETING	ENGIN'G	COMMENTS
4. HARDWARE	(List Approximate Number of Machines Running GIS/CAD Software.)				
Stand-Alone PC and Mac					
Networked PC and Mac					
Standalone UNIX Workstation					
Networked UNIX Workstation					
Mainframe or Mini Terminals					
5. DO YOU SHARE DATA WITH OTHER DEPARTMENTS?	(Fill in the Matrix with the Graphical/Mapping Data that Are Shared.)				
DEPARTMENT	PLANNING	SCHEDULING	MARKETING	ENGIN'G	COMMENTS
PLANNING	■				
SCHEDULING		■			
MARKETING			■		
ENGINEERING				■	

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6. IF YOU SHARE MAPPING DATA WITH OTHER DEPARTMENTS, DO YOU HAVE ANY DATA-SHARING PROBLEMS? Specify what kind of problems are encountered e.g. different scales, different segmentation, different representation and node numbering.

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7. WHO IS RESPONSIBLE FOR BASE MAP UPDATES AND MAINTENANCE? Specify WHO does the maintenance and updating of shared mapping data and HOW (e.g., no one; IS or planning; Inter-departmental Committee; regularly vs. ad-hoc; etc).

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8. OTHER COMMENTS

APPENDIX 2

Names and Addresses of Survey Participants

ORGAN ID	AGENCY	NAME	TITLE	ADDRESS	PHONE
ACTD	AC Transit District	Lars Sandstrom	Assistant Transport planner	1600 Franklin St., 7th Floor, Oakland CA. 94612	510-891-7132
BART	Bay Area Rapid Transit District (BART)	Tom Spiekerman	Planner	800 Madison St., LMA-4, Oakland, CA 94607	510-464-6149
BSDA	Bi-State Development Agency	David Beal	Planner	707 N. 1st St., St. Louis, MO 63102	314-982-1400 ext. 1808
COTA	Central Ohio Transit Authority (COTA)	Craig D. Bloom	Senior Service Analyst	1600 Mc Kinley Av., Colombus OH. 43222	614-275-5837
CTA	Chicago Transit Authority	Ross Patronsky	Manager, Data Services	Merchandise Mart Plaza, Chicago, Illinois 60654	312-664-7200 ext. 4048
DART	Dallas Area Rapid Transit	B. Claybrook A. Gorman	GIS Apps. Manager GIS DBA	P.O.Box 660163, Dallas, TX 75266-7243	214-749-3020 214-749-3059
DDOT	Detroit Department of Transportation	Donald Ray Smith	Socio economic planner	1301 E.Warren Detroit, MI 48207	313-833-1196
KCATA	Kansas City Area Transportation Authority	Donna J. Brown	Planning Manager	1200 E. 18th St Kansas City, MO 64108	816-346-0311
LACMTA	Los Angeles County Metro Transport Authority	Paul Burke	Planner	County Wide Planning MTA P.O.Box 194, L.A, CA 90053	213-244-7090
MCTS	Milwaukee County Transit System	Greta Gneiser	Director, MIS	1942 N. 17th St. Milwaukee, WI 53205	414-937-3284
METRA	Metra Commuter Rail	Claire Bozic	Senior System Planner	547 W. Jackson Chicago, IL 60661	312-322-8035
MMTA	Maryland Mass Transit Administration	Stuart Sirota	GIS Coordinator	300 W. Lexington St., Baltimore, MD 21201-3415	410-333-3381

ORGAN ID	AGENCY	NAME	TITLE	ADDRESS	PHONE
MTAHC	Metropolitan Transit Authority of Harris County	Imad Ismail	Senior Transport. Planner	1201 Louisiana POBox 61429, Houston Texas 77208-1429	713-739-3724
NJT	New Jersey Transit	Louis Millan	GIS Project Manager	1 Penn Plaza East, Newark, NJ 07105	201-491-7749
NYCTA	New York City Transit Authority	James Barry	Manager	130 Liningston Street, Room 7041, Brooklyn NY 11201	718-694-3355
RT	Sacramento Regional Transit (RT)	Joseph Costa	Senior Planner	P.O.Box 2110, Sacramento, CA 95812	916-321-2868
RTA	Regional Transportation Authority	Supin Yoder	Senior Analyst	181 W Madison St., Suite 1900, Chicago, IL 60602	312-917-0761
RTD	Regional Transportation District	Dave Shelley	Senior Planner	1600 Blake Street, Denver, CO 80202	303-299-2408
SEPTA	Southeastern Pennsylvania Transport. Auth. SEPTA	Jerry Kane	Senior Operations Planner	841 Chestnut St., Philadelphia, PA. 19107	215-580-7151
SMART	Suburban Mobility Authority for Regional Transport	Andrew Thorner	Planner III	660 Woodward, Suite 950, Detroit, MI 48226	313-223-2357
SORTA	Southwest Ohio Regional Transit Authority	Ted Meyer Carl Waldbillig	Mang. of Plan. & Schedl.	1014 Vine Street, Cincinati, OH 45202	513-632-7547 513-632-7630
TRIMET	TRI-County Metropolitan Transportation District of Oregon	Dennis Schutt	Manager Scheduling System	4012 SE 17th Avenue, Portland Oregon 97202	503-238-5831
WMATA	Washington Metro Area Transit Authority	Lamin Jeng	Planning Analyst	WMATA, Rm. 7D-10, 600 5th St. NW, Washington DC. 20001	202-962-1265

APPENDIX 3

**The "Period Route Segment" Ridership Forecast Model
Formulations of the Model**

The following are the formulations of the model for each period:

$$BOARD_i^d = PROD_i * OPP_i^d * LOS_i^d$$

where:

$BOARD_i^d$ is the boarding on segment i in direction d;

$PROD_i$ is the trip production factor in area around segment i;

OPP_i^d is the opportunity factor in direction d from zone i;

LOS_i^d quality of service in segment i in direction d.

A.M Peak:

$$PROD_i = 0.015\ DIST_i\ [(\ (AFAC_i)\ (ADULT_i) + 0.339\ XRIDER_i\ ) / DIST_i]^{0.813}$$

$$OPP_i^d = [\ EMPLOP_i^d + 0.75\ POPOP_i^d\ ]^{0.296}$$

$$EMPLOP_i^d = \frac{(\ ORIGBD_i * EMPL_{6-35}^d + 0.339\ XRIDER_i * EMPL_{3-15}^d\ )}{ORIGBD_i + 0.339\ XRIDER_i}$$

$$POPOP_i^d = \frac{(\ ORIGBD_i * POP_{6-35}^d + 0.339\ XRIDER_i * POP_{3-15}^d\ )}{ORIGBD_i + 0.339\ XRIDER_i}$$

$$ORIGBD_i = AFAC_i * ADULT_i$$

$$LOS_i^d = WTFAC_i^d * CTFAC_i^d$$

Midday:

$$PROD_i = 0.0079 DIST_i\ [(AFAC_i * POP_i + 0.339 XRIDER_i + 0.144 EMPL_i) / DIST_i]^{0.813}$$

$$OPP_i^d = [\ 0.21\ EMPLOP_i^d + POPOP_i^d\ ]^{0.277}$$

$$EMPLOP_i^d = \frac{(\ ORIGBD_i * EMPL_{6-35}^d + 0.339\ XRIDER_i * EMPL_{3-15}^d\ )}{ORIGBD_i + 0.339\ XRIDER_i}$$

$$POPOP_i^d = \frac{(\ ORIGBD_i * POP_{6-35}^d + 0.339\ XRIDER_i * POP_{3-15}^d\ )}{ORIGBD_i + 0.339\ XRIDER_i}$$

$$ORIGBD_i = AFAC_i * POP_i + .144\ EMPL_i$$

$$LOS_i^d = WTFAC_i^d$$

where :

$DIST_i$ is the length of segment i;

$AFAC_i$ is an income adjustment factor in zone i;

$ADULT_i$ is the adult population in zones around segment i;

POP_i is the total population in zones around segment i;

$EMPL_i$ is the number of employments in zones around segment i;

$XRIDER_i$ is the riders on routes that cross or feed into segment i;

$EMPLOP_i^d$ is the employment opportunity in zone i in direction d;

$POPOP_i^d$ is the population opportunity in zone i in direction d;

$ORIGBD_i$ is an originating boarding term for zone i;

$EMPL^d_{6\text{-}35}$ is the employment within a quarter mile of the route in direction d between 6 and 35 minutes of bus ride time from segment i;

$EMPL^d_{3\text{-}15}$ is the employment within a quarter mile of the route in direction d between 3 and 15 minutes of bus ride time from segment i;

$POP^d_{6\text{-}35}$ is the population within a quarter mile of the route in direction d between 6 and 35 minutes of bus ride time from segment i;

$POP^d_{3\text{-}15}$ is the population within a quarter mile of the route in direction d between 3 and 15 minutes of bus ride time from segment i;

$WTFAC_i^d$ is a wait time factor in segment i based on service frequency in direction d;

$CTFAC_i^d$ is a seat availability factor in segment i in direction d.