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Evaluating the Impact of ITS on Personalized Public Transit

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Evaluating the Impact of ITS on Personalized Public Transit

Final Project Report

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ABSTRACT

The focus of this project is to study alternative system architectures and ITS technologies that can improve the efficiency of personalized public transit and demand responsive systems such as paratransit. This report reviews available and emerging ITS technologies that have been deployed or are being considered for this industry. We also conducted a survey of commercially available computer aided dispatching software. We list the numerous features offered by these software packages. Also, included in this report is a statistical analysis of travel patterns of a paratransit provider in Los Angeles County. This data analysis forms the basis for our testbed in the second phase of the project. The second phase compares the performance of a strictly curb-to-curb system with a hybrid system that is a mixture of curb-to-curb and fixed route. On nine days worth of data, the analysis showed that shifting some of the demand to a hybrid service route (18.6% of the requests) reduces the on-demand vehicle distance by 16.6% and the overall customer trip time by 8.7% over their current approach.

EXECUTIVE SUMMARY

The passage of the American with Disabilities Act (ADA) has created renewed interest in Demand Responsive Transit (DRT) Services. At the same time, the introduction of Intelligent Transportation Systems (ITS) such as dispatching and scheduling software, automatic vehicle location (AVL) devices, mobile data terminal (MDT), etc. has made such systems less complex to operate because of the automatic processing of information. This advancement in technology, which is recognized by transit providers, has caused many vendors to develop specialized software and other equipment to support management of paratransit and demand responsive service. This report summarizes the work of the project entitled "Evaluating the Impact of ITS on Personalized Public Transit". The objective of this research is to investigate the use of ITS technologies to improve the service efficiency of DRT providers and to evaluate the different opportunities it creates to improve the overall performance of DRT systems.

We reviewed different technologies that have been implemented or are being considered for implementation by the transit providers. Technologies that have been implemented include AVL, advanced wireless communication, MDT, computerized vehicle navigation, and geographic database. Emerging technologies that have potential for implementation include internet dispatching, superphones, personal data assistants, and smartmaps.

It is anticipated that the responsiveness and costs of demand responsive transit may be improved by utilizing these ITS technologies. For example, real-time control and decision-making technologies may be applied to improve the quality of transit service and to facilitate intermodality. In most cases specialized software can facilitate this task. As part of the research efforts, we conducted a review of the commercial software in order to record their functionality. We identified twenty vendors who distribute potential commercial software that have the potential to support the paratransit industry. Of these vendors, three firms completed the survey that we administered. The other firms stated that they did not believe their software package was suitable for the industry, they did not currently support the product, or the company no longer exists or changed their address. Our review shows that most of the software has the capabilities to automate reservation,

scheduling, billing and maintenance. The intent of this review was not to make a recommendation of any particular software. The purpose was to list the features of the available software and to identify if they have capabilities to support real-time scheduling and reservation of DRT service within the paratransit industry. We note that this industry is changing very rapidly due to changes in the marketplace. There has been numerous mergers leading to decreasing number of software packages specifically addressing the paratransit market while their capabilities are continuously increasing. Most of the packages have built-in interfaces to accommodate AVL devices, global positioning systems (GPS), and MDT.

In order to document how public agencies are adopting the software and technology, we conducted an in-depth phone interview with OUTREACH, Inc. who is the paratransit provider for the Santa Clara Valley Transportation Authority. Also, we conducted a site visit at Antelope Valley Transit Authority. We met with representatives of the agency as well as the contractor that provides paratransit service for the region, Laidlaw. Antelope Valley was selected based on suggestions from Access Services personnel who felt that this region was where it might be beneficial to use a hybrid fixed route and curb-to-curb system. The travel distances in Antelope Valley are large enough to justify a transfer point between the two different types of transit services. Furthermore, most of the disabled and elderly passengers travel to a central location where most of the hospitals are located. Finally, AVTA is a small to mid-size agency so that there is opportunity for effective communication between their fixed route and paratransit services. AVTA provided data of their operations including pickup time, travel distances, fleet size, etc. This data was used to form statistical distributions of representative paratransit operations.

In the next phase of the research, we concentrated on studying alternative system designs. In particular, we compared a strictly curb-to-curb system with a hybrid curb-to-curb and fixed route system. Clearly, a curb-to-curb system as opposed to a hybrid system minimizes the travel time for the passenger. However, shifting some of the demand to fixed routes may alleviate some of the demand pressures caused by ADA requirements. The fundamental question that is addressed in this phase of the research is whether transferring passengers to fixed routes will result in significant reduction in

service level. The alternative configurations were tested using nine days of data from AVTA. The analysis showed that shifting some of the demand to a hybrid service route (18.6% of the requests) reduces the on-demand vehicle distance by 16.6% and the overall customer trip time by 8.7% over their current approach.

1.0 Introduction

The growth of personalized public transit and demand responsive transit (DRT) began in the late 1970s and early 1980s with large demonstration projects developed in Rochester, NY and Santa Clara County, CA among others. These early systems failed to meet expectations due to low demand requests and deficiency in communication and computer technology to effectively manage such systems (Lave, Teal, and Piras, 1996). However, with the passage of the Americans with Disabilities Act (ADA), which requires that transit agencies provide paratransit or on demand service for the disabled, there has been renewed interest in demand responsive transit. The passage of ADA has increased the obligations of the transit providers to adhere to strict service standards. In addition the demand of these of type transit services is also likely to continue increasing rapidly (Levine, 1997). For example, as reported in the June 24, 1993 issue of the *Wall Street Journal*, the paratransit market was a $500 million industry. Today, it is around a $1 billion industry. In Los Angeles County alone more than 5000 vans and 4200 cabs provide service, generating 8 million trips per year.

Due to the lack of advanced communication and tracking technologies, the early systems tended to operate as advanced reservation systems with some service providers requiring users to place a reservation at least one day in advance of their travel. As reported in the Transit Cooperative Research Program Report #18 (Lave, Teal, and Piras, 1996), this mode of operation has been associated with much lower service productivity. Despite these problems, they are commonplace because they ration capacity easily and are much less complex to implement than on-line real-time reservation systems. However, with the introduction of Intelligent Transportation Technologies (ITS) such as mobile data terminals (MDTs), automatic vehicle location (AVL) devices , and geographic information system (GIS), a real-time system becomes less complex to operate due to the automation of information processing. The increase in demand and the need to provide a high quality of service has forced this industry to consider adopting these technologies as well as studying alternative transit delivery methods. Examples of the introduction of some of these information technologies include:

- Vehicle tracking, such as GPS, which allows to locate vehicles within 3-meter accuracy

- Wireless communication, via satellite, cellular and paging networks, which enable 2-way communication with mobile fleets
- Navigable map databases, from which point-to-point distances can be calculated
- Real-time information services, which allow for dynamic calculation of travel speeds

It is anticipated that the responsiveness and costs of personalized public transit and demand responsive transit may be improved by utilizing certain ITS technologies. For example, real-time control and decision-making technologies may be applied to improve the quality of transit service and to facilitate intermodality. In most cases, specialized software such as Computer Aided Dispatching (CAD) software can facilitate this task.

The first phase of this research focused on completing the following tasks:

- reviewed and identified technologies that are currently being implemented and emerging technologies that have the potential to improve system performance,
- surveyed commercial scheduling and dispatching software in order to record their functionality,
- conducted in-depth phone interviews and held site visits at transit agencies in order to document how public agencies are adopting the software,
- and statistically analyzed travel pattern data from Antelope Valley Transit Authority (AVTA), a representative paratransit provider in Los Angeles County.

The second phase of the research, concentrated on studying alternative system designs. In particular, we compared a strictly curb-to-curb system with a hybrid curb-to-curb and fixed route system. The alternative configurations were tested using the analyzed data provided by AVTA. The performance metrics that will be studied include:

- *productivity* - This metric is often measured as the number of riders per trip. By increasing productivity, transit service providers can decrease their direct costs (e.g., gasoline, labor) and capital costs (e.g., fleet size). In Los Angeles County, the average number of riders per trip is around 1.1. Ridesharing in demand responsive transit is low because schedulers mostly dispatch vehicles in a manner similar to taxis. Access Services Inc. (ASI), the agency responsible for coordinating paratransit service within

Los Angles County, believes that through improved vehicle scheduling, there is a potential in Los Angeles County to increase this metric to at least 1.8.

- *on-time performance* - This metric is measured as the percentage of times a vehicle picks-up a passenger within the scheduled arrival time window. In this research, on-time performance is treated as a hard constraint that must be satisfied regardless of the delivery method.
- *travel time* - Clearly, curb-to-curb systems minimize travel time over a hybrid system. However, it may be possible to shift some of the demand to accessible fixed route lines without significantly increasing passenger travel times, thereby alleviating some of the high demand pressure generated by the ADA requests. This issue is the primary focus of the research.

The remainder of this report is organized as follows. A review of past studies on DRT systems is provided in section 2. Section 3 reviews the existing and emerging ITS technologies that can support DRT systems. Section 4 surveys available software for scheduling and dispatching of paratransit vehicles with a detailed comparison of the available features. Section 5 presents a case study of a paratransit service provider implementing ITS. The statistical analysis of data provided by Antelope Valley Transit Authority is presented in section 6. Section 7 presents the proposed hybrid delivery heuristics and the comparison with a strictly curb-to-curb system. Concluding comments are made in section 8.

2.0 Literature Review

The Americans with Disabilities Act (ADA) has drastically augmented the responsibility of transit service providers and costs associated with it. Levine (1997) lists the ADA requirements for transit service providers. ADA required all agencies to provide accessibility, including wheelchair accessibility to all new and renovated transit vehicles, offer complementary paratransit service to individuals who, because of their disability, are unable to make use of mainline public transportation. Such complementary paratransit was to be phased in over a five-year period ending in 1997. Levine describes the relationship between a standard fare based approach and an incentive fare based approach for paratransit planning. Comparing the two systems, he finds that a very low fare of $0.35 has a dramatic effect on the demand pattern. By using a regression model, he concludes that even low cross price elasticities can lead to cost savings.

There are numerous paratransit delivery methods such as single contracts, multiple contracts, or direct service (Simon, 1998). Rufolo, Strathman and Peng (1997) show in a case study in Portland, Oregon that the service cost for demand responsive transit decreased by a half when switching from direct service to contract service primarily due to labor cost differences. Gilbert and Cook (1999) state that a Federal Transit Administration Study found that 7.6% of total expenditures by transit operators was spent on purchased transportation.

Nalevanko and Cook (1999) describe a methodology that provides guidance to rural and small urban transit operators in selecting appropriate Advanced Public Transportation Systems (APTS) to meet their unique needs. The methodology tries to answer two general questions: Where Do We Start? How Far Should We Go? A decision tree assesses the information provided by a user and decides the appropriate technology to implement. The following factors are considered in the decision tree:

1.System Characteristics
2.Fleet Size
3.Average Requests and Subscription Trips
4.Available Funds and Resources

They also developed a web site that identifies appropriate and adequate technology that supports paratransit service in small urban and rural areas. The address of the web site is: http://www2.ncsu.edu/eos/service/ce/research/stone_res/tahmed_res/www/index.html

Chira-Chavala (1999) and Chira-Chavala and Venter (1997) describe the benefits of implementing ITS Technology at Santa Clara Valley Transportation Authority. They study the cost and productivity impact of implementing an ITS based system. After implementing ITS, they show a 17% increase in ridesharing, 13% savings in transportation cost, and 28% reduction in total personnel salaries. Higgins, Laughlin and Turnbull (2000) evaluate the impact on the performance of implementing ITS at Houston METROLift paratransit service. By deploying AVL and an Advanced Paratransit Scheduling System, service efficiency has increased by 10.3% in four years, even though the service area during this period has been increased by 26.9%.

Wallace (1997) describes a novel way of deriving results by modeling customer satisfaction. Using the results of customer surveys and to avoid problems of redundancy and repetitiveness that generally plague regression analysis a casual model of the factors and variables contributing to customer satisfaction is developed. The modeling efforts show that satisfaction with both the reservation system and on-board service contributes to overall customer satisfaction. This work revealed a strong link between the quality of the customer service and satisfaction with the trip scheduling process.

Balog, Morrison, and Hood (1997) describe the integration of curb-to-curb paratransit service with fixed route transit services and the importance of vehicle transfer requirements to customers. A conjoint analysis technique is used in determining the effect of the two services and a utility value is established which indicate the relative importance of the attributes. The results show the importance of providing easy and secure transfers between the two modes of transportation. Furthermore, transfer stops should be located in sheltered locations.

In summary, the previous work shows the potential benefit of deploying ITS in DRT systems. However, deploying ITS alone is not the complete answer for meeting the increased demand of these types of services and for satisfying the strict guidelines of ADA. New innovative service delivery methods that complement the technology need to be studied. As previously stated, the objective of this study is to compare the productivity and service effectiveness of a curb-to-curb system with a hybrid system. In the next sections, we identify the technologies that can support these types of systems. We also present the results of a statistical analysis of actual data from a representative paratransit operation that will be used in the comparison.

3.0 Intelligent Transportation Systems

ITS technologies have the potential to improve the service and productivity of personalized public transit systems. These technologies are useful for both strictly curb-to-curb systems and hybrid systems. Various ITS technologies currently being used by the transit agencies include:

- Scheduling and dispatching software
- Automatic vehicle location devices (AVL)
- Advanced wireless communication
- Mobile data terminals (MDT)
- Computerized vehicle navigation
- Geographic database

The following emerging technologies are under development:

- Internet dispatching
- Wireless internet dispatching
- Superphones
- Personal data assistants (PDA)
- Smartmaps
- Smart bus technologies

The above technologies are described in detail next.

3.1 Scheduling and Dispatching Software

Different tasks such as reservation, scheduling, dispatching, routing, billing etc. lead DRT providers to adopt computer assistance for efficient handling of passenger request and transport. The complexity associated with DRT operations necessitates that the providers use some form of computer assisted dispatching and scheduling system, which creates opportunities for vendors to develop custom and generic software applications for DRT systems. In Section 4, we review some of the commercially available CAD software. Due to increasing demand, strict ADA guidelines, and complexity of operating such systems, many DRT providers are purchasing off-the shelf CAD software or developing customized software to meet their specific needs. A large number of software packages are available in the marketplace which can support either manual or fully automated systems. The automated systems have built-in functionality to interact with other technologies such as AVL, MDT, etc. For example, Houston METROLift has implemented the Trapeze PASS paratransit scheduling system which interacts with their AirTouch AVL system. Houston METROLift current service efficiency of 2.35 passengers per hour ranked among the highest of paratransit providers of comparable size. This improvement has occurred despite a 26.9 percent increase in service area (Higgins, Laughlin and Turnbull, 2000).

3.2 Automatic Vehicle Location Devices

Automatic vehicle location devices are an electronic communication system for tracking and reporting the location of the vehicles to a central dispatching center. By knowing the location of the vehicle at the time of scheduling (assigning a specific trip request to a specific vehicle), it may be possible to improve the productivity of the system by better matching the passenger’s request location with the vehicle location. AVL systems also have the potential to reduce fleet sizes significantly. AVL systems based on GPS are now well established in the marketplace and are becoming the dominant AVL technology. The table in Appendix A shows the DRT providers that are using different types of AVL systems. The ratio of the agencies using GPS based AVL to the agencies using other AVL is very high.

3.3 Advanced Wireless Communication

Due to possible inaccuracies of AVL technologies, it is preferable to augment these systems with the use of radio to get the correct location and to help the driver in cases like flat wheels, accidents, traffic problems, and many unavoidable disruptions. Commercial radios are widely used for both voice and digital data transmission. They will continue to be used for some time, especially in conventional communications that require relatively little data transmission. These devices are simple and relatively inexpensive. Rather expensive, cellular phones are used in many systems as effective means of communication. Transit agencies do not have to build the radio infrastructure like transmission towers; rather they can rent the service of a cellular provider (Stone, Ahmed, and Nalevanko, 2000). However, because of the increasing use of MDTs and the expensive nature of these devices, their usage is very limited. METROLift is integrating their AVL system with the dispatching and scheduling software and radio communication. They hope this integration will enable them to schedule the vehicle trips more efficiently in the case of cancellations and no-shows (Jim Laughlin-Houston METROLift).

3.4 Mobile Data Terminals (MDT)

An MDT is an in-vehicle piece of equipment that receives and sends digital messages, which can be displayed on the screen. MDTs serve as the communication hub between the vehicle and computers at the control center. They automatically send vehicle location, passenger counts, mileage, status of the passenger, and other information. They communicate digitally with a host computer system, display messages to the driver, process and collect data generated in the course of operation. Advancements in microelectronics has made the development of comparatively powerful, sturdy and inexpensive processing units possible. MDTs are widely available for transportation applications in various forms with different ranges of performance characteristics.

3.5 Emerging Technologies

The information on the emerging technlogies was collected from the following web site at North Carolina State University.

http://www2.ncsu.edu/eos/service/ce/research/stone_res/tahmed_res/www/Sec2.html#S9

Wireless Internet Dispatching

Wireless Internet Dispatching systems depend upon “superphones" with Internet access, and server capacity at the provider.

Superphones

Superphones are basically compact hand-held, lightweight computers with two-way phone capability and Internet access. They provide drivers with e-mail access in the vehicle, and direct two-way data transmission and talk facility. They come with a built-in cell phone and Internet access so that they can send e-mail and access special web pages for dispatching and other usages. Other benefits include but are not limited to getting access to phone number lookups, map directions, and traffic and weather reports.

Personal Data Assistant (PDA)

A Personal Data Assistant is a palm computer that creates a driver profile. They are the best alternative to manual data entry by drivers. This helps to speed up data collection and allows quick processing in billing, performance reports, etc. A PDA can be given to the driver each morning to record the log of the day. When the driver returns to the depot, the data can be downloaded into a central computer.

4.0 Paratransit Software

We conducted a review of the commercially available DRT scheduling and dispatching software in order to record their functionality. One reference source used to identify the vendors who distribute this software was the *Software in Transit Handbook* by APTA (American Public Transit Association). Although this is a comprehensive handbook, this industry is changing very fast. Companies are consistently merging and disappearing so the information gets out of date in a short amount of time. Thus, we supplemented the handbook by searching recent transportation magazines and the Internet for related articles and advertisements. Based on the search, a list of companies was identified. Table 1 shows the list of the companies that were contacted.

Table 1. List of DRT Scheduling and Dispatching Software Providers

Software Company
Ramos Systems, Inc.
GIRO, Inc.
Les Conseillers Consultants INC.
Inventek, Inc.
Spear Technologies
Multisystems, Inc.
StrataGen Systems
RouteLogic, Inc.
Intelect Corporation
Teleride, Inc.
Edgar Consultants
TRW Communications
Aleph Computer Systems, Inc.
Fleet-Net Corporation
Trapeze Software, Inc.
Bernardin Lochmueller & Associates, Inc.
BG Consulting
Arrowhead Technologies, INC.
Melton Technoligies, Inc.
Computer Technology
Digital Dispatch Systems

Of the twenty contacted vendors, three firms completed the survey that we administered. They were Stratagen Systems, Trapeze Software Inc., and RouteLogic Inc. The other firms stated that they did not believe their software package was suitable for the industry, they did not currently support the product, or the company no longer exists or changed their address.

4.1 Evaluation Criteria

Each of the different software packages offers a numerous amount of features and capabilities. The features were grouped in seven main categories:

User Management	Fields that are related with the overall management of the paratransit service such as whether an individual is ADA eligible
Reservation	Fields that handle the passenger pick-up reservation process whether made in advance or in real-time
Scheduling	Fields that are related to vehicle scheduling to determine passenger pick-up or drop-off times
Software Features	Fields that describe the operating characteristics of the software such as its security and networking capabilities
Vehicle/Driver Data	Fields that contain records and information regarding the drivers and vehicles
Statistical Reports	Fields that contain statistical results regarding system performance
External Modules	Fields that describe the hardware, which can interact with the paratransit software

These evaluation criteria are categorized in subfields and are listed in Table 2. We developed a comprehensive set of fields in order to understand the complete functionality of these systems that are useful for paratransit scheduling and other operations.

Table 2. Evaluation Criteria

User Management Fields	
Eligibility determination for ADA specification	A field specifying whether the software supports the ADA specifications to determine if the passenger is covered by this law
Special driver preference	A field specifying a pickup driver for each passenger
Individual loading times	An unique loading/ unloading time for each passenger
"Problem passenger" determination	A field indicating any special treatment of the passenger associated with past behavior
Max time in vehicle for individual	Specifying maximum travel time for an individual passenger
Special needs for individuals	Allows to input characteristic of individual (for example different types of wheelchairs, other mobility devices, etc.) and to insert different loading times for each characteristic
Reservation Fields	
Advanced trip reservation	Allows the passenger to make advanced reservations
Group reservation	Supports reservations for a group of passengers
Number of riders	Considers the number of riders for one reservation in the scheduling algorithm
Multiple reservation	Allows to open multiple days to schedule multiple reservations in advance for example 14 days prior
Accompanying riders type	Allows to distinguish between Personal Care Attendants (PCAs) and Guests
Call back confirmation	Supports automatic callback confirmation
Call for changes	Notifies the passenger if the pickup time changes
Choice of performance criteria, priority	Different performance criteria or priority for reservation as selected by the operator and allows user to to specify various measures to be captured or calculated
On-line time estimates	Provides on-line time estimates when the passenger makes the reservation and actual vehicle assignments and update in real time when combined with AVL/MDT/GPS
Real time operations	Capability to support real-time reservations
Automatic name search capabilities	Search capability of names of people calling or places they want to go
On-line address verification	Pickup/ Drop-off address verified through a geographic database for existence and correctness
List of common destinations	Provide "indexable" list of common destinations a particular passenger may make
Transfer to fixed route transit	Supports the capability to transfer to a fixed route transit and the fixed route transit schedule is available for scheduling the ride. Furthermore specifies the accessibility of fixed route bus stop
Redundant reservation warning	Informs the operator in real-time that the same reservation was already scheduled

Input verification for errors, completeness	Checks for completeness/correctness before the reservation is scheduled and repeats the booked trip back to the passenger
Cancellation, change of request	Allows for cancellation by a passenger if the pickup time changes or for rescheduling it. If outside the Cancellation Window, add the passenger in "No Show" list.
Pick up/ Drop off Window	If the passenger can specify a pick up/drop off window when calling for a reservation
Scheduling Fields	
On-line scheduling	Scheduling is done on-line versus batched scheduling/off-line
Vehicle routing/mapping system	Vehicle routing/mapping system is used to determine the routes between points
Distance out of the Way	Supports the maximum distance of a traveled route away from a straight line
Fully computerized scheduling / dispatching	The computer software determines the schedule and trip assignments to vehicles with no human intervention
Batch scheduling/dispatching	Determine schedule for a set of many trips all at one time
Dynamic scheduling	Allows for re-optimizing of the schedule when reservations are made
Manual override of computer schedule	Operator can manually influence the schedule of a specific vehicle and override the given solution by the software
Paratransit transfers	Allows for passengers transferring between vehicles for performance improvement
Traffic considerations	Current traffic conditions are considered by the software when the route is selected
Graphical trip display	Graphically displays the current/future trip of a vehicle overlaying the layout of the service area/city
Refueling considerations	Considers the operation time and fuel consumption of a vehicle when the trips are scheduled
Driver schedules and vehicle operation time	Includes individual driver schedules and vehicle operation times in the scheduling algorithm (for example 10 minute break for the driver every 4 hours) with flexibility to shift the breaks/lunch back to accommodate additional rides
No-show / Cancellation	Reschedules the route when no-shows / cancellations are made
Max number of rides/day	Max number of rides/day or by some other time interval the software is able to schedule
Multiple contractors	Handles multiple contractors in the scheduling algorithm
Software Features Fields	
Networking capabilities	Handles multiple operators/ users of the software at the same time over a network
Multi-tiered security	Multi tiered security system is in place to stop unauthorized access to sensitive data of users/system
On-line help system	On-line access to manuals/help screens while scheduling a ride
Operation simulation capabilities	Simulates the operation of a day/ week in advance with statistical/ real data

Required hardware	Necessary hardware required to run the main software (UNIX, PC, Mainframe, Network computer)
Account software included	Handles the accounting parts of the operation (e.g., payroll, billing of customers, accounts payable, …)
Allows "What if" questions	The software allows easy testing of various alternatives by determining the impact of changes in the parameters
Fleet maintenance	Handles the maintenance operations of the fleet and automatically schedules inspections and repairs
Customize report	Provides customized reports of the all accounting details
Vehicle/Driver Data Fields	
Variable/individual vehicle parameters	Allows for specific parameters to be entered for each vehicle and considers them in the scheduling algorithm
Individual driver parameters	Allows for specific parameters to be entered for each drivers and considers them in the scheduling algorithm
Static vehicle assignments	Permits to assign vehicles to a static route/ schedule for continuous scheduled trips (work trips everyday)
Service area size	Specifies a service area for a vehicle
Data feedback into system	Provides driver feedback into the system about passengers/routes
Autonomy of driver for route selection	Allows driver to be responsible for his own route
Statistical Reports Fields	
Driver evaluation	Statistics on the driver are collected
Time statistics on time in motion	Statistics on the time in motion for each vehicle are collected
Time statistics on pickup time	Statistics on pickup time are collected
Time statistics on loading time	Statistics on loading time are collected
Time statistics on no request motion time	Statistics on time vehicle does not serve any requests but still is in motion (e.g., relocation, back to garage, maintenance) are collected
Statistics on "ride reasons"	Statistics on "ride reasons" are collected by the software
Statistics on service use of different riders	Statistic on the use of the service for different riders is collected
Performance statistics	Statistic on the performance of the service is collected
Import/Export	Capability to read and write in a standard format called ASCII, spreadsheet software and word processing software
External Modules Fields	
Smart Card support	Software provides an interface for support for smart card terminals in the vehicles
Mobile Data Terminals	Software provides an interface for mobile data terminals in the vehicles

Automated Vehicle Location (GPS)	Software provides an interface for automated vehicle location system
In-Vehicle Computers	Software provides an interface for in-vehicle computers (computational power in the vehicle itself)
Radio transmission	Software provides an interface for radio transmissions to/ from the vehicle
Paging	Software provides an interface for paging services to the vehicle

4.2 Software Survey

Most of the software packages cover most of the criteria mentioned in Table 2. Some software packages however have more features than others. Table 3 lists the features of each of the evaluated software packages.

Table 3. Software Survey

Features	Stratagen Systems	Trapeze Software Inc.	RouteLogic Inc.
Key			
Criteria is included -> **X**			
Could not be determined -> ##			
Criteria is not available -> **NA**			
User Management Fields			
Eligibility determination for ADA specification	X	X	X
Special driver preference	X	X	X
Individual loading times	X	X	X
"Problem passenger" determination	X	X	X
Max time in vehicle for individual	X	X	X
Special needs for individuals	X	X	X
Reservation Fields			
Advanced trip reservation	X	X	X
Group reservation	X	X	X
Number of riders	X	X	X
Multiple Reservation	X	X	X
Accompanying riders type	X	X	X
Call back confirmation	##	X	NA

Call for changes	**X**	**X**	**NA**
Choice of performance criteria, priority	**X**	**X**	**X**
On-line time estimates	**X**	**X**	**X**
Real time operations	**X**	**X**	**X**
Automatic name search capabilities	**X**	**X**	**X**
On-line address verification	**X**	**X**	**X**
List of common destinations	**X**	**X**	**X**
Transfer to fixed route transit	**X**	**X**	**X**
Redundant reservation warning	**X**	**X**	**X**
Input verification for errors, completeness	**X**	**X**	**X**
Cancellation, change of request	**X**	**X**	**X**
Pick up/ Drop off Window	**X**	**X**	**NA**
Scheduling Fields			
On-line scheduling	**X**	**X**	**X**
Vehicle routing/mapping system	**X**	**X**	**X**
Distance out of the Way	##	**X**	**NA**
Fully computerized scheduling / dispatching	**X**	**X**	**X**
Batch scheduling/dispatching	**X**	**X**	**X**
Dynamic scheduling	**X**	**X**	**X**
Manual override of computer schedule	**X**	**X**	**X**
Paratransit transfers	**X**	**X**	**X**
Traffic considerations	**X**	**NA**	**NA**
Graphical trip display	**X**	**X**	**X**
Refueling considerations	**X**	**X**	**NA**
Driver schedules and vehicle operation time	**X**	**X**	**X**
No-show / Cancellation	##	**X**	**X**
Max number of rides/day	**X**	**X**	**X**
Multiple contractors	**X**	**X**	**X**
Software Features Fields			
Networking capabilities	**X**	**X**	**X**
Multi-tiered security	**X**	**X**	**X**
On-line help system	**X**	**X**	**X**
Operation simulation capabilities	**X**	**X**	**X**
Required Hardware	**X**	**X**	**X**
Account Software Included	**NA**	**NA**	**X**
Allows "What if" questions	**X**	**X**	**X**
Fleet Maintenance	**X**	**NA**	**X**
Customize Report	**X**	**X**	**X**
Vehicle/Driver Data Fields			

Variable/individual vehicle parameters	X	X	X
Individual driver parameters	X	X	NA
Static vehicle assignments	X	X	X
Service area size	X	X	NA
Data feedback into system	X	X	X
Autonomy of driver for route selection	##	X	##
Statistical Reports Fields			
Driver Evaluation	X	X	X
Time statistics on time in motion	X	X	X
Time statistics on pickup time	X	X	X
Time statistics on loading time	X	X	NA
Time statistics on no request motion time	X	X	X
Statistics on "ride reasons"	X	X	X
Statistics on Service use of different riders	X	X	X
Performance statistics	X	X	X
Import/Export	X	X	X
External Modules Fields			
Smart Card support	X	X	X
Mobile Data Terminals	X	X	X
Automated Vehicle Location (GPS)	X	X	X
In-Vehicle Computers	X	X	X
Radio transmission	X	X	X
Paging	X	X	X

Our review shows that most of the software has capabilities to automate reservation, scheduling, billing and maintenance. The intent of this review was not to make a recommendation of any particular software. The purpose was to list the features of the available software and to identify if they have the capabilities to support automated operation of DRT service within the paratransit industry. We note that this industry is changing very rapidly due to changes in the marketplace. There has been numerous merges leading to decreasing number of software packages specifically addressing the paratransit market while their capabilities are continuously increasing. Most of the packages have built in interfaces to accommodate AVL, global positioning systems (GPS), and MDT. We note that the functionality of these systems can be easily extended to also support hybrid systems.

5.0 ITS At OUTREACH

5.1 Background

OUTREACH Inc. is the paratransit provider for Santa Clara Valley Transportation Authority. Our phone interview contact was Mr. Jarrod Clark. Appendix B contains the list of questions that we prepared for the interview.

They provide services to the elderly and customers under ADA compliance. OUTREACH provides these services for the entire Santa Clara County District. The service area is approximately 328 sq. miles. OUTREACH contracts the service to private taxi and van operators. A customer can make a reservation14 days prior to the requested pickup time and must make it at least before 5 p.m. of the previous day. In some cases, OUTREACH can provide same day service based on vehicle availability. OUTREACH has almost 200 contracted vehicles and provides 2500 trips per day. They perform only booking and scheduling of the contracted vehicles. The private taxi and van operators are responsible for the actual delivery of the passengers. OUTREACH also provides Will-Call service, which is a service request with an open return time when the trip is booked. These trips are deployed using a different set of vehicles.

The number of trips per year has increased dramatically for this region. According to one study in 1995, OUTREACH provided about 326,000 person-trips to about 10,500 clients (Chira-Chavala and Venter, 1997). In order to serve this volume of demand, OUTREACH first implemented automated scheduling and routing software and digital geographic database. In the second phase of implementation, AVL was deployed.

5.2 Implemented ITS

OUTREACH has completed Phase III of the ITS implementation with the help of $750,000 from the federal-and-state funded Smart Paratransit Project.

The technologies implemented include:

- <u>Automated trip scheduling and dispatching software</u> – Trapeze
  When a customer requests are made, the software inserts the trip into the schedule and shared rides are built automatically. The system assigns the trip to a vehicle

based on minimizing a weighted objective function of productivity and service level. This schedule is given to the vehicle contractors. The contractor is responsible for dispatching the vehicles. However, OUTREACH employees can assist the contractor in dispatching.

- Automatic vehicle location devices – Trimble System
  Out of 200 vehicles operating for OUTREACH, 85 vehicles have AVL. The system displays the movement of the vehicle on a map. This provides the flexibility of tracking the vehicle and enables OUTREACH employees to determine better estimates of sojourn time. Due to this, they are better able to answer questions from customers who are waiting for the vehicle to arrive. The information regarding trip cancellations and insertions can be transferred directly to the vehicle through AVL. It also allows the dispatcher to help drivers who are facing unusual problems like flat tire, lost, uncertain of directions, traffic congestion, etc.
- Digital geographic database
  The Digital geographic database (DGD) contains city, street names and the address of each block. It also includes some traffic characteristics. Geocoding of addresses is done using a longitude/latitude coordinate system. Distances between two points can be calculated, and street locations can be viewed on a computer screen. Data files of the street addresses can be managed using this system.

5.3 Benefits of ITS

Chira-Chavala and Venter (1997) concluded that without the automated trip scheduling system OUTREACH would not have been able to accommodate the increases in paratransit demand nor able to meet the full ADA compliance. They describe the following benefits of ITS implementation.

- Increase in the percent shared rides (the percentage of time that there are two or more requests in vehicle) from 38% to 55%
- 13% savings in the unit transportation cost per passenger mile
- Total personnel salaries decreased by 28%

- Clients did not perceive a significant difference in the level of service between before and after ITS. Hence, service costs decreased without a resulting drop in service level.

5.4 Future Technology Implementation

After the current phase of technology implementation, OUTREACH would like to implement the following technologies:

- Smartcard
- Automated Interactive Voice Response
- Online booking and cancellation
- Wireless communication devices / Palm computers

OUTREACH is also investigating methods to move some of the requests to accessible fixed routes, in order to better meet the increase in demand.

6.0 AVTA Data Analysis

6.1 Background

Antelope Valley Transit Authority (AVTA) was selected based on suggestions from Access Services personnel, the agency responsible for coordinating paratransit service within Los Angeles County, who felt that this region was where it might be beneficial to use a hybrid fixed route and curb-to-curb system. The travel distances in Antelope Valley are large enough to justify a transfer point between the two different types of transit services. Furthermore, most of the disabled and elderly passengers travel to a central location where most of the hospitals are located. Finally, AVTA is a small to mid-size agency so that there is opportunity for effective communication between their fixed route and paratransit services. AVTA provided data of their operations including pickup time, travel distances, fleet size, etc. This data will be used to form statistical distributions of representative paratransit operations, which will form the basis for our testbed in comparing the performance of a strictly curb-to-curb system with a hybrid system.

Antelope Valley Transit Authority provides fixed route and paratransit services in Lancaster County. The total service area is divided in three parts, Urban Zone, Rural Zone 1 and Rural Zone 2 as shown in Figure 1.

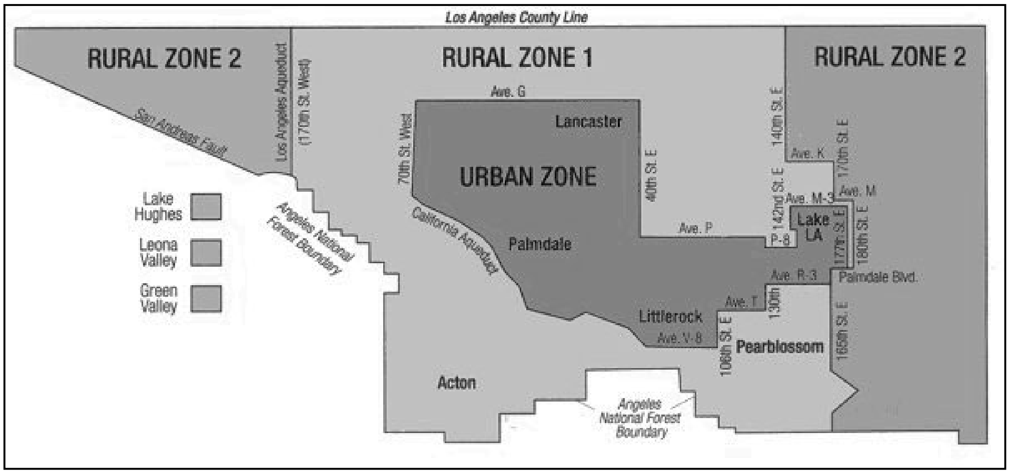


Figure 1. Dial-A-Ride Service Area for AVTA

We received data in the hard format for the period of two weeks, February 14, 2000 to February 25, 2000. We only considered weekdays. Thus, we received nine days of data. AVTA operates from 6:00 AM to 7:30 PM during the weekdays. The total number of requests served during these days was 1242. The number of drivers per day varied from 4 to 12 during this period (Average=9.22). The average number of requests served per day per driver was 15.79 with the maximum number being 30.33 on any given day. The data provide the following details for each requested trip:

- The unique identification number
- Number of attendants and companions
- Pick-up/Drop-off destinations
- Requested pick-up/drop-off time window
- Actual pick-up/drop-off time
- Cumulative miles

We entered these data in a spreadsheet and the distributions for vehicle travel time, pick-up time, travel distance and other important results were tabulated.

6.2 Statistical Data Analysis

The collected data was analyzed to determine the travel patterns of a representative DRT operation. All summary statistics are presented in Table 4.

6.2.1 Miles Traveled per Request

Figure 2 shows a histogram of the distance traveled in miles. As the figure shows, the most common request is within the range of 6 to 10 miles. However, there still is a significant amount of passengers traveling greater than 10 miles which is significant enough of a distance to justify a transfer to an accessible fixed route bus.

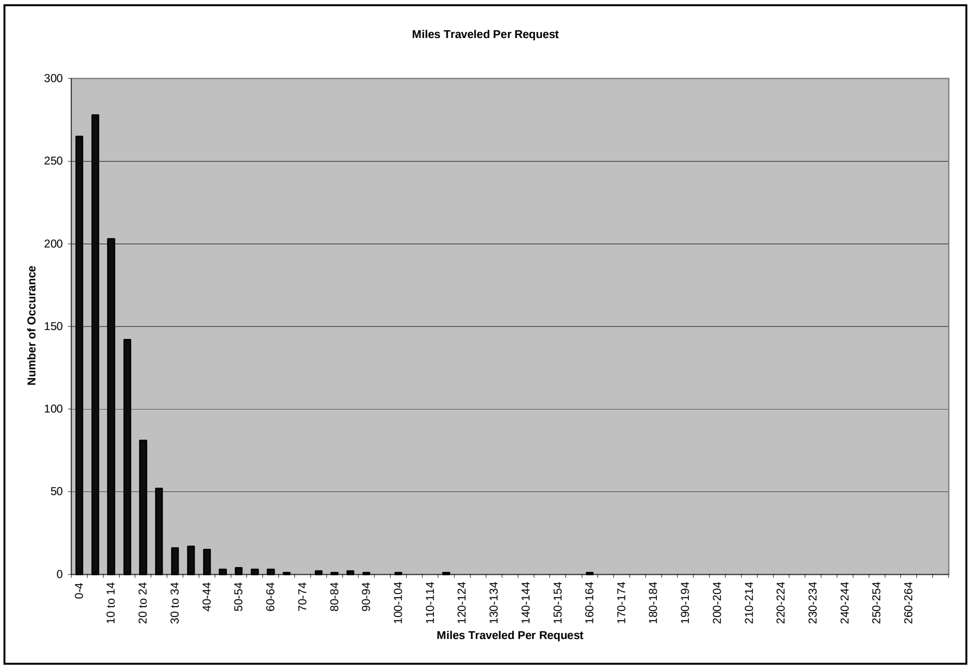


Figure 2. Miles Traveled Per Request

6.2.2 Pick-up Time

Figure 3 shows the frequency of the actual pick-up times. Most of the requests were during late morning and early afternoon. The number of requests after 7:00 pm is very low since the working hours for AVTA is from 6:00 am to 7:30 pm. Almost in all the cases, the demand was satisfied within the requested time window. We note that the peak of the pick-up time distribution matches closely with the high frequency periods of the fixed routes.

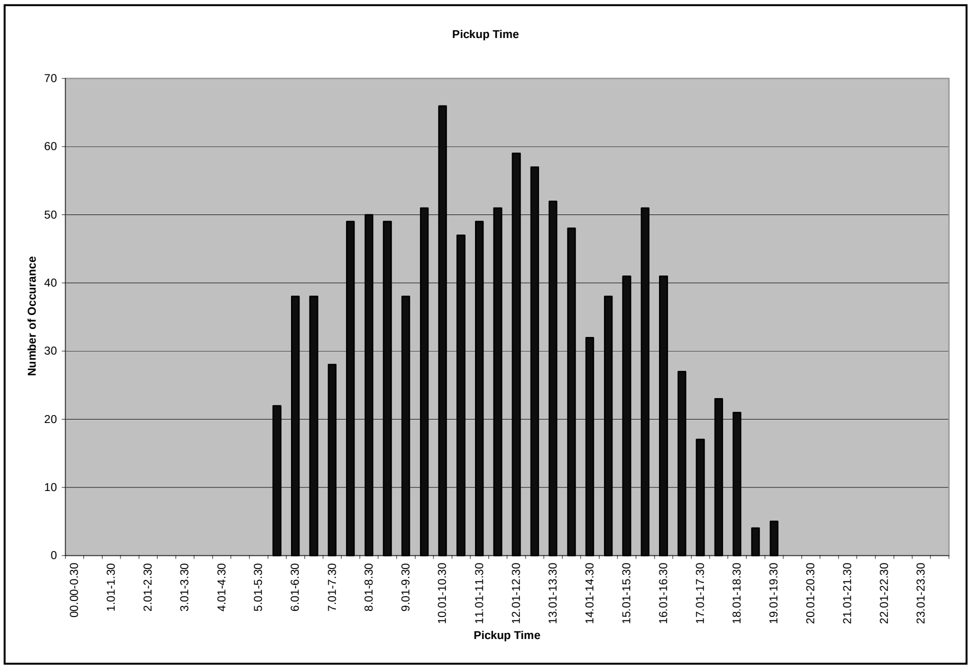


Figure 3. Actual Pick-up Time

6.2.3 Drop-off Time

Figure 4 shows the frequency of the actual drop-off times. There were no drop-offs between 6:00 and 6:30 am because it is the start of the day. Although AVTA closes at 7:30 pm, there are some drop-offs after this time since the request was accepted during the working day, and AVTA is responsible for dropping off these requests even after working hours. As can be seen, the shape of the drop-off time distribution is similar to that of the pick-up time distribution except slightly shifted to the right

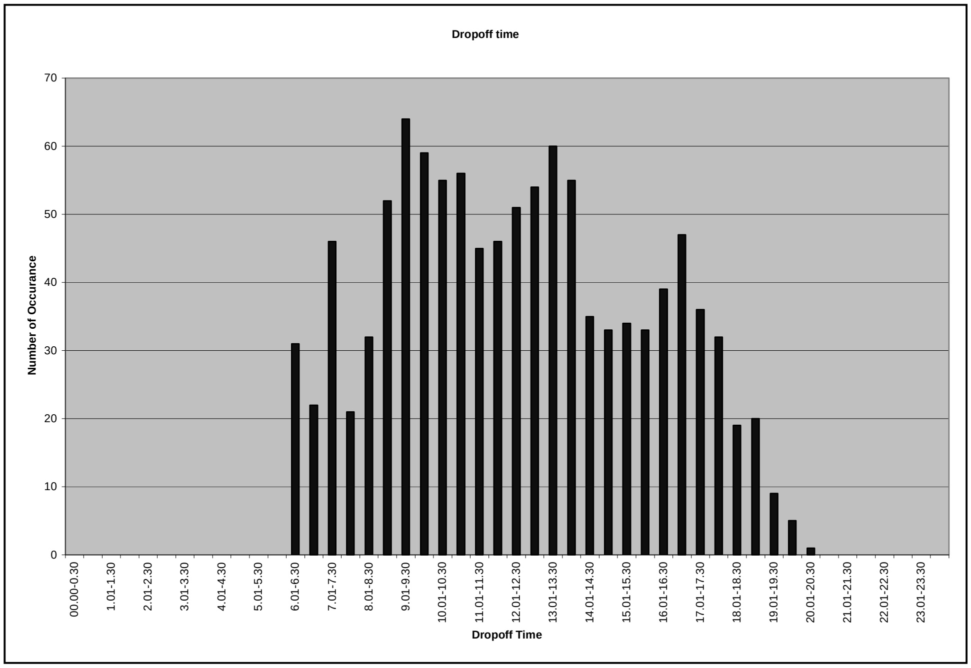


Figure 4. Actual Drop-off Time

6.2.4 Vehicle Occupancy Rate

Figure 5.1 shows the fraction of the total travel time during which the vehicle was occupied by a request. When occupied, there may be more than one passenger in the vehicle. As is shown in the figure, more than half of the time the vehicle is empty implying possibly that the vehicle travels great distances to pickup passengers. Improved coordination between pickup locations in the schedule could improve this performance measure. Figure 5.2 shows the results based on miles instead of time. Note there is not much difference in the figures.

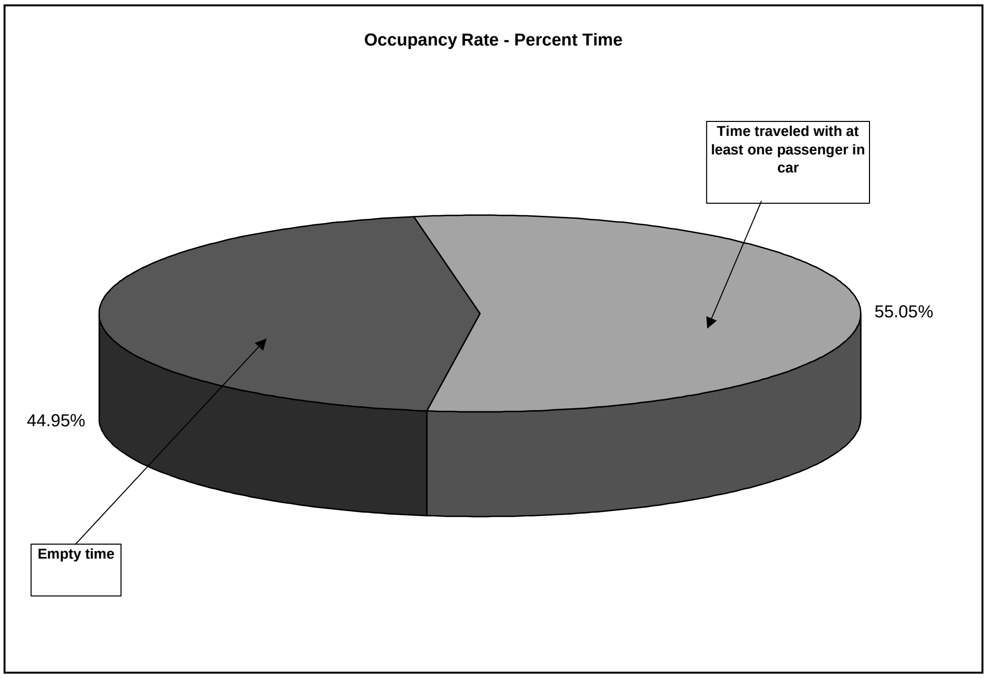


Figure 5.1. Occupancy Rate – Percentage Time

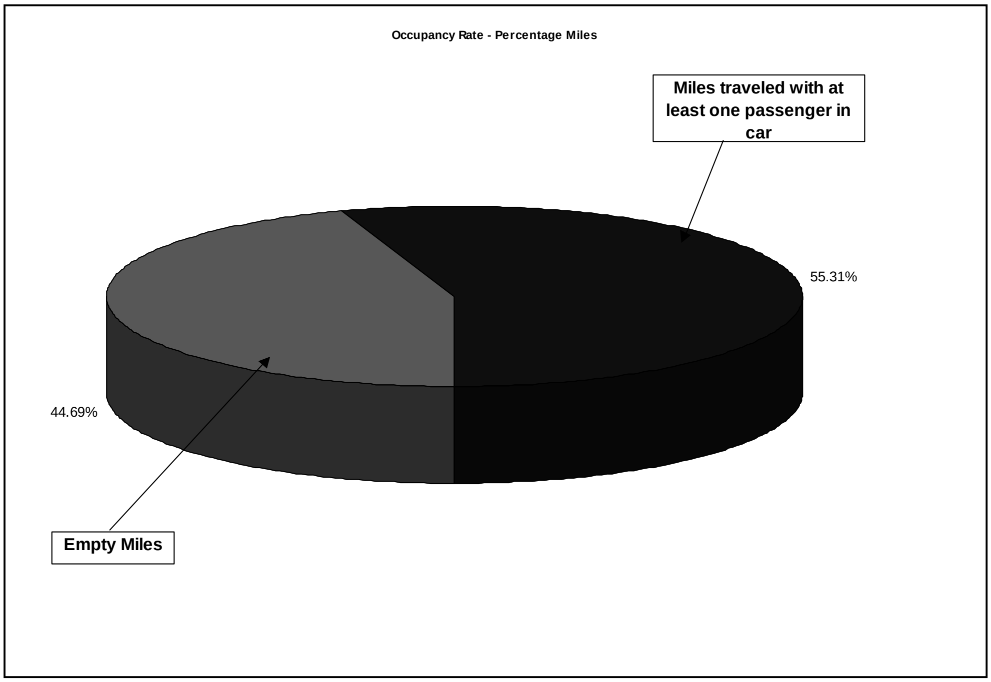


Figure 5.2. Occupancy Rate – Percentage Miles

6.2.5. Number of Passengers per Request

Figure 6 provides details on the number of passengers picked up per request. In some cases, elderly, disabled and patients need one more person as their attendant to assist them. Also a companion can travel with the passenger. As shown in the graph, in almost 90% of the cases, there is only one passenger associated with each request. In some cases, there are two passengers associated with each request and in rare cases there are three. These results are useful for determining vehicle capacity requirements.

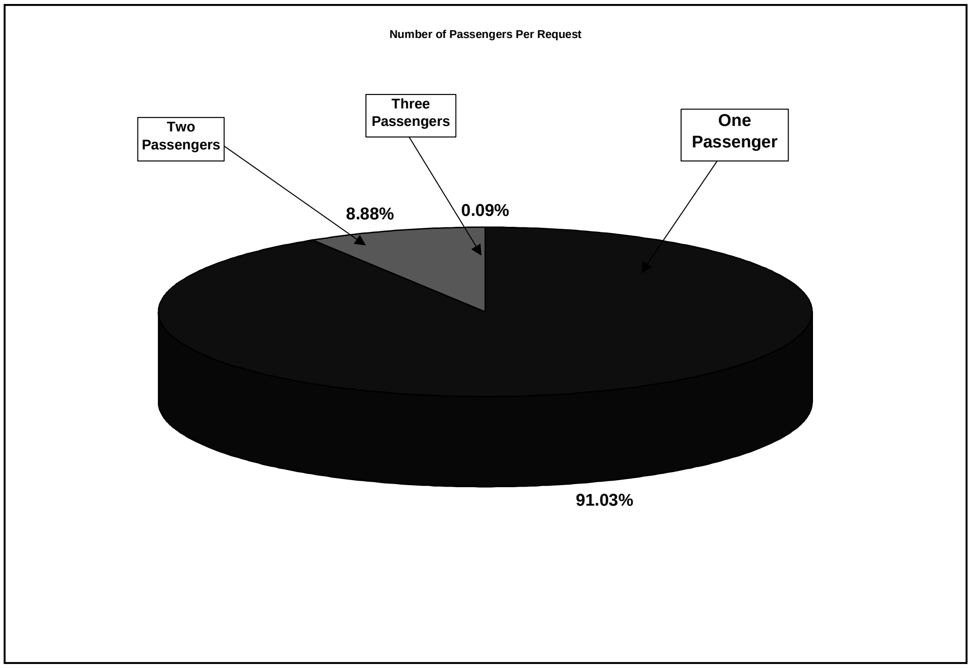


Figure 6. Number of Passengers per Request

6.2.6 Ridesharing

Figure 7 shows the fraction of time in which there was more than one request in the vehicle. As shown in the figure, around a third of the time there were more than two requests in the vehicle. We differentiate between number of requests and number of passengers since each request can be associated with more than one passenger. We consider the case only when there are multiple requests currently being served by the vehicle as ridesharing.

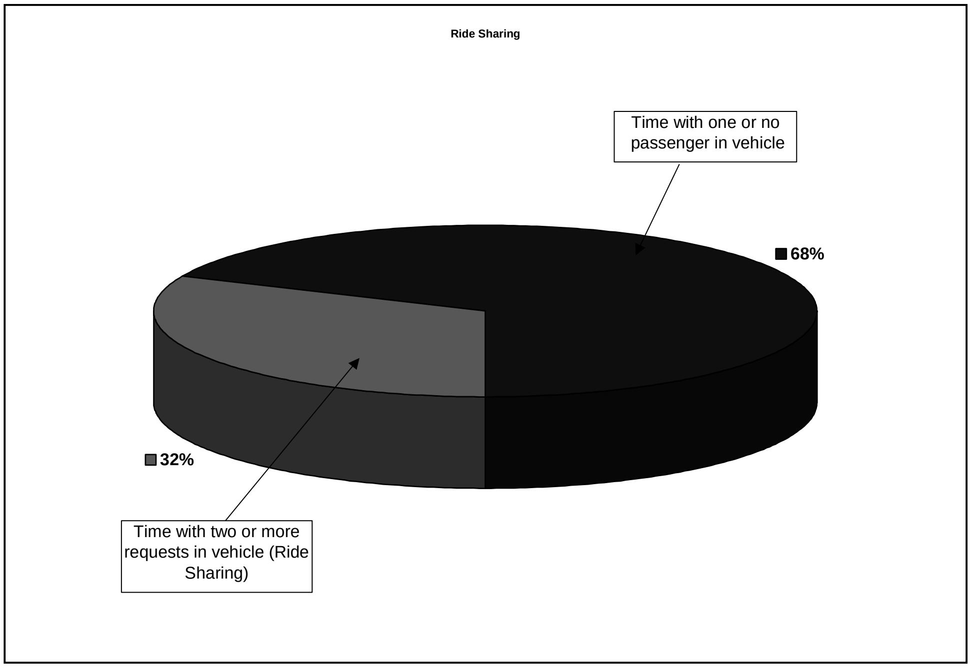


Figure 7. Ridesharing

6.2.7 Miles Traveled per Day

Figure 8 shows the distribution of the number of miles traveled by a driver per day. We can see from the graph that the maximum that was driven by a driver was over 180 miles. The average number of miles driven by a driver is around 165 miles. Note that a hybrid system has the potential to reduce these averages.

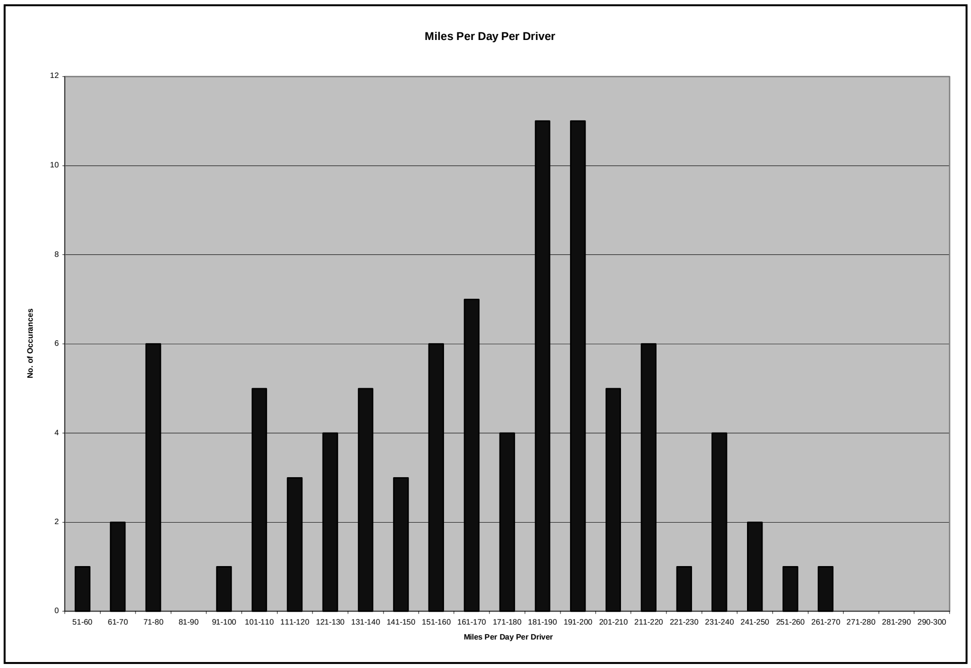


Figure 8. Miles Traveled Per Day

6.2.8 Summary

Table 4 summarizes the results of the statistical analysis.

Table 4. Summary of the Statistics

1	Travel Distance Per Request in Miles	
	Average	12.75
	Standard Deviation	13.00
	Median	10
	Mode	4
	Maximum	163
	Minimum	0
2	Pickup Time	
	Average	11.87
	Standard Deviation	3.41
	Median	11.58
	Mode	9.55
	Maximum	20.07
	Minimum	5.48
3	Drop-off Time	
	Average	11.89
	Standard Deviation	3.41

	Median	11.58
	Mode	9.55
	Maximum	20.07
	Minimum	5.48
4	Total Number of Requests Served	1242
5	Total Number of Passengers Transported	1872
7	Number of passengers per request (%)	
	One passenger	91.03
	Two passenger	8.88
	Three passenger	0.09
8	Percentage of time more than one request in vehicle (Ridesharing)	31.78
9	Percentage of time traveled with passenger	55.05
10	Percentage of time traveled empty	44.95
11	Percentage of distance traveled with passenger	55.31
12	Percentage of distance traveled empty	44.69
13	Average number of requests served per day per driver	15.79
14	Maximum number of requests served per day per driver	30.33
15	Average distance traveled per day	1132.69
16	Distance traveled per driver per day	
	Average	165.45
	Standard Deviation	49.06
	Median	174
	Mode	166
	Maximum	262
	Minimum	53

7.0 Hybrid Delivery Method for Paratransit Operations

7.1 Background

Although the above studies show the potential of APTS in improving the productivity of dial-a-ride programs and alleviating some of the drawbacks of the earlier systems, technology alone cannot solve the problem of operating such systems under increased demand since most dial-a-ride programs for the transport of elderly and disabled persons are heavily subsidized programs. In Los Angeles County, the average cost per trip for such systems is around $17-20 per passenger trip with the average fare being around $2-3 as opposed to fixed route transit which has an average cost per passenger trip of around $2 with average fares of around $0.50. Thus, the increased usage of these curb-to-curb services has put significant budget pressures on most transit agencies. In fact this is such a major concern in Los Angeles County that the agency responsible for paratransit services, Access, is allowing all ADA eligible passengers to ride for free on the fixed route bus lines in order to shift some of the passengers to this mode of transit service. Hence, there is a need to evaluate different service delivery methods that can meet the increased demand of this type of service and satisfy the strict guidelines of ADA. In this work, we consider an approach that integrates a curb-to-curb system with fixed route bus lines.

The conventional problem of dial-a-ride concerns with routing and scheduling vehicles in order to satisfy transportation requests from customers. Each request has an origin point, destination point, number of riders, and desired pickup or drop-off time. From the perspective of the user, on-demand curb-to-curb service is the most preferred mode of service delivery method. It clearly minimizes the passenger travel time. However, this type of service may not be the most cost-effective method of transporting people.

There is a significant body of research on scheduling curb-to-curb systems. The problem of scheduling curb-to-curb systems is sometimes referred to as the Pickup and Delivery Problem (PDP) in the literature. Savelsbergh and Sol (1995) provide an excellent review of this work. Some exact solution procedures for solving this problem include the work of Psaraftis (1980, 1983), Kalantari et al. (1985), Desrosiers, Dumas, and Soumis (1986), Fischetti and Toth (1989), Dumas, Desrosiers, and Soumis (1991), and Ruland and Rodin (1997). Since the PDP is NP-hard (Savelsbergh and Sol, 1995), most of the research has focused on heuristics. More recent approximation solution procedures include the column management scheme by Savelsbergh and Sol (1998), the insertion heuristic developed by Madsen, Ravn, and Rygaard (1995), the clustering algorithm developed by Ioachim et al. (1995), and the parallel insertion heuristic developed by Toth and Vigo (1997).

Although there has been a significant body of research on scheduling curb-to-curb systems, there has been limited work that attempts to integrate curb-to-curb services with the fixed route bus lines. We refer to a transit system that integrates these two modes of transportation as a "hybrid" service delivery method. Clearly, a curb-to-curb system as opposed to a hybrid system minimizes the travel time for the passenger. However, shifting some of the demand to fixed routes may alleviate some of the demand pressure for the on-demand vehicles caused by ADA requirements. The limited research in this area includes the work of Liaw, White, and Bander (1996), and Hickman and Blume (2000). Both of the above approaches are based on developing insertion heuristics. Hickman and Blume (2000) use the insertion procedure developed by Jaw et al. (1986) in their approach. Liaw, White, and Bander (1996) test their heuristic on a data set from Ann Arbor, Michigan while Hickman and Blum (2000) test their insertion heuristic on a data set from Houston, Texas.

We build on this earlier work by expanding on the insertion heuristic approaches by adding an improvement as well as a Tabu Phase to the solution procedure. Tabu search is considered to be one of the most useful meta-heuristics for solving routing problems. For example, Rochat and Taillard (1995), Badeau et al. (1997), and Taillard et al. (1997) use a tabu search procedure for solving the vehicle routing problem while Nanry and Barnes (2000) use it to solve the pickup and delivery problem.

We test our methodology on an actual paratransit service provider. The selected agency is Antelope Valley Transit Authority (AVTA). This agency is selected since their service area is ideal for a hybrid system. For example, most ADA passengers travel to a central area where the hospitals and shopping malls are located. In addition, the distances traveled by many of the passengers are large enough to justify a transfer to a fixed route bus line.

7.2 Problem Description

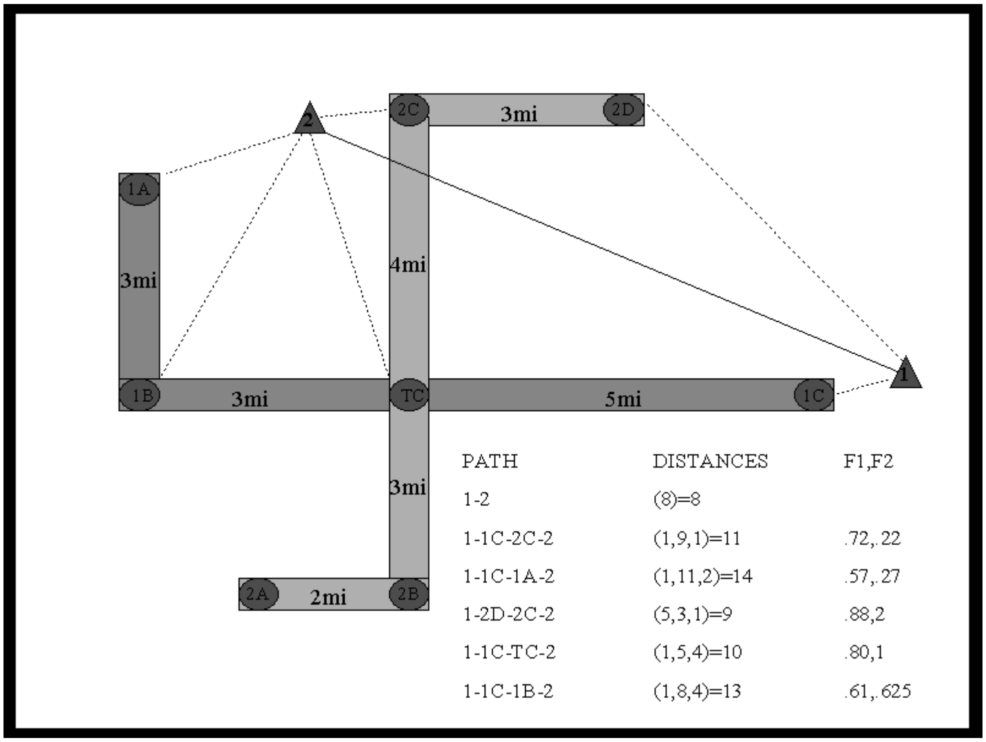
In a certain day, there are a number of requests of a set of N customers who need to be picked up from origin points and dropped off at destination points. Every request has a desired pickup time and drop-off time. Also, associated with each desired pickup time is a hard time window which specifies the earliest and the latest times the customer can be picked up. We assume that all requests are made in advance. For example, they are made one day before the service day.

The main idea is to integrate two modes of transportation, curb-to-curb service and fixed route transit, to satisfy the above requests. We refer to such a system as a *hybrid* service delivery method. The paratransit curb-to-curb system includes a set of M paratransit vehicles with a known capacity that are used to pick up the passengers from their origins or from the bus stops and drop them off at their final destinations or at the bus stops. All the paratransit vehicles dispatch and return to their depot at the end of the workday.

On the other hand, the fixed bus route system includes a set of R fixed bus routes. Every fixed bus route has a number of buses that travel through it, a set of bus stops and a time schedule. The capacity of the buses is relatively large and is not considered a constraint in this problem. We assume that at most two transfers can be made for any customer in the system and no transfers can be made between the same mode. We refer to passengers that are strictly served by the on-demand vehicles as door-to-door requests while those passengers that transfer to a fixed route bus line are referred to as hybrid requests.

To help illustrate the problem, Figure 9 shows a simple network that has hybrid service. In this example, the triangle with a one is the origin while the triangle with a two is the destination. There are two fixed route bus lines in this example. As the diagram shows, there are a number of different alternatives to go from the origin to the destination using a hybrid service. Obviously, one path is to take the direct distance using only the on-demand vehicle. Another path is to take a vehicle to stop 1C then get on a fixed bus line to either stops TC, 1B, and 1A and transfer to another vehicle. Clearly one of the functions of any solution procedure is to select the entry and the exit bus stops. In this case, stop 1A is the closest to the final destination but requires the passenger to sit in the bus longer. Furthermore, the request that the vehicle serves next may be closer to stop TC. Hence, any solution procedure needs to consider all these factors in selecting the best route/path.

Note that in a strictly door-to-door system (e.g., dial-a-ride service) the decision variable is primarily to determine the on-demand vehicle schedule. In a hybrid system, the on-demand vehicle schedule as well as the delivery path for each request needs to be determined as illustrated in the above example.



PATH	DISTANCES	F1,F2
1-2	(8)=8	
1-1C-2C-2	(1,9,1)=11	.72,.22
1-1C-1A-2	(1,11,2)=14	.57,.27
1-2D-2C-2	(5,3,1)=9	.88,2
1-1C-TC-2	(1,5,4)=10	.80,1
1-1C-1B-2	(1,8,4)=13	.61,.625

Figure 9. Hybrid Network

Our objective function considers two distinct performance measures. They are:

1. Minimize the total travel distance of the on-demand vehicles, and
2. Minimize the total travel time of the passengers.

Most of the work on scheduling dial-a-ride systems minimizes the first objective (total travel distance of the on-demand vehicles) subject to meeting the time window and vehicle capacity constraints. They typically do not consider the total passenger trip time in the objective function. It is usually incorporated as a constraint expressed either as a maximum ride time constraint or a time window constraint associated with the delivery point. For the extreme case such as taxi service, where there is no ridesharing, the total passenger trip time is insensitive to the schedule. As ridesharing is incorporated to the system the schedule can have some impact on the total passenger trip time. However, for hybrid systems, the selection of the path for a request can greatly impact the total passenger trip time. The passenger trip time can vary significantly depending on the path that is chosen.

In fact, in hybrid systems, it can be easily seen that the two above objectives can conflict. From the viewpoint of the customer, the second objective is the most relevant, and a strict taxi type system minimizes this objective, however, at the expense of a high cost associated with on-demand vehicle travel distance. On the other hand, the service provider prefers to minimize the first objective. Minimizing on-demand vehicle miles minimizes variable costs such as fuel consumption and the number of needed deployed vehicles to satisfy the demand. We do not consider the travel distance of the fixed route buses in the objective since from a day to day operational point of view they are considered a fixed cost.

7.3 Proposed Heuristic Approach

Due to the combinatorial nature of the problem, it is not possible to find optimal solutions to practical size problems in a reasonable amount of computation time. Therefore, heuristics are necessary to find a near optimal or good solution to the problem. We first derive an initial solution using an Insertion/Improvement procedure. The Insertion/Improvement procedure consists of three phases. In the first phase, all the candidate routes/paths that meet a certain criterion for each request are identified. In the second phase, an initial solution is determined by identifying a feasible path from the candidates' list that has the shortest on-demand vehicle distance. In the last phase, the initial solution is fed into an Improvement procedure. In this procedure, we try to identify an alternative path that reduces the total passenger trip time for requests that have multiple hybrid paths.

The solution from the Insertion/Improvement procedure is the initial solution in the Tabu Search. The Tabu Search consists of two functions: Re-sequencing and Re-assigning. In the Re-sequencing function, we hold the request to vehicle assignment fixed and consider alternative feasible sequences. In the Re-assigning function, we attempt to exchange requests between vehicles.

Before presenting the methodology of the proposed heuristic algorithms, we present some additional notation.

BB (r, B1, B2)	*Direct distance from bus stop B1 to bus stop B2 on fixed route r*
DD (n)	*Direct door to door distance of request n*
PB(r, B1, n)	*Direct distance from the origin point of request n to bus stop B1 on route r*
DB(r, B2, n)	*Direct distance from bus stop B2 on route r to the drop-off (destination) point of request n*

We refer here the direct distance as the Euclidean distance between any two geocoded locations (lat1, long1) and (lat2, long2) using the sphere equation:

distance = (3963*acos(cos (radians (90-lat1))*cos (radians (90-lat2))+sin (radians(90-lat1))*sin (radians (90-lat2))*cos (radians (long1-long2))))

For each bus route, we now have the distance between bus stop B1 to each pick-up point and the distance between bus stop B2 to each drop-off point. This is the total distance of request n that is traveled using the paratransit vehicle for a hybrid system. Let this variable be *DBD (r, B1, B2, n).*

$$DBD(r, B1, B2, n) = PB(r, B1, n) + DB(r, B2, n)$$

The hybrid total distance is the total distance that is traveled by the on-demand vehicle and fixed bus line. This distance is always greater than or equal to the direct distance of the same request. Let this variable be *HYB (r, B1, B2, n).*

$$HYB(r, B1, B2, n) = (DBD(r, B1, B2, n) + BB(r, B1, B2)) \geq DD(n)$$

7.3.1 Insertion/Improvement Procedure

Our heuristic procedure consists of three phases. They are:

1. Identify the candidate path set.
2. Identify an initial solution using an Insertion Procedure.
3. Update the solution using an Improvement Procedure.

Phase I of the procedure identifies candidate paths that meet the following three criteria:

- The ratio of the direct distance over the hybrid distance must be greater than or equal to a threshold level F1.

  $DD(n) / HYB(r, B1, B2, n) \geq F1$
- The ratio of the distance traveled by the on-demand vehicle over the distance on the fixed bus route must be less than or equal to a threshold level F2.

  $DBD(r, B1, B2, n) / BB(r, B1, B2) \leq F2$
- The door-to-door distance of the request must be greater than or equal to a threshold level F3.

  $DD(n) \geq F3$

We can look at the first condition as the rider’s service level or convenience. The second condition ensures that the door-to-door portion of the hybrid distance is less than the fixed route portion of the trip to justify a transfer. The third condition makes sure that no transfer to a fixed route is made if the distance of the request is short. The above three conditions work together and a path needs to satisfy all of them in order to be considered a candidate path. Figure 9 shows how the candidate paths for the hybrid system can be found using F1=0.7, F2=1, and F3=8. In the Experimental Analysis Section, we show how to compute the best values for the thresholds.

We note that Liaw, White, and Bander (1996) consider only ratio F1 in their procedure while Hickman and Blume (2000) base their selection criteria on absolute threshold values. We use both ratios F1 and F2 in our procedure since they represent a trade off between the customer service level and overall efficiency of the system. Note that the number of candidate requests and paths increases as the ratio F1 decreases and ratio F2 increases.

Note that for some requests, there may not exist any path that satisfies all the above criteria. These requests will be served strictly by the on-demand vehicles and will be referred to as “Door-to-Door”. Alternatively, some candidate requests may have one or more candidate path that satisfies the above conditions. We refer to these requests as “Hybrid”. We illustrate this differentiation between candidate request and candidate path using the Antelope Valley Transit Data, AVTA, (see Section 4.0 for a complete description of this data set). A sample of 47 requests (94 points) from the AVTA that is served by one vehicle in one day is taken to test the first phase of the heuristic algorithm using the existing 10 fixed bus routes.

Figure 10 shows the number of the candidate requests that meet the ratio F1 and F2 for various values. Figure 11 shows the number of the candidate paths that meet the ratios F1 and F2 for various values. We emphasis here that a request is considered a candidate if it has at least one candidate path. Thus many requests may have many alternative candidate paths. As it is shown in these two charts, the number of candidate requests and paths increase as the ratio F1 decreases and ratio F2 increases. Using the values of F1=0.7 and F2=1, 25 (53%) requests are found to be candidates for using the hybrid system. These requests have a total of 63 candidate paths. If we let F1=0.4 and maintain F2=1, 43 (91%) requests are found to be candidates for using the hybrid system with a total of 321 candidate paths. The sensitivity of these ratios represents a trade off between the customer service level and overall efficiency of the system.

Our heuristic procedure determines:

1. The on-demand vehicle schedule,
2. The best candidate path for each request.

As previously mentioned, the objective of the heuristic procedure is to minimize both the total distance traveled by the on-demand vehicles, TVD, and the total passenger trip time, TTT. Let t_n be the total trip time of request n including time on-board the on-demand vehicle(s), time on-board the fixed route bus, and waiting time at the enter and exist bus stops, p(i,v) be the direct predecessor of location i in sequence S_v for on-demand vehicle v (the first and last location in the sequence S_v is the depot), and dist(i,j,v) be the direct distance between locations i and j in sequence S_v. Given NT total requests, M vehicles, sequence S_v for each vehicle v, and N_v requests in S_v, TVD and TTT are computed as follows:

$$TTT = \sum_{n=1}^{NT} t_n$$

$$TVD = \sum_{v=1}^{M} \sum_{i=1}^{2Nv+1} dist(p(i,v), i, v)$$

Note that the depot is represented by locations 0 and $2N_v$+1.

We remark that the on-demand vehicle schedule has a greater impact on the TVD performance measure than that for the TTT performance measure. For example, for taxi systems the schedule has no impact on TTT. However, the selection of the best candidate path for each request greatly impacts the TTT performance measure. Hence, instead of trying to minimize the two above objectives simultaneously, our approach minimizes the appropriate objective based on the purpose of the particular routine of the heuristic. That is, an initial on-demand vehicle schedule is determined using an Insertion procedure that holds the candidate paths fixed. Since the Insertion procedure does not search for the best candidate path, we focus only on TVD in this phase. Then, this initial solution is fed into an Improvement procedure that attempts to find a better solution in terms of the passenger trip time, TTT, that does not reduce, TVD. The Improvement procedure searches the alternative candidate path list in an attempt to reduce TTT.

Figure 12 shows the steps of the Insertion procedure. For each hybrid request, the candidate paths that has the shortest distance traveled by the on-demand vehicles (i.e., the distance from origin to entry bus stop plus the distance from exit bus stop to the final destination) is selected. These candidate paths are held fixed in the Insertion procedure. The requests are then ranked based on the earliest pickup time and stored in set N. The requests are then sequentially inserted into an existing vehicle schedule if it is feasible. Feasibility here refers to no violation of time window or capacity constraints.

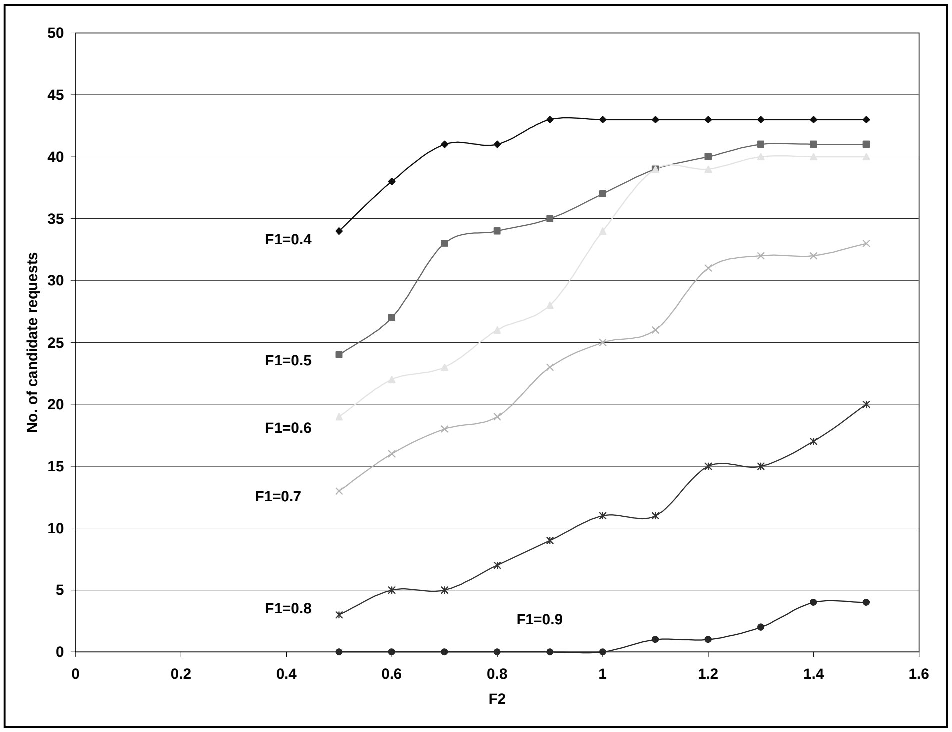


Figure 10. Number of Candidate Requests

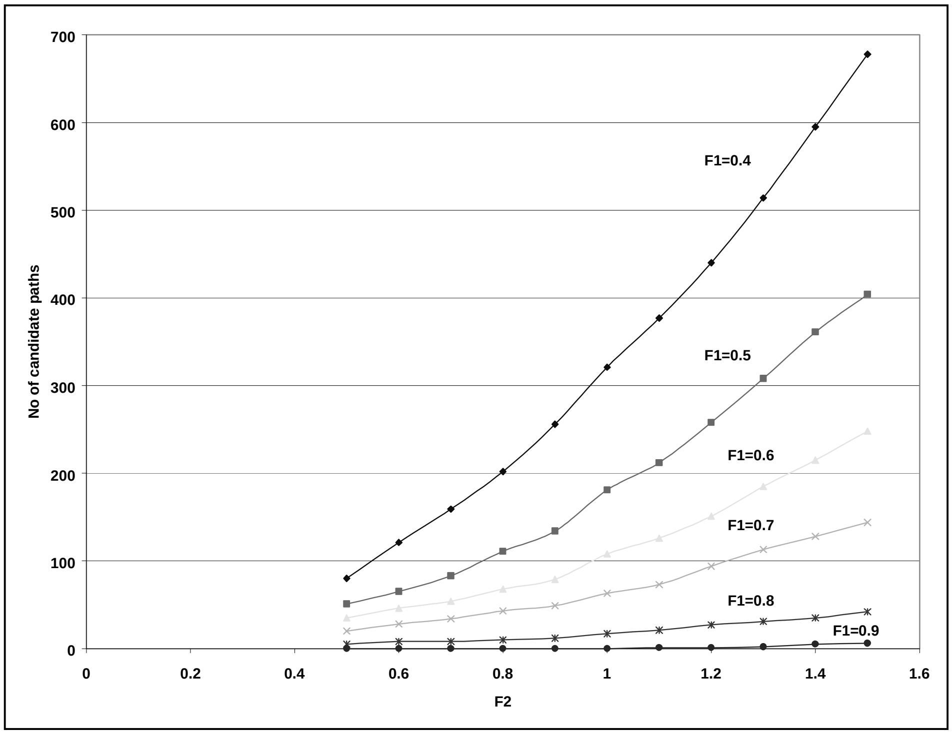


Figure 11. Number of Candidate Paths

Otherwise, a new vehicle schedule is created. As the figure shows, the on-demand vehicle that results in the smallest increase in the total distance traveled by the on-demand vehicle, TVD, is selected. The pickup and drop-off points of the current request are tentatively inserted in all feasible combinations after the pickup point of the last request in the vehicle's schedule. Feasible combinations are those in which the pickup point of a request precedes the delivery point of the same request and vehicle capacity is not violated. The request is then permanently inserted in the combination that results in the smallest increase in the total on-demand vehicle distance. Note that if the first leg of a hybrid request is inserted in the schedule, the second leg is placed into set N.

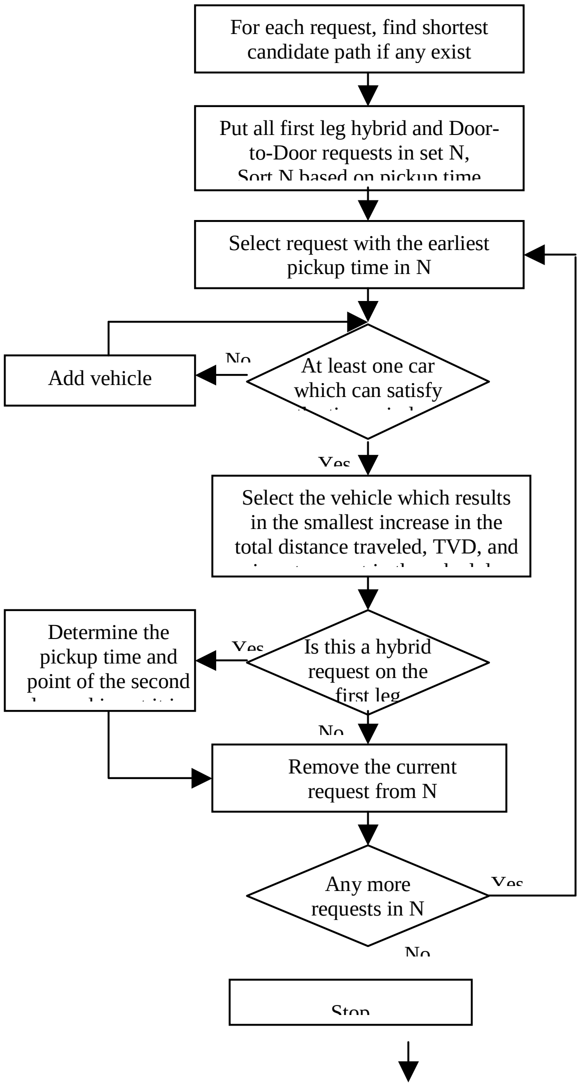


Figure 12. Insertion Procedure

The following are two examples to show how we can insert a request in an existing schedule of a vehicle. In the first case, the vehicle picks up the first passenger and then drops the same passenger off before picking up the second passenger (P1D1P2D2). In the second case, the vehicle picks up both passengers first and then drops them of (P1P2D1D2). We now illustrate the possible combinations of inserting a new passenger request. In the first case, three alternatives are evaluated while in the second case nine alternatives are evaluated.

$$\underline{\textbf{\textit{P1 D1 P2 D2}}} \left\{ \begin{array}{l} \text{P1 D1 P2 P3 D3 D2} \\ \text{P1 D1 P2 P3 D2 D3} \\ \text{P1 D1 P2 D2 P3 D3} \end{array} \right.$$

$$\underline{\textbf{\textit{P1 P2 D1 D2}}} \left\{ \begin{array}{l} \text{P1 P2 P3 D3 D1 D2} \\ \text{P1 P2 P3 D1 D3 D2} \\ \text{P1 P2 P3 D1 D2 D3} \\ \text{P1 P2 P3 D3 D2 D1} \\ \text{P1 P2 P3 D2 D3 D1} \\ \text{P1 P2 P3 D2 D1 D3} \\ \text{P1 P2 D1 P3 D3 D2} \\ \text{P1 P2 D1 P3 D2 D3} \\ \text{P1 P2 D1 D2 P3 D3} \end{array} \right.$$

The Improvement Procedure takes the initial solution from the Insertion Method and attempts to find a better solution in terms of the total passenger trip time that does not reduce the TVD. In the Insertion Method, the candidate path with the shortest on-demand vehicle travel distance is selected for the Hybrid requests. This may not be a good rule in terms of minimizing the passenger trip time since the path with the shortest on-demand vehicle travel distance may connect to a fixed route bus line that will require waiting at the bus stop and have a long travel time on the bus. That is, the selection of the candidate path can greatly impact the TTT performance measure. The Improvement Procedure searches for other candidate paths of each hybrid request that can reduce the passenger trip time. Figure 13 shows the steps of the Improvement phase.

Note that the Improvement procedure does not enumerate all possible combinations in determining the solution. That is, once the best candidate path for a particular request is found it is held fixed. Suppose that there are 4 candidate (hybrid) requests that have 8, 7, 6 and 9 candidate paths respectively. The total number of solutions considered will be 8+7+6+9=30. This means that 30 different solutions are considered. However, if we enumerate all the possible combinations of the candidate paths we would need to consider 8*7*6*9=3024.

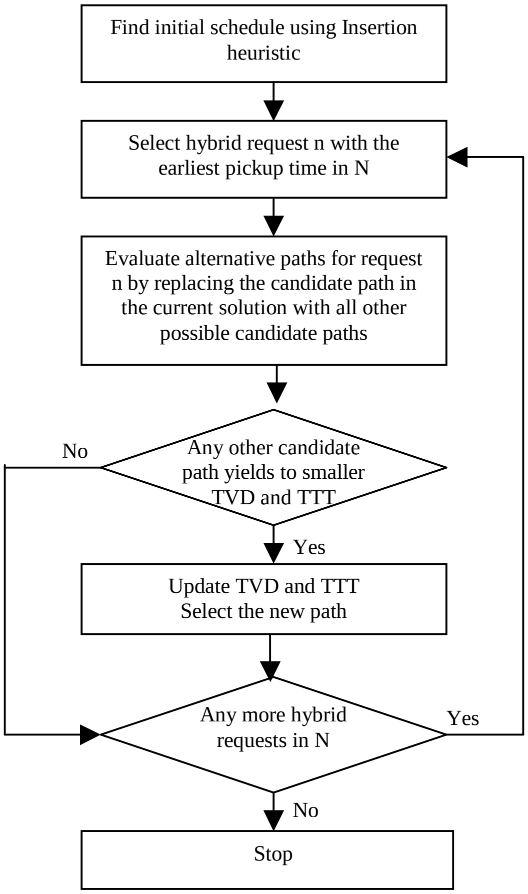


Figure 13. Improvement Procedure

7.3.2 Tabu Search

In the Tabu Search procedure we attempt to find an improved vehicle schedule holding the selection of the candidate paths fixed from the Improvement Procedure. Hence, the Tabu Search focuses on finding a better solution in terms of the total travel distance of the on-demand vehicles, TVD, while not degrading the solution quality of the total passenger trip time, TTT. That is, a solution is only updated only if it improves TVD without decreasing TTT.

The main idea behind the Tabu Search is to maintain a list of forbidding moves by which solutions are prevented to be visited again, thus preventing infinite cycles. As we previously mentioned Tabu Search has shown to be effective in solving routing problems.

The Tabu Search consists of two strategies to improve the vehicle and customer schedule, which are a Re-sequencing strategy and Re-assigning strategy. The Re-sequencing strategy re-sorts the sequence within a vehicle while the Re-assigning strategy searches to remove a request from a particular vehicle to insert it in another vehicle. The two strategies aim to detect better vehicle schedules. Figure 14 displays the proposed overall methodology. Note that we iterate between the Re-sequencing and Re-assigning procedures because we try to find a better sequence when a new request to vehicle assignment is found.

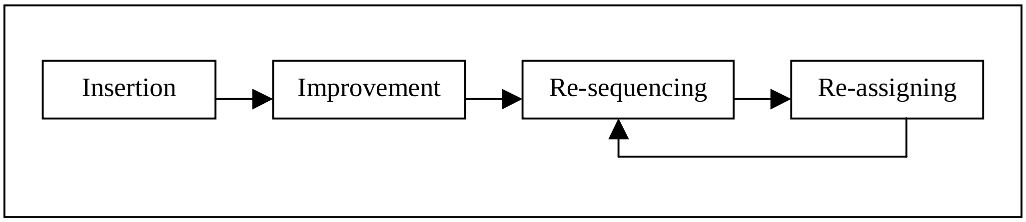


Figure 14. Proposed Methodology

<u>Re-sequencing</u>

In this strategy, we use a Tabu Search technique in order to find an improved requests sequence, which leads to shorter vehicle distance in every vehicle while holding the request to vehicle assignment fixed. In the case of a strictly door-to-door delivery method, requests are entirely satisfied at the delivery point. Hence, the schedule of the vehicles is going to be always feasible if we just satisfy the pickup time windows of the requests during Re-sequencing. However, this is not true for the hybrid delivery method where hybrid requests have two delivery points (two legs) serviced by possibly two different vehicles. Also, due to the dependency between the two trips of the hybrid request, it is necessary to set a delivery as well as a pickup time window of every first leg of a hybrid request in each vehicle schedule in order to maintain the feasibility in every vehicle schedule. To clarify this issue, we present the following example where BS1 is the entry bus stop and BS2 is the exist bus stop:

Suppose there is a hybrid request which has the following schedule (7:00 – 7:07) from origin point to BS1 using vehicle 1, (7:10 – 7:25) from BS1 to BS2 in the bus, and (7:27 – 7:32) from BS2 to final destination in vehicle 2. By re-sequencing vehicle 1's schedule without adding a delivery time window, the passenger might end up with a delivery time of 7:11 to BS1. In this case he/she will miss the 7:10 bus and use the 7:30 bus, which arrives at the exit bus stop (BS2) at 7:45. Therefore, ignoring the delivery time of the first leg of a hybrid request in one on-demand vehicle might end up with an infeasible schedule in another on-demand vehicle.

In the Re-sequencing strategy, the schedule is improved by moving individual predecessor (pickup point) and/or successor (delivery point) forward and/or backward in their corresponding route. Three conditions need to be satisfied while moving the pickup and delivery pair in order to have a feasible schedule. The first one is the precedence constraint where the pickup point of any request must be visited before the delivery point of the same request. The second is the on-demand vehicle capacity constraint. The third one is the pickup time window (and the delivery time window for the first leg of the hybrid requests). Since the problem in this technique is single vehicle PDP, the coupling constraint can not be violated. The coupling constraint is that once the vehicle picks up a passenger, the same vehicle must drop him/her off at his/her final destination point.

To minimize the search space and consequently the *Tabu* memory, the search is restricted by what we refer to as min (S_n) and max (E_n) request positions. These tell how far, the request can be moved backward and forward without causing guaranteed infeasibility (Barnes and Carlton, 1995).

Below we show an illustration of the above concept for two possible cases. Figure 15.a shows a single vehicle schedule where the first and the last nodes represent the dispatching center or the depot. The pickup point and delivery point of request "n", which is intended to be moved, are the fourth and the sixth nodes respectively (e.g., $P_n = 4$, $D_n = 6$). After finding the min ($S_n=2$) and max ($E_n=8$) position of the request, we can determine the set of all the possible sequences of request n, which is {(3,4), (3,5), (3,6), (3,7), (4,5), (4,6), (4,7), (5,6), (5,7), (6,7)}.

In figure 15.b, $(P_n,D_n)=(4,5)$ and $(S_n,E_n)=(3,6)$. The set of all the possible sequences equals {(4,5)}. Consequently, determining the values S_n and E_n before starting Re-sequencing is significant in minimizing the search space.

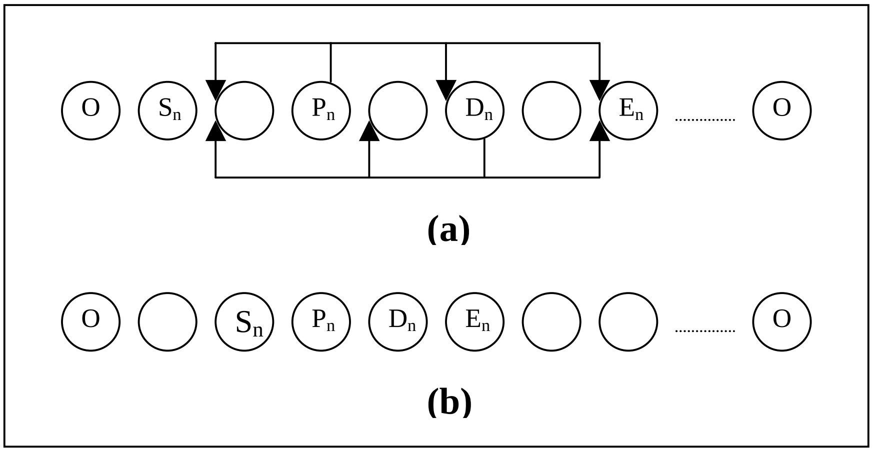


Figure 15. Illustration of the S_n and E_n Concept

We use a tabu search description similar to the one introduced by Rardin (1998) to illustrate both the Re-sequencing and Re-assigning strategies. The following are the steps of the Re-sequencing strategy:

- Initialization: The initial schedule (SCH (0)) is obtained by the improvement heuristic and the initial sequence is added to the Tabu list. Let the current best schedule (SCH*) equal SCH (0) and let the iteration index (t) equal 0. Let TVD* and TTT* be the resulting total on-demand vehicle distance and total passenger trip time.
- Stopping: If there is no non-tabu sequence leading to a feasible solution neighbor of the current schedule SCH (t) or $t = t_{max}$, then stop. The current SCH* is an approximate optimum schedule.
- Move: Select a non-tabu feasible sequence neighbor to the current schedule SCH(t) and find SCH(t+1).
    - Criterion: In this sequence selection step, all the feasible moves as shown in Figure 15 are evaluated. The sequence that leads to the best value of the objective function, TVD, without increasing TTT, is selected.
- Compare: If the objective function value of SCH(t+1) is superior to that of SCH*, let SCH* = SCH(t+1), set TVD*=TVD and TTT*=TTT.

- Tabu List: Remove from the list of forbidden tabu sequences any that have been on it for a sufficient number of iterations, and add the current sequence of SCH(t+1) to the list.
- Increment: Let t = t + 1, and go back to the stopping step.

<u>Re-assigning</u>

In this strategy, we try to search for a better request to vehicle assignment using a tabu search technique to produce a better solution (shorter vehicle distance). The search space of this method is larger than the one for the Re-sequencing method. Therefore, only few requests with a high potential for improvement are considered to be moved from their current vehicle schedule to another vehicle schedule. The main idea behind the Re-assignment is to move to undiscovered regions and try to search for better solutions there.

In the Re-assigning approach, two questions need to be answered. They are (1) which request should be removed from its current vehicle schedule, and (2) where should it be inserted? To answer the first question, we set the following criteria:

- Remove the request, which has the maximum saving distance if it is removed, which equals the distance of the removed arcs minus the distance of the added arcs.

Figure 16 illustrates the above criteria. In Figure 16.a, the request that will be removed from the current on-demand vehicle schedule is request “n” which has adjacent pickup and delivery points. The eliminated arcs are $X_{\alpha,Pn}$, $X_{Dn,\beta}$ and $X_{Pn,Dn}$. The arc $X_{\alpha,Pn}$ represents the distance required to reach the pickup point of the request from the previous adjacent point ”α”. The arc $X_{Dn,\beta}$ represents the distance from the request delivery point to the next adjacent point ”β”. The arc $X_{Pn,Dn}$ represents the distance from the request pickup point to the delivery point. The new arc that will be added after removing the request ”n” is $X_{\alpha,\beta}$ which represents the distance from α to β. The double lines in Figure 16.a are the eliminated arcs while the dotted lines are the new added arcs.

Saving = $X_{\alpha,Pn} + X_{Dn,\beta} + X_{Pn,Dn} - X_{\alpha,\beta}$

In Figure 16.b, the request that will be removed “n” does not have adjacent pickup and delivery points. Following the same notation concept, the saving distance will be:

$$\text{Saving} = X_{\alpha,Pn} + X_{Dn,\beta} + X_{Pn,\gamma} + X_{\gamma,Dn} - X_{\alpha,\gamma} - X_{\gamma,\beta}$$

We use the saving function as the criterion for selecting the node removal. Also, the same concept of removing is followed for insertion. We will evaluate the insertion of this request on all other on-demand vehicles. The feasible schedule that has the minimum increment of distance will be chosen. The time window and capacity constraints need to be satisfied in order to call the schedule feasible.

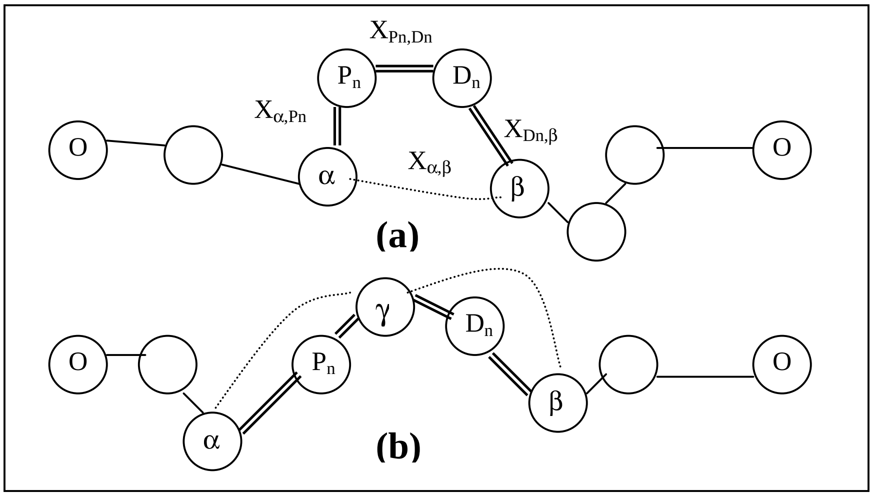


Figure 16. Illustration of the Saving Concept

The following are the steps of the Re-assigning strategy:

- Initialization: The initial schedule (SCH (0)) is obtained by the final solution of the Tabu sequencing procedure and the Tabu List is empty. Let the current best schedule (SCH*) equal SCH (0) and let the iteration index (t) equal 0. Let TVD* and TTT* be the resulting total on-demand vehicle distance and total passenger trip time.

- Stopping: If there is no non-tabu move leading to a feasible solution neighbor of the current schedule SCH (t) or t = t_{max}, then stop. The current SCH* is an approximate optimum schedule.
- Move: Select a non-tabu feasible move neighbor to the current schedule SCH(t) and find SCH(t+1).
  - Removing Criterion: Remove the request from vehicle (V1) that results in the largest decrease in the total distance traveled.
  - Insertion Criterion: Insert the request in vehicle (V2) that results in the smallest increase in the total distance traveled.
  - Re-sequence V1 and V2 using the Tabu re-sequencing procedure.
- Compare: If the objective function value of SCH(t+1) is superior to that of SCH*, let SCH* = SCH(t+1), set TVD*=TVD and TTT*=TTT
- Tabu List: Remove from the list of forbidden tabu requests any that have been on it for a sufficient number of iterations, and add the current request of SCH(t+1) to the list.
- Increment: Let t = t + 1, and go back to the stopping step.

7.4 Experimental Analysis

This section presents the computational experiments that have been performed to test the heuristics using Antelope Valley Transit Authority (AVTA). This agency was selected because the travel distances in Antelope Valley are large enough to justify a transfer point between the two different types of transit services. Furthermore, most of the disabled and elderly passengers travel to a central location where most of the hospitals are located. This is shown in Figure 17. The area around Palmdale Street (Lower circle) is mostly a residential area while the area around Avenue J-8 (Upper circle) is mostly hospitals and a commercial district. Furthermore, there are fixed bus routes that connect these two areas, which are also shown in the figure by dark lines.

Antelope Valley Transit Authority provides both fixed route and dial-a-ride services in Lancaster County, California. The fixed route portion of their service consists of ten lines with each line consisting of many bus stops. In terms of their on-demand service, we received data for the period of two weeks, February 14, 2000 to February 25, 2000 for a total consisting of nine weekdays. AVTA operates from 6:00 AM to 7:30 PM during the weekdays. The total number of requests served during these days was 1029. The number of drivers per day varied from 4 to 12 during this period (Average=9.22). The average number of requests served per day per driver was 15.79 with the maximum number being 30.33 on any given day.

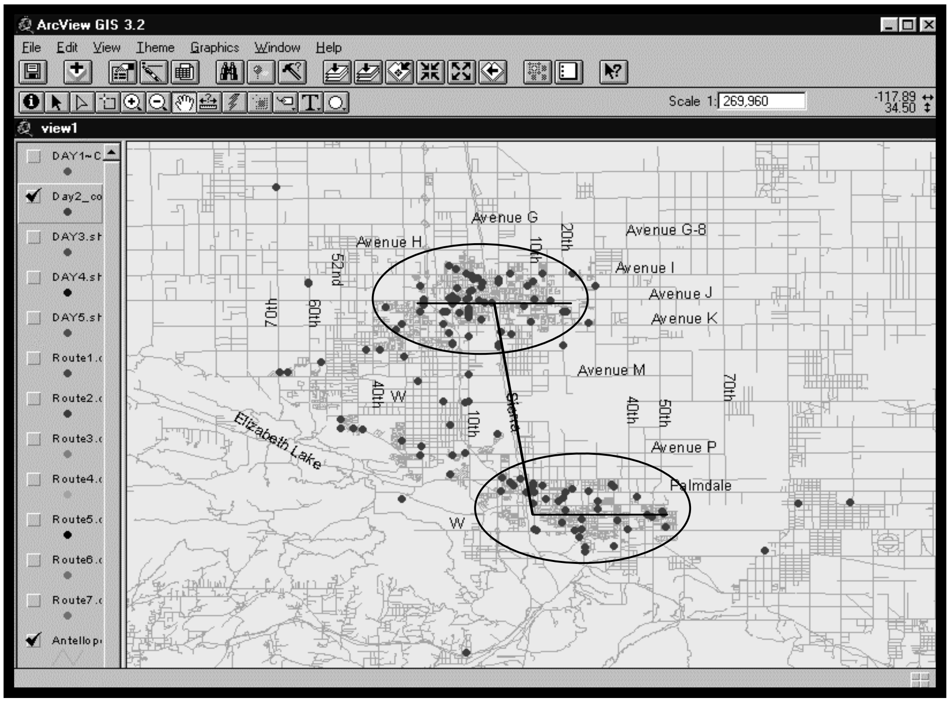


Figure 17. Snapshot of Arcview for the AVTA data

The various heuristics methods are compared using the AVTA data in terms of total on-demand vehicle distance and total customer trip time. We benchmark the results against AVTA's manual schedule. In these comparisons, we use the same number of on-demand vehicles as used by AVTA. The heuristic methods are compared to each other in terms of solution quality and computational time. We implemented the algorithms using C++ on a SUN Enterprise E4500/E5500 System.

Table 5 summarizes the AVTA data. For each day, we list the number of on-demand vehicles, the number of transportation requests, and the number of requests that are candidates for the hybrid system. We also list the F1, F2, and F3 values used for that day. In general, the selected ratios give 18.6% of the requests as candidates for the hybrid system.

We next demonstrate the analysis that we used for selecting the appropriate ratios F1 and F2. Figures 18 and 19 show the sensitivity of the vehicle distance and customer trip time to various values of the ratios F1 and F2 for one of the days using the Insertion Procedure. As the figures show, these two measures are sensitive to the ratios F1 and F2, and there is a trade off between balancing the vehicle distance and customer trip time. For example, the combination (F1 = 0.6, F2 = 0.95) that gives the smallest vehicle distance results in a high customer trip time. Thus, for this day we use a combination of (F1 = 0.6, F2 = 1.1).

Table 5. Summary Data

Day	Number of Vehicles	Requests	Hybrid Requests	F1,F2, F3
1	6	76	15	.6,1.1, 9
2	12	155	30	.65,1.2, 9
3	10	150	29	.65,.95, 9
4	10	135	18	.75,.9, 9
5	10	138	17	.75,1, 9
6	10	103	19	.65,.85, 9
7	12	139	22	.6,.8, 9
8	4	42	14	.6,.85, 9
9	9	91	27	.65,.9, 9
Total	83	1029	191	
Percent			18.6%	

Table 6 presents a general comparison between all the rules in terms of total vehicle distance and total customer time. The Re-sequencing strategy is called TABU-S and the Re-assigning strategy is called TABU-A in this section. Recall, the initial solution for the TABU-S heuristic is the solution from the Improvement procedure, and the TABU-A procedure reiterates between the Re-sequencing and Re-assigning strategies. As the table shows, the hybrid scheduling delivery method (TABU-S) decreases both the total vehicle distance and total customer time by 16.6% and 8.7% respectively compared to the manual schedule that uses strictly the curb-to-curb delivery method. Table 7 shows the on-demand vehicle distance and customer trip time for each day for each routing heuristic. For the nine days, the distance traveled by the on-demand vehicles decreases as the CPU time needed to implement the heuristic increases, which shows the common trade off between the solution quality and the computational time.

Also, it is shown that by applying TABU-A after TABU-S, the solutions are not significantly improved at the expense of a relatively large CPU time.

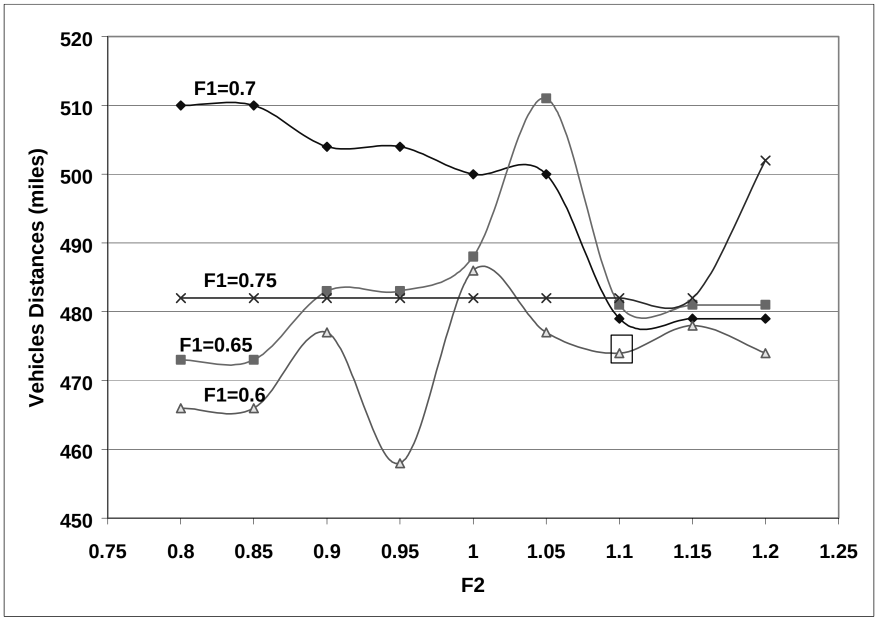


Figure 18. Sensitivity Analysis (Vehicle Distance)

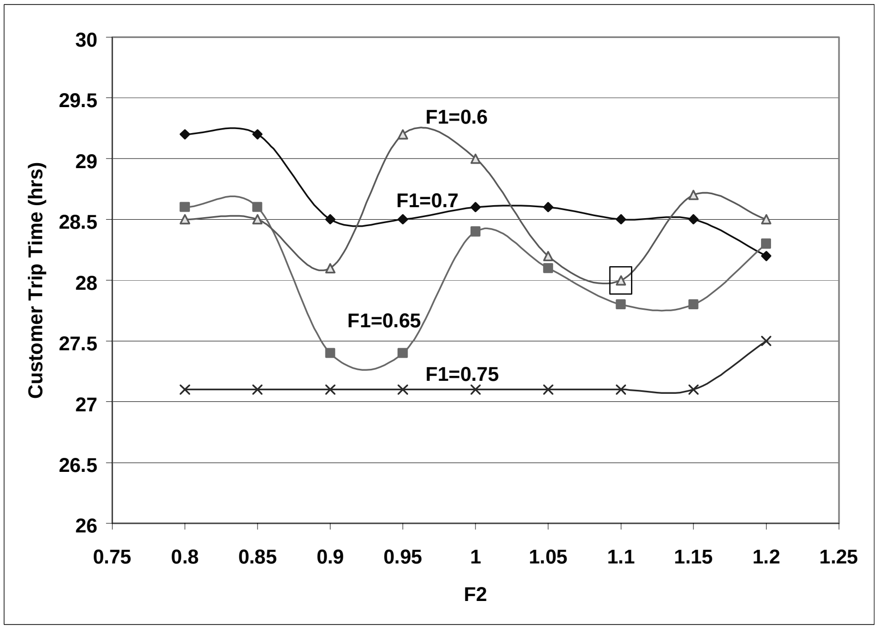


Figure 19. Sensitivity Analysis (Customer time)

Table 6. Total Vehicle Distance and Customer Time

Rule	Vehicle Distance (miles)	Customer Time (hours)	(+/-) % of Manual Distance	(+/-) % of Manual Time	CPU Time (seconds)
Insertion	6737	442.5	-11.8%	-1.6%	9
Improvement	6593	422.7	-13.6%	-6.0%	231
TABU-S	6365	410.6	-16.6%	-8.7%	623
TABU-A	6338	411.7	-17.0%	-8.5%	1357
Manual	7635	449.7	0.0%	0.0%	NA

Table 7. Daily Vehicle Distance and Customer Time

	Insertion		Improvement		TABU-S		TABU-A	
Day	Vehicle Distance (miles)	Customer Time (hours)	Vehicle Distance (miles)	Customer Time (hours)	Vehicle Distance (miles)	Customer Time (hours)	Vehicle Distance (miles)	Customer Time (hours)
1	487	29.0	474	28.0	459	26.6	453	25.9
2	1001	67.9	973	62.6	949	61.5	945	61.4
3	918	61.3	915	60.5	882	59.3	881	59.3
4	809	47.9	804	47.8	787	46.5	779	47.1
5	947	58.1	915	55.0	897	53.4	897	53.4
6	694	49.7	657	43.6	640	42.8	640	42.8
7	1024	74.6	1007	72.5	946	69.4	943	69.4
8	297	16.5	295	16.4	273	15.7	273	15.7
9	560	37.5	553	36.3	532	35.4	527	36.7

We next examine the total customer trip time in more detail for the hybrid requests. Note that the previous reported trip times included all requests (i.e., hybrid and strictly door-to-door). For hybrid requests, the total trip time includes the time on the on-demand vehicles, time waiting at the entry and exit bus stops, and time on the fixed bus routes. Table 8 shows the breakdown of the total trip time for the schedules generated by the TABU-S heuristic. For example, in Day 2, of the 61.5 total hours of customer trip time 37.0 is for the hybrid requests. The last four columns show the breakdown into the various components. The entry bus stop is stop 1 and the exit bus stop is stop 2. In the table, we also list the percentage above the manual schedule for the hybrid customer trip times. When considering all the customers, we previously showed that the TABU-S heuristic generated schedules with lower total customer trip times than the manual schedule. However, when only counting the hybrid requests, Table 8 shows that for these passengers their trip times will increase moderately with an overall 5.4% increase over the manual schedule. This is to be expected since these passengers require two modes of transportation to satisfy their requests.

Another important observation from this table is that the customer waiting time at the exit bus stop is significantly less than the customer waiting time at the entry bus stop. This is due to the fact that there are time windows associated with the exit bus stop since it is considered a pickup point. Thus these windows place a restriction on the waiting time at the exit bus stop. Since the entry bus stop is considered a destination point, there are no time windows associated with these locations. We attempt to minimize the waiting time at the entry bus stops by inserting vehicle idle time if possible in order to have the passenger arrive as close as possible to the departure time of the fixed bus line.

Table 8. Components of Customer Trip Time for TABU-S

Day	All Requests Total Time	Door-to-Door Requests Total Time	Hybrid Requests Total Time	% Above Manual	Hybrid Requests Time in Vehicle	Hybrid Requests Time in Bus	Hybrid Requests Time at Bus Stop1	Hybrid Requests Time at Bus Stop2
1	26.6	14.65	11.95	-7.4%	4.1	6.6	1.2	0.05
2	61.5	37.0	24.5	+1.3%	8.9	11.2	3.4	1.0
3	59.3	33.9	25.4	+1.5%	6.7	11.1	6.6	1.0
4	46.5	34.1	12.4	+1.8%	4.5	5.3	1.8	0.8
5	53.4	41.0	12.4	+6.5%	4.5	5.3	1.3	1.3
6	42.8	27.1	15.7	+36.5%	7.3	5.8	1.9	0.7
7	69.4	51.4	18.0	+17.9%	5.1	8.5	3.6	0.8
8	15.7	7.2	8.5	-11.6%	2.4	4.0	1.8	0.3
9	35.4	15.7	19.7	+5.9%	6.3	9.6	3.0	0.8
Total	410.6	262.05	148.55	+5.4%	49.8	67.4	24.6	6.75

Although the above analysis shows that the hybrid approach outperforms the manual scheduling method used at AVTA, we next compare it against using an insertion algorithm on the data set assuming all requests are served as strictly curb-to-curb. Table 9 displays the results for this case. Comparing it against the Improvement Method when some of the requests are hybrid (results in Table 6), the total vehicle miles increases by 11.04% when there are no hybrid requests, but the total customer trip time decreases by 1.23%. This illustrates the benefit of using a hybrid approach in reducing the miles traveled by the on-demand vehicles. However, this may come at the expense of increased passenger trip times. Our proposed approach attempts to balance these two components in determining a schedule.

Table 9. Comparison with Strictly Curb-to-Curb Service

	Door-to-Door	
Day	Vehicle Distance (miles)	Customer Time (hours)
1	507	28.2
2	1125	63.2
3	1022	56.3
4	876	49.5
5	1012	55.6
6	704	41.5
7	1107	70.6
8	323	16.3
9	645	36.3
Total	7321	417.5

8.0 Conclusion

We have reviewed and identified technologies that are currently being implemented and emerging technologies that have the potential to improve system performance, surveyed commercial scheduling and dispatching software in order to record their functionality, and conducted in-depth phone interviews and held site visits at transit agencies in order to document how public agencies are adopting the software. Although this review shows the potential benefit of deploying ITS in DRT systems, it alone is not the complete answer for meeting the increased demand of these types of services and for satisfying the strict guidelines of ADA. New innovative service delivery methods that complement the technology need to be studied.

Since most dial-a-ride programs for the transport of elderly and disabled persons are heavily subsidized programs, the increased usage of these curb-to-curb services has put significant budget pressures on most transit agencies. In this research, we have investigated a hybrid system consisting of both on-demand vehicles and fixed route lines for servicing this type of request. We developed a heuristic solution approach for scheduling a hybrid system.

The first heuristic procedure consists of three phases. In the first phase, all the candidate routes/paths that meet a certain criterion for each request are identified. In the second phase, a feasible path from the candidates' list that has the shortest on-demand vehicle distance is selected and inserted into the vehicle schedule. The solution of the Insertion procedure is fed into the Improvement procedure. In this procedure, we try to identify an alternative path for requests that have multiple hybrid paths that can satisfy the demand. The second type of heuristic is based on Tabu Search which uses the solution from the Improvement procedure as the initial solution.

We tested our heuristics on actual data from AVTA. Overall, this analysis showed that shifting some of the demand to a hybrid service route (18.6% of the requests) reduces the on-demand vehicle distance by 16.6% and the overall customer trip time by 8.7% over the manual schedule using the TABU-S heuristic. However, for these customers who take the hybrid delivery method (18.6% of the requests), their trip time will increase on average by 5.4%.

In terms of computation time, the Tabu methods (TABU-S and TABU-A) took considerable more CPU time in finding a solution. The Improvement heuristic was computationally efficient with a solution quality close to the Tabu methods. This characteristic is especially important when applying the proposed approach to a real-time environment. The Tabu methods may take too long computationally to apply in real-time.

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http://www2.ncsu.edu/eos/service/ce/research/stone_res/tahmed_res/www/index.html

http://www2.ncsu.edu/eos/service/ce/research/stone_res/tahmed_res/www/Sec2.html#S9

Software vendor web sites for information

Others

Wall Street Journal, Issue June 24, 1993

Appendix A

This information is taken from the APTS Deployment Report developed by the U.S. Department of Transportation in 1999.

Table A.1. List of Transit Agencies Deploying AVL

Sr No.	Transit Authority	Automatic Vehicle Location System
1	Birmingham-Jefferson County Transit Authority, Birmingham, AL	GPS
2	City of Mesa, Mesa, AZ	Unspecified
3	Regional Public Transportation Authority, Phoenix, AZ	GPS
4	Sun Tran, Tucson, AZ	GPS
5	ASI, Los Angeles, CA	GPS
6	Alameda Contra Costa Transit District, Oakland, CA	GPS
7	Antelope Valley Transit Authority Lancaster, CA	GPS
8	Arcadia Transit, Arcadia, CA	GPS
9	Camarillo Area Transit, Camarillo, CA	GPS
10	Central Contra Costa Transit Authority Concord, CA	GPS
11	City of Alameda Ferry Services, Alameda, CA	DGPS
12	City of Glendale, Glendale, Ca	GPS
13	City of Riverside Special Transportation, Riverside, CA	GPS
14	Eastern Contra Costa Transit Authority (Tri-DeltaTransit),Antioch,CA	GPS
15	Emery Go Round, Oakland, CA	GPS
16	Fairfield-Suisan Transit, Fairfield, CA	GPS
17	Fresno Area Express, Fresno, CA	GPS
18	Gardena Municipal Bus Line Gardena, CA	GPS
19	Golden Empire Transit District, Bakersfield, CA	Unspecified
20	Golden Gate Bridge, Highway and Transportation District, San Francisco, CA	Unspecified
21	Livermore/Am adore Valley Transit Authority, Livermore, CA	GPS
22	Los Angeles County Metropolitan Transportation Authority, Los Angeles, Ca	SO, DGPS
23	Modesto Area Express, Modesto, CA	GPS

24	North San Diego County Transit District,	GPS
	Oceanside, CA	
25	Norwalk Transit System, Norwalk, CA	GPS
26	Omnitrans, San Bernardino, CA	DGPS
27	Orange County Transportation Authority,	GPS
	Orange, CA	
28	Outreach and Escorts Inc., San Jose, CA	DGPS
29	Riverside Transit Agency, Riverside, CA	DK
30	San Diego Transit Corporation, San Diego, CA	GPS
31	San Diego Trolley, San Diego, CA	GPS
32	San Francisco Municipal Railway,	SO
	San Francisco, CA	
33	San Joaquin Regional Transit District,	DGPS
	Stockton, CA	
34	San Mateo County District (Samtrans),	GPS
	San Carlos, Ca	
35	Santa Clara Valley Transit Authority,	DGPS
	San Jose, CA	
36	Santa Monica Municipal Bus Lines,	OTR
	Santa Monica, CA	
37	Simi Valley Transit, Simi Valley, CA	Unspecified
38	Sonoma County Transit, Santa Rosa, CA	GPS
39	Stanislaus Regional Transit, Modesto, CA	GPS
40	Sunline Transit Agency, Thousand Palms, CA	GPS
41	The Vine/Napa Valley Transit, Napa, CA	GPS
42	Thousand Oaks Transit, Thousand Oaks, CA	GPS
43	Vallejo Transit and Baylink Ferry, Vallejo, CA	GPS
44	Avon/Beaver Creek Transit, Avon, CO	GPS
45	Colorado Springs Transit, Colorado Springs, CO	DGPS
46	Eagle County Regional Transportation Authority,	Unspecified
	Avon, CO	
47	Mesa County, Grand Junction, CO	GPS
48	Regional Transit District, Denver, CO	DGPS
49	Transfort, Fort Collins, CO	Unspecified
50	Connecticut Limousine, Milford, CT	DGPS
51	Greater New Heaven Transit District, Hamden, CT	GPS
52	DART First State, Delaware Transit Core,	GPS
	Dover, DE	
53	Arc Transit, Palatka, FL	GPS
54	Broward County Mass Transit, Pompano Beach, FL	GPS
55	Central Florida Regional Transportation Authority	GPS
	(LYNX), Orlando, FL	
56	Gainsville Regional Transit System, Gainsville, FL	Unspecified
57	Hillsborough Area Regional Transit Authority,	SO
	(HART), Tampa, FL	
58	St. Lucie County Council on Aging,	GPS
	Prot St. Lucie, FL	

59	Tri-County Commuter Rail Authority,	GPS
	Ft Lauderdale, FL	
60	Metropolitan Atlanta Rapid Transit Authority,	DGPS
	(MARTA) Atlanta, GA	
61	Oahu Transit Services (The Bus), Honolulu, HI	GPS
62	City of Davenport, Davenport, IA	Unspecified
63	City of Dubuque-Keyline Transit, Dubuque, IA	GPS
64	Des Moines Metropolitan Transit Authority,	GPS
	Des Moines, IA	
65	Five Seasons Transportation and Parking,	GPS
	Cedar Rapids, IA	
66	Metropolitan Transit Authority of Black Hawk County,	GPS
	Waterloo, IA	
67	Sioux City Transit System, Sioux City, IA	Unspecified
68	University of Iowa, CAMBUS, Iowa City, IA	GPS
69	Chicago Transit Authority, Chicago, IL	DK
70	Cook-Dupage Transportation Company Inc.,	OTR
	Chicago, IL	
71	PACE Suburban Bus, Arlington, Heights, IL	GPS
72	Rock Island County Mass Transit (METROLINK),	GPS
	Rock Island, IL	
73	Urbana Champaign Mass Transit District, Urbana, IL	GPS
74	Bloomington Public Transportation Corporation,	GPS
	Bloomington, IN	
75	Muncie Indiana Transit System, Muncie, IN	Unspecified
76	Northern Indiana Commuter Transportation District,	Unspecified
	Chesterton, IN	
77	Wichita Metropolitan Transit Authority, Wichita, KS	GPS
78	Transit Authority of River City, Louisville, KY	SO
79	City of Alexandria, Alexandria, LA	Unspecified
80	Crescent City Connection Division, New Orleans, LA	Unspecified
81	Cape Cod RTA, Dennis, MA	GPS
82	Cape Island Express Lines Inc., New Bedford, MA	Unspecified
83	GATRA, Attleboro, MA	DGPS
84	Maryland Transit Administration (MARC Train	OTR
	Service), BWI Airport, MD	
85	Montgomery County Transit, Rockville, MD	DGPS
86	Monhegan-Thomston Boat Line, Port Clyde, ME	GPS
87	Ann Arbor Transportation Authority, Ann Arbor, MI	SO
88	Battle Creek Transit, Battle Creek, MI	Unspecified
89	Capital Area Transportation Authority, Lansing, MI	GPS
90	Detroit Transportation Corporation, Detroit, MI	Unspecified
91	Suburban Mobility Authority For Regional	GPS
	Transportation (SMART), Detroit, MI	

92	Mankato Heartland Express, Mankato, MN	Unspecified
93	Metro Transit, Minneapolis, MN	GPS
94	St. Cloud Metropolitan Transit Commission, St. Cloud, MN	GPS
95	Kansas City Area Transit Authority, Kansas City, MO	SO
96	Asheville Transit Authority, Asheville, NC	SO
97	Capital Area Transit, Raleigh, NC	Unspecified
98	Greensboro Transit Authority, Greensboro, NC	GPS
99	Rocky Mount Transit, Rocky Mount, NC	GPS
100	Winston-Salem Transit Authority, Winston-Salem, NC	Unspecified
101	Transit Authority of City of Omaha, Omaha, NE	GPS
102	COAST, Portsmouth, NH	GPS
103	New Jersey Transit, Newark, NJ	SO, GPS
104	City of Santa Fe (Santa Fe Trails), Santa Fe, NM	Unspecified
105	SunTran, Albuquerque, NM	GPS
106	Citizen Area Transit, Las Vegas, NV	DGPS
107	Regional Transportation Commission of Washoe County, Reno, NV	Unspecified
108	Capital District Transportation Authority, Albany, NY	NY
109	Liberty Lines Transit, Yonters, NY	SO
110	Long Island Bus, Garden City, NY	GPS
111	New York City Department of Transportation, New York, NY	GPS
112	New York City Transit, Brooklyn, NY	DGPS
113	Niagara Frontier Transportation Authority, Buffalo, NY	GPS
114	Rockland County DO Public Transport, Pomona, NY	Unspecified
115	Suffolk County Department of Public Works-Transportation Divison, Yaphank, NY	Unspecified
116	Westchester County DOT, White Plains, NY	SO, GPS
117	Central Ohio Transit Authority, Columbus, OH	SO
118	Greater Cleveland Regional Transit Authority, Cleveland, OH	DGPS
119	Lake Tran, Grand River, OH	GPS
120	Metro Regional Transit Authority, Akron, OH	GPS
121	Miami Valley Regional Transit Authority, Dayton, OH	Unspecified
122	Southwest Ohio Regional Transit Authority, Cincinnati, OH	GPS
123	Western Reserve Transit Authority, Youngstown, OH	GPS
124	Metropolitan Tulsa Transit Authority, Tulsa, OK	GPS
125	Lane Transit City Bus, Eugene, OR	GPS
126	Tri-County Metropolitan, Portland, OR	DGPS
127	Area Transportation Authority of North Central	Unspecified

	Pennsylvania, Johnsonburg, PA	
128	Beaver County Transit Authority, Rochester, PA	GPS
129	County of Lackawanna Transit System (COLTS),	GPS
	Scranton, PA	
130	Luzerne County Transportation Authority, Kingston, PA	GPS
131	Southeastern Pennsylvania Transportation Authority,	DGPS
	Philadelphia, PA	
132	Metropolitan Bus Authority, San Juan, PR	SO, GPS
133	Puerto Rico Highway and Transportation Authority,	OTR
	San Juan, PR	
134	Rhode Island Public TA, Providence, RI	GPS
135	Pee Dee Regional Transportation Authority,	GPS
	Florence, SC	
136	Santee Wateree Regional Transportation Authority,	GPS
	Sumter, SC	
137	Johnson City Transit System, Johnson City, TN	GPS
138	Metropolitan Transit Authority, Nashville, TN	Unspecified
139	Corpus Christi Regional Transportation Authority,	Unspecified
	Corpus Christi, TX	
140	Dallas Area Rapid Transit (DART), Dallas, TX	GPS
141	Metro Transit Authority of Harris County, Houston, TX	Unspecified
142	Sun Metro, El Paso, TX	Unspecified
143	Via Metropolitan Transit, San Antonio, TX	DGPS
144	Blacksburg Transit, Blacksburg, VA	GPS
145	Potomac and Rappahannock Transportation Commission,	GPS
	Woodbridge, VA	
146	Tidewater Transportation District Commission (TTDC),	Unspecified
	Norfolk, VA	
147	Virginia Railway Express, Alexandria, VA	Unspecified
148	Ben Franklin Transit, Richland, WA	GPS
149	King County Metro, Seattle, WA	SO, GPS
150	Kitsap Transit, Bremerton, WA	GPS
151	Spokane Transit Agency, Spokane, WA	GPS
152	Kenosha Transit, Kenosha, WI	GPS
153	Milwaukee County Department of Transportation,	DGPS
	Milwaukee, WI	
154	Sheboygan Transit System, Sheboygan, WI	LC

Appendix B

List of Questions for Phone Interview

- What intelligent transportation system technologies are you using?
- How do you use software in scheduling, dispatching, reservation, real time scheduling, maintenance, vehicle tracking, data transferring etc.? (for example, are the schedules determined manually or by the computer software?)
- How do you find the performance of these systems? (In terms of system effectiveness and cost)
- Does your system offer the facility of dynamic scheduling? (New trip insertion as new requests are made)
- When do you intervene in the system to accommodate changes?
- Do you provide same day services? Within what time period?
- What are the main features of these systems that attract you to use it?
- What do you do at the time of "No Shows"?
- Do you think that with the use of these technologies that ridesharing is increased?
- How do you encourage individuals with disabilities to travel on accessible fixed routes?
- Do you consider the demand of disabled individuals in constructing your routes for fixed bus lines?
- What is your total daily demand?
- What types of training programs would improve your service?
- Do you subcontract the services of individuals with disabilities to private contractors?
- Would you consider integrating your dial-a-ride program with your fixed route service?