GIS-Based Support System for On-Demand Flexroute Transit Service

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Abstract

Geographic Information Systems (GIS) are a proven resource for public transportation service planning and evaluation. In particular, their spatial analysis and database management capabilities make them well suited for such applications. The primary cost incurred in a GIS application is for the development and maintenance of high-quality spatial databases. Due to this cost, public transportation agencies want to utilize these databases to support a wider array of applications. As desktop GIS software and computer hardware become more powerful, GIS can be used to develop applications for "real-time" operations. In this research effort, a GIS-based prototype system was developed and tested to support the scheduling and dispatch functions of an on-demand flexroute transit service. The effectiveness of the prototype demonstrates the potential of GIS to support time-critical transit operations.

Introduction

GIS has proven to be a valuable resource for public transportation agencies. These agencies have applied GIS to a number of challenges, ranging from data management to service design. Although GIS provides numerous benefits, they are not realized without costs. Public transportation agencies have made significant investments in establishing and maintaining the spatial databases required by GIS. There is a great desire to take advantage of these investments in as many applications as possible.

In the past, GIS has been used almost exclusively for "off-line" planning and analysis applications in public transportation. However, recent advances in computer hardware and GIS software have now made the use of GIS in real-time operations feasible. Such applications may enable public transportation agencies to meet their goals of enhancing transportation services and capitalizing on spatial database investment.

Although real-time transit applications of GIS are conceptually feasible, there have been no rigorous analyses of such potential applications. In this research effort, the concept of using GIS to support the real-time analysis and data management needs of flexroute transit was examined by developing a prototype GIS-based scheduling and dispatching support tool. Flexroute transit, also referred to as "route deviation transit," is a hybrid of fixed-route transit and paratransit. In a flexroute system, fixed-route service is provided at a limited number of fixed stops, and slack time is built into the schedule between these stops to allow buses to pick up and drop off passengers on an on-demand basis. Scheduling trips for on-demand customers and dispatching vehicles to on-demand locations require sophisticated spatial analysis and substantial data management. Based on the positive results of the research, it is likely that GIS will play a key role in meeting real-time public transportation operations needs.

State of the Practice: GIS and Public Transportation

Public transportation providers have used GIS for nearly a decade. The main impetus for transit agencies to use GIS is to allow for the integration of data from a variety of sources to perform a number of planning analyses that were traditionally completed manually and were quite time consuming. GIS has allowed transit agencies to store, manage, display, manipulate, and analyze their spatial and attribute data efficiently. The power of GIS lies in its analytical capabilities that simultaneously consider spatial and attribute information. Today's desktop GIS software allows users to perform routine spatial analyses, and use complex relational database management concepts to address elaborate planning problems using standard personal computing hardware.

Traditionally, transit agencies have used GIS to statically (offline) manage real estate assets and perform traditional transit analyses such as ridership forecasts, service route planning, and demographic analyses (Schweiger 1991). Today, these traditional uses remain the foundation of most transit agencies' GIS efforts, and to a large extent, dictate the data needs of the agency.

The management of public transportation real estate within a GIS normally includes both fixed assets and land management. To demonstrate the size and scope of databases required for these activities, consider the management of fixed assets. The fixed assets for a transit agency include items such as the location, inventory, and condition of transit stations; fixed bus stops; bus stop signage; and even storage yards. Each of these features possesses a host of descriptive attributes. With fixed bus stops, for example, a GIS database stores, for each stop, its physical location (latitude and longitude), its position along the route, whether it is a transfer facility, if it has a shelter, if it has a bench, and the number of embarking and disembarking riders.

A recent survey conducted by the *Urban Transportation Monitor* revealed that a primary GIS application in public transportation is to support core transit planning analyses (1999). These analyses, which include ridership forecasting, service route planning, and demographic analyses, are fundamental planning practices of any transit agency. Although actual processes associated with each of these analyses have not changed dramatically with the introduction of GIS, the ability of the transit agency to perform a more in-depth, exhaustive analysis has greatly improved. That is, more frequent updates of data are available, the amount of data has increased, and a number of data sources/data types are now available that allow for nontraditional "what-if" analyses to be performed.

Investments Required

The implementation of a GIS for any size transit agency is complex and time consuming. The GIS is composed of essentially three components: hardware, software, and data. The hardware and software required can be obtained relatively quickly and, with few exceptions, can be used for multiple applications. The data, however, are often dependent on the specific application. It is the acquisition of data that is one of the most important and expensive steps in effectively applying GIS.

Estimates of the costs associated with the development of GIS databases that will perform off-line analyses range from 50 percent to 80 percent of the total cost of GIS implementation (Huxhold and Levinshohn 1995; Opiela 1993). Although these estimates include database design and maintenance, the acquisition of data comprises the largest portion of these costs. What is clear, especially when the survey results of the *Urban Transportation Monitor* are considered, is that transit agencies view their investment in GIS data as significant, and they feel this investment must be capitalized on as much as possible (1999).

Most of the operations processes required of a public transportation agency rely on the management and analysis of spatial and attribute data. For example, when monitoring the status of a bus fleet, a transit agency needs to know the locations of vehicles and their attribute characteristics. Further, when vehicles are determined to be behind schedule, network analysis is required to determine the best approach to rectifying the problem. Most of these functions, as well as the data required to support them, are available in modern desktop GIS packages and existing transit spatial databases. In the past, these tools have not been used to provide this functionality due to the immaturity of GIS software and the relatively slow processing speed of moderately priced computers. This forced many agencies to purchase proprietary, specialized software that required data in formats that were often incompatible with standard GIS packages. To capitalize on GIS investments, and to avoid compiling similar spatial databases in different, incompatible formats, many feel that the time has come for operational applications of GIS in transit. This article details a prototype system of this type.

Prototype GIS-Based System

Although the use of GIS to support real-time public transportation operations is conceptually feasible, it is well known that the complexity of an application is not fully understood until it is developed. To explore real-time GIS applications fully, this research effort focused on developing a prototype GIS-based support system for flexroute transit. Such a system must meet strict real-time requirements to support flexroute operations effectively and, therefore, provides an excellent test case for this effort. A full description of flexroute transit and a discussion of its challenges are presented below.

To provide further context for the research effort, the flexroute support system was designed and developed in cooperation with the Peninsula Transportation District Commission (Pentran), the public transportation provider in the Hampton/Newport News area of southeast Virginia. Pentran officials guided the development of the system to support flexroute service along two of its existing fixed routes that serve relatively low-density, suburban areas. Pentran believes this area holds high potential to support flexroute service, and is currently working to obtain funding to purchase the necessary equipment to implement the service on a trial basis.

An important aspect of working jointly with Pentran was that it allowed the development of the flexroute support system to be driven by functional requirements. A major change in the GIS application process required by real-time systems is to shift from an "experimental" approach to a software development approach. Off-line analysis applications typically require that an expert analyst work directly with the GIS in an experimental fashion attempting to derive information from the data through a series of queries and analytical processes. This approach is driven by the quest to derive information to support decision-making. Alternatively, real-time applications of GIS must be approached in a software development manner. The application is being developed to support a mission-critical operation. A rigorous set of software development techniques has evolved in the software engineering community to support the growth of applications that satisfy mission-critical requirements. These approaches, whether the classic waterfall or the newer rapid prototyping approaches, are based on a sound, thorough elicitation of the application's requirements (Eisner 1998). Pentran's involvement in this research allowed the team to develop the prototype application based on a full set of requirements.

The GIS software chosen as the foundation for this effort is ESRI's ArcView. ArcView was chosen for the following key reasons:

- It is an off-the-shelf package that is readily available.
- It can be customized through its internal programming language, Avenue.
- ESRI is an industry leader, and its spatial data format, the Shapefile, is publicly available. This ensures that the data required can be imported/exported from this application to other GIS applications.

Flexroute Transit

Flexroute service can be defined as "a service where the transit vehicle stops at fixed locations on predetermined schedules while also providing on-demand service to customers off the standard route between the fixed stops." As seen in Figure 1, the underlying network structure for flexroute service is different than that of fixed-route and paratransit services. The primary objective in designing a fixed-route service is to locate the fixed stops within a 0.25-mile walking distance of the surrounding population (Gray and Hoel 1992), whereas a flexroute service must be designed with the objectives of (1) serv-

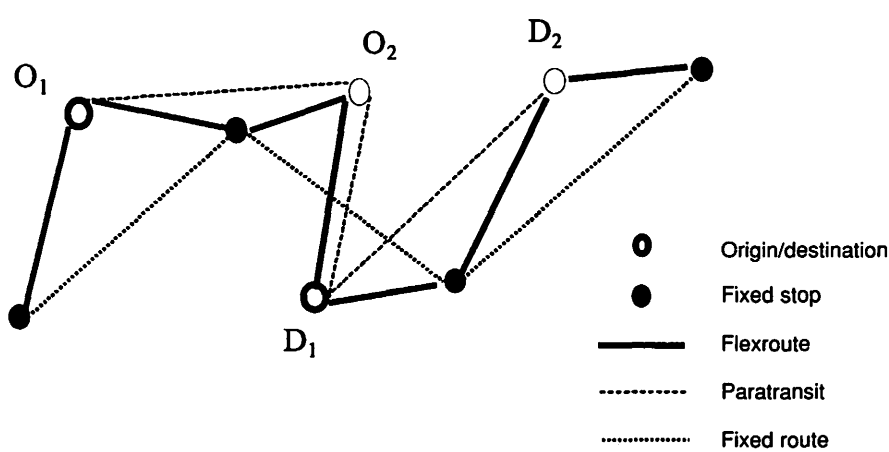

Figure 1. Flexroute, dial-a-ride, and fixed-route services

ing high-ridership fixed stops and (2) building the necessary slack time in the schedule to allow for deviated, on-demand pickups and deliveries. As in fixed-route service, the bus makes mandatory stops at the fixed stops and adheres to the constraint of arriving on schedule at these stops.

A service zone in a flexroute service is defined as the region between two consecutive fixed stops. The service zone defines how far away from the standard route a vehicle may deviate to pick up or drop off a passenger (i.e., the maximum deviation distance). It does not imply that everyone within the zone is guaranteed a deviated trip. At times, other committed rides will force a requested trip from within a service zone to be denied.

Two directions of travel are defined between the end points of the routes: inbound and outbound. These directions are global, and the definitions hold for all routes in a flexroute system. The bus is said to be traveling in the inbound direction if it is traveling in a general direction that is going toward the downtown area of the city, and the reverse is true for the outbound direction. For this study, the total end-to-end travel time for a route was one hour, along with one-hour headways at each stop in each direction of the route. This design choice was dictated by a desire to maintain consistency with the rest of Pentran's fixed-route service.

The total end-to-end time includes slack time for deviation. A run or a pass of a bus is defined as "continuous travel of the bus from one end of the route to the other in one direction." Thus, in a time span of one hour, the bus on a route would have made one pass in one direction. This is an important definition specific to this problem and serves as a method to track customer pickups and deliveries for a given time period.

The scheduling and dispatching of a flexroute service in a real-time urban environment require certain essential system components (Round and Cervero 1996). First, there must be an automatic vehicle location (AVL) system so that a dispatcher has access to instantaneous information about the location of the vehicles in the system. Second, a spatial database is required to locate enroute vehicles on a map of the service area, store system-specific information, and view the street network. Third, there must be a communication system that can send information between the vehicles and the transit control center. Finally, a support system that is specifically designed for flexroute service is needed to process the real-time inputs from the subsystems, along with managing customer requests for service.

There are significant institutional, political, and technical issues to resolve before flexroute service will serve as a viable public transportation alternative. For example, it is unlikely that on-demand flexroute service can be provided on narrow residential streets using the current standard, 40-foot transit vehicles. These issues are real and substantive. However, they are of little significance if flexroute service is not feasible from a scheduling and dispatching perspective. Therefore, this research focuses on the challenge of flexroute scheduling and dispatch. Future efforts are required to investigate the equipment considerations involved in the implementation of flexroute transit.

Flexroute Scheduling and Dispatching Problem Decomposition

The routing and scheduling of a flexroute request in real time is a difficult task because of the combined characteristics of fixed-route and demand-responsive service. For instance, when a request for deviation is received, three important attributes must be determined before proceeding with the scheduling process:

1. The *direction* of travel for the trip request to determine the appropriate fixed-route vehicle for trip assignment. This is required because of the fixed-route component of flexroute service.
2. The *spatial* location of the pickup and delivery point relative to the fixed stops and the service area for flexroute.
3. The traveler's *temporal* requirements of the pickup and delivery points relative to the scheduled times of the fixed stops.

This spatio-temporal nature of flexroute service renders it different from the general paratransit scheduling problem. To solve it efficiently, the overall problem was decomposed into several subproblems. This was done by taking advantage of the unique service characteristics of the flexroute problem. Unlike paratransit services, the scheduled fixed stops in the route deviation service provide spatial and temporal anchor points on the route traversed by the transit vehicle. The transit vehicle must visit the fixed stops at the scheduled times amid picking up and dropping off on-demand riders.

In addition, on-demand service is provided only in the region between two successive fixed stops. This implies that each on-demand (as opposed to fixed-stop) pickup or delivery is restricted to the region between the fixed stops. This relationship between pickup and delivery points and service areas was used in the scheduling process. Further, each service zone on each route and direction is distinguished by a unique identification. The spatial and temporal location of the pickup and delivery points for a given trip request can be identified by determining the service zone it falls in. The functional steps involved in scheduling a flexroute trip are described below.

Locate the Pickup and Dropoff Point

Upon receipt of a call requesting flexroute service, the geographic location of the passenger's pickup and dropoff point relative to the service area must be determined. The spatial location should be identified given the street addresses of the two points.

Find the Global Direction of Travel

To assign the customer to a particular bus, first the global direction of travel for the request must be determined. This can be done by defining a fixed reference axis for the entire network. The reference axis is arbitrarily defined so that the axis passes through an origin point so that the entire service area falls in one quadrant (see Figure 2). The angles Θ and ϕ are defined as:

$\Theta =$ The angle between the reference axis and the line joining the pickup point and the origin of the axis.

$\phi =$ The angle between the reference axis and the line joining the delivery point and the origin of the axis.

Figure 2 clearly illustrates how the angles for the origin and destination (O-D) will be determined. The customer's global direction of travel can be determined from the following:

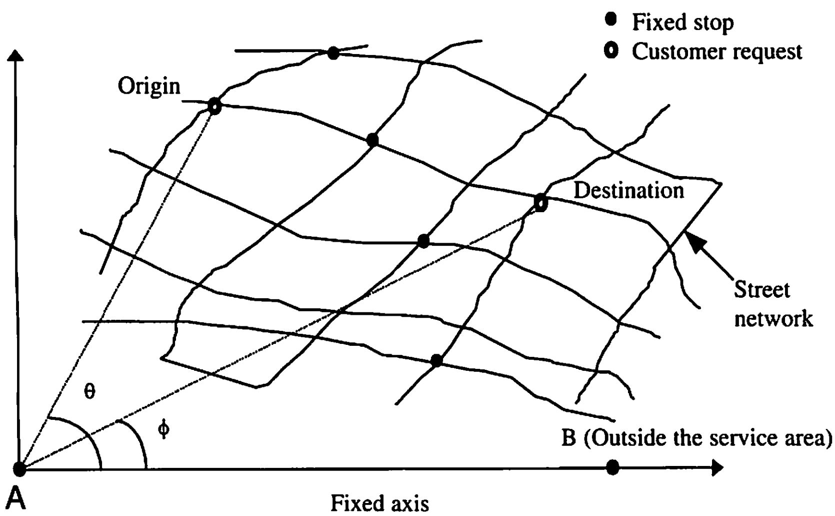

Figure 2. Finding the global direction of travel

$$\text{Direction} = \begin{cases} \text{Inbound, if } \theta \geq \phi \\ \text{Outbound, if } \theta \leq \phi \end{cases}$$

To determine the angles, it is necessary to know the coordinates of the origin (x^o, y^o) and the destination (x^d, y^d) points. The reference axis is a line passing between an arbitrary point A and another point B that is on the outer limit of the service area. Point A will be assigned such that $y_A = y_B$ and $x_A \neq x_B$. The value of the angles can then be calculated by:

$$\theta = \tan^{-1}\left(\frac{y_a - y_A}{x_a - x_A}\right) \text{ and } \phi = \tan^{-1}\left(\frac{y_d - y_A}{x_d - x_A}\right)$$

Identify Eligibility for Service

Once the spatial locations of the pickup and delivery points are found, the next step is to see if the passenger is eligible for flexroute service. The following criteria were used to determine eligibility for service:

1. The pickup and delivery points of a request should lie entirely within the designated service zones of a flexroute service.
2. Both the pickup and delivery points should not be within 0.25 mile of a fixed stop.

In other words, the proximity of the pickup and delivery points to the service zones and fixed stops must be determined to identify a passenger's eligibility for service.

Store a List of Previously Committed Rides

One of the important inputs to the scheduling process is the information on previously committed ride requests for a given service zone and pass of the bus. Therefore, information on the estimated time of pickup and delivery and their spatial locations must be stored for each previously committed ride for each service zone and bus pass combination. This information is needed to determine the feasibility of accepting the new ride request.

Solve the Network Problem

From the previous steps, important information about the spatial and temporal location of the request's pickup and delivery point is known. The problem now distills to determining whether a customer can be picked up and dropped off within the respective service zones without violating the time constraints at the fixed stops on either end of a zone as well as the time window constraints of previously committed riders in that zone. The answer to this problem can be obtained by finding the shortest path starting from one fixed stop, traversing through the intermediate pickup/dropoff points in that zone (including prescheduled and the current request under consideration), and ending at the subsequent fixed stop.

Prototype GIS-Based Scheduling and Dispatch System

To investigate the feasibility of using GIS as a foundation to meet the flexroute scheduling and dispatch requirements described above, a prototype GIS-based system was developed for the two Pentran routes. A description of how the capabilities of GIS were used to meet the requirements outlined in the previous section is provided below.

Address Geocoding

The address geocoding capabilities of GIS were used to meet the first requirement of determining the spatial location of the pickup and dropoff points for a trip request. Most desktop GIS software, such as ArcView, includes full geocoding capabilities. A street address is geocoded within a GIS by querying the table of street names with address ranges and using a scoring system to determine if a match has been found. This table is the attribute table for the street network layer. Once a match is found, the latitude/longitude coordinates of that street segment are assigned to the point and it is plotted on the map. The latitude/longitude coordinates of points within a GIS provided a convenient preexisting system for determining the angles θ and ϕ in the second requirement for finding the global direction of travel. The reference axis was created as a line feature on the map.

Analysis of Spatial Relations

Complex spatial relation analyses can be performed using most standard, off-the-shelf GIS software. For instance, in a spatial relation analysis, the user can select point features in one layer that are at a certain distance from the line features in another layer. This functionality, usually referred to as "buffering," allows GIS to assist in proximity analyses needed in applications such as flexroute scheduling and dispatching.

In this study, the developers created the individual service zones associated with each pair of consecutive fixed stops along each route as polygon features and stored them as a separate layer. Two such layers were created for each direction of travel. This was achieved by using the buffer feature of a standard GIS software, such as ArcView. A unique pair of fixed stops, the fixed route it belongs to, and the direction of travel identified each zone or polygon. The service zones in which the O-D fell were determined by performing an "overlay" selection on the point layer containing the O-D locations and the polygon layer with the service zones. Based on the selection, the system can immediately find the nearest pair of fixed stops for the O-D points of a request, depending on the polygon they fall within. In this step, the system also determines if there is a transfer involved in the trip by checking if the origin bus route and the destination bus route are the same.

Similarly, layers with point features were created to store the information describing previously committed rides for each zone, direction, route, pass, and day of the week, for the past one week. The nomenclature used to name each of these point layers was:

<Day>_<Time>_<Route>_<Direction>_<Segment-ID>

For example, the point layer with the name "MON_1500_11_IN_12" contains the scheduled requests for the most recent Monday, for the 3 P.M. pass on Route 11 in the inbound direction on zone 12. The attribute tables of these layers contain the information on the scheduled time of arrival or departure for each prescheduled on-demand stop. This information was used in the next step to check for violation of time windows. For each request, point layers for the O-D zones are obtained and passed on as inputs to the next step.

The layer chosen depends on the particular pass on the route in question. The pass is selected based on the passenger's preferred pickup or arrival times. In some cases, it may be necessary to analyze more than one pass to identify the itinerary that best suits the passenger's needs.

Network Analysis

Most desktop GIS software packages have basic network analysis capabilities, such as solving the shortest path between a set of points. For this research, the Network Analyst extension of ArcView was used to solve the shortest-path problem. Network Analyst can solve the following cases:

1. Find the shortest path given a set of points in the given order.
2. Find the shortest path through a set of points in the given order and returning to the origin.
3. Find the shortest path through a set of points by finding the best order of

traversal and also returning to the origin. This option is similar to the traveling salesman problem. The best order is found exhaustively by computing the shortest path from each point to every other point.

Unfortunately, the shortest-path problem formulation required for this application does not fit one of these three categories. In this case, the path between two fixed stops and the intermediate on-demand stops could be addressed as a shortest-path problem with time window (SPPTW) constraints (due to the nature of the fixed stops). To implement this form of network search in ArcView, some modifications were made using the scripting language Avenue. The checks for the fixed-stop schedule violations and the time window constraints violations were performed by querying the attribute table of the resulting spatial layers created by the Network Analyst. Time window violations were checked only for the prescheduled requests for which the estimated pickup time (EPT) or estimated delivery time (EDT) were present. No time window checks were needed for the current pickup or delivery location. The total path cost found by the shortest path was then compared with the schedule of the fixed stop at the end of the segment to check for violation of schedule constraints. If no constraints are violated, then the trip is considered feasible and the order of traversal is stored. Here, the cost or time of arrival at the current location is noted and is then fixed as the EPT or EDT for the current location. The time window violation test used was:

EPT - 5 (minutes) ≤ (the new computed cost) ≤ EPT + 5 (minutes), or
EDT - 5 (minutes) ≤ (the new computed cost) ≤ EDT + 5 (minutes)

Apart from the spatial layer showing the final path and the best order and cost of traversal of the points, the Network Analyst also stores and displays directions for the path. The results from this final step can be divided into four possible scenarios: (1) both the pickup and delivery of the request are feasible, (2) only the pickup is feasible, (3) only the delivery is feasible, and (4) both the pickup and delivery are not feasible. A request is considered "feasible" and is entered into the table of requests only for case (1).

It is likely that as a flexroute transit service gains in popularity, the large number of committed rides will increase the difficulty of meeting both pickup and delivery requests while maintaining the schedule at fixed stops. In this event, the system provider may choose to modify the service to provide more slack time between fixed stops (to accommodate more deviations) or to decrease the headway between bus passes (to reduce the number of deviations per pass).

System Performance

The prototype system performed very well. On average, an operator could schedule a request for flexroute service within four minutes using a Pentium-class personal computer. This time includes the customer interaction time required for the task (such as the time spent waiting for the customer to state his or her origin and destination). This meets the real-time requirements for such a service. It also demonstrates that desktop GIS software and "standard" desktop hardware are capable of supporting the complex spatial analyses and database management required for sophisticated real-time transit applications. Furthermore, the data used to support the application were derived from readily available spatial data currently used by transit agencies. This demonstrates the ability to realize a greater return on a transit agency's investments in spatial databases.

Conclusions

The prototype GIS-based support system reported here can be used as the foundation for developing full-fledged flexroute scheduling and dispatch software. Further, the results of this study demonstrate the applicability of GIS software for developing a customized decision-support system for real-time transit operations. The findings also demonstrate the capabilities of the GIS software in handling complex spatial and network analyses. With desktop GIS software becoming more and more powerful and easier to use, there are many advantages to storing and managing all of a transit agency's spatial and attribute data within a GIS database. Such a system could be used to support transit operations and conventional planning simultaneously, potentially eliminating the need to invest in separate, proprietary scheduling software. In addition, with both the scheduling and planning systems in one place, any updates to the database can be made efficiently.

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