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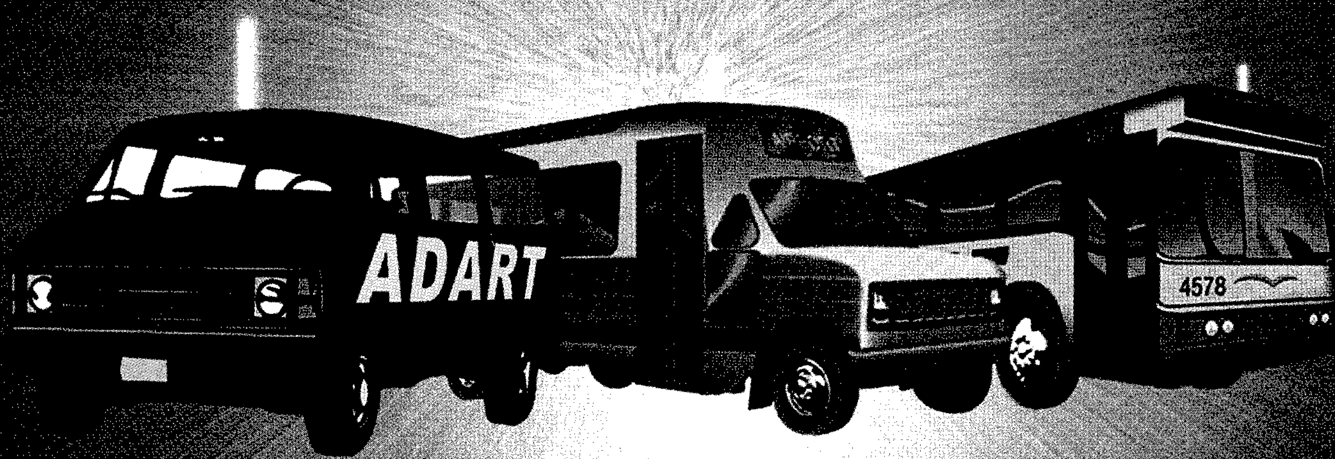
Autonomous Dial-A-Ride Transit



TECHNICAL OVERVIEW

Federal Transit Administration
Office of Research, Demonstration and Innovation
Service Innovation Division

Volpe National Transportation Systems Center
Office of System and Economic Assessment
Service Assessment Division

Autonomous Dial-a-Ride Transit
Part 1- Technical Overview

Prepared for
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16. Abstract Is autonomous-dial-a-ride (ADART) and idea whose time has come with the advent of technologies? This report describes the essential features of an experimental ADART service and establishes a context for ADART implementation based on urban transit industry characteristics. ADART is a demand-responsive transit service with fully automated dispatching and autonomously managed vehicles carrying all command-and-control facilities onboard. It is proposed as a many-to-few demand responsive service that uses modern computer technology to boost productivity and reduce labor requirements. Subscribers to ADART could use the service to travel from their homes to one or more attraction centers or from attraction centers to their homes or other dispersed destinations. Potential benefits, as compared to conventional dial-a-ride service, include reduced costs and improved service with the advantages of ADART increasing as the scale of operations expands. Computerized dispatching, ADART's distinguishing characteristic, eliminates order-entry clerks to arrange travel. Instead, a fully automated distributed system assigns trips to vehicles, devises itineraries, and plans routes. This technical overview consists of four chapters/papers. It begins with an introductory overview of ADART, followed by deliberations on the prospects for ADART implementation in terms of historical precedent, logistics, and costs. The third and fourth chapters review the state-of-the-art of technologies crucial to ADART operations--mobile communications and vehicle navigation hardware and software systems. The final chapters present study conclusions. ADART is a flexible system that may be the answer for transit services to low-density areas.

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- "Autonomous Dial-a-Ride Transit Introductory Overview" by Robert B. Dial of the U.S. Department of Transportation/Volpe National Transportation Systems Center

- "State of the Practice in Dial-a-Ride Transit" by Mark Bucciarelli, Consultant

- "Autonomous Dial-a-Ride Transit Mobile Communications" by Franco Vitaliano of VXM Technologies, Inc.

- "Review of Vehicle Navigation Hardware and Software Systems" by William C. Schwegler, Telcontar, Inc.

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GLOSSARY OF ACRONYMS AND ABBREVIATIONS

ADART	Autonomous Dial-a-Ride Transit
ADM	Automated Dispatching Machine
API	Application Program Interface
APTS	Advanced Public Transportation Systems
ARDIS	Advanced Radio Data Information Service
ATM	Automatic Teller Machine
CAD	Computer-aided Dispatching
CDMA	Code Division Multiple Access
CDPD	Cellular Digital Packet Data
CGI	Common Gateway Interface
CT/DS	Computer Telephony/Dispatch Server
DBMS	Data Base Management System
DGPS	Differential Global Positioning System
DDE	Dynamic Data Exchange
ETA	Estimated Time of Arrival
FAD	Fully Automated Dispatching
FDA	Frequent Division Multiple Access
GIS	Geographical Information System
GPS	Global Positioning System/Satellite
HDML	Handheld Device Markup Language
LAN	Local Area Network
LL	Latitude and Longitude
LSM	Limited Size Messaging
MAN	MOBITEX Access Number
NFS	Network File System
ODC	Open Database Connectivity
OEM	Original Equipment Manufacturer
OLE	Object Linking and Embedding
OSI	Open System Interconnection
PAL	Personal Address List
PC	Personal Computer
PCS	Personal Communications Service
PDN	Packet Data Network
PIN	Personal Identification Number
PMAN	Personal MOBITEX Access Number
ROSI	Radio Signaling Protocol
RSS	Routing and Scheduling System

GLOSSARY OF ACRONYMS AND ABBREVIATIONS (continued)

SC	Service Center
TCP/IP	Transmission Control Protocol/Internet Protocol (IP)
TDMA	Time Division Multiple Access
TTS	Text-to-Speech
UDP	User Datagram Protocol
VC	Vehicle Computer
VNS	Vehicle Navigation System
VRP	Vehicle Routing Problem
WAN	Wide Area Network

1.0 AN OVERVIEW OF AUTONOMOUS DIAL-A-RIDE TRANSIT

This report describes the essential features of Autonomous Dial-A-Ride Transit (ADART) and establishes a context for ADART implementation based on urban transit industry characteristics. ADART is proposed as a many-to-few demand responsive service that uses modern computer technology to boost productivity. Subscribers to ADART could use the service to travel from their homes to one or more attraction centers or from attraction centers to their homes or other dispersed destinations. Potential benefits compared to conventional dial-a-ride include not only reduced costs, but also improved service, with the relative advantages of ADART increasing as the scale of operations expands.

1.1 ADART Operations Defined

ADART costs more than a bus but provides flexible routing to serve dispersed points of origin or destination; it costs less than a taxi but does not provide complete door-to-door service. It ignores the off-the-street occasional users. From the customer's point of view, ADART has four salient features or advantages: subscription use, many-to-few service, convenience, and reliability. From the operator's point of view, ADART's important features include cashless/checkless revenue collection, fully automated dispatching, on-board information, command-and-control systems, high driver productivity, low operating overhead, and easy adaptability to demand.

ADART is likely to be most viable as a "many-to-few" operation oriented to serving recurring trips, including travel to attraction centers for the purposes of working, shopping, and recreation. ADART would target these trips because they form a lucrative market, providing the "repeat business" that is the life's blood of an enterprise profiting on high volume. In contrast, taxis illustrate the model of a many-to-many service. While ADART technology could be applied to taxi operations as easily as a many-to-few service, a many-to-many mode of operation like taxi service cannot consolidate trips to the same extent. As a result, load factors are low, dictating correspondingly high fares, which in turn reduces ridership.

Computerized dispatching--ADART's distinguishing characteristic--eliminates order-entry clerks to arrange travel. Instead, a fully automated distributed system (Figures 1 and 2) assigns trips to vehicles, devises itineraries, and plans routes without human intervention; most important, all dispatching and software is on-board individual vehicles. Using a customer interface similar to an automatic teller machine (ATM) and a bank-by-phone service, ADART passengers never talk to telephone operators, only to on-board vehicle computers. Accounting functions are executed through the use of bank credit cards and electronic funds transfer for processing accounts receivable, obviating traditional fare collection.

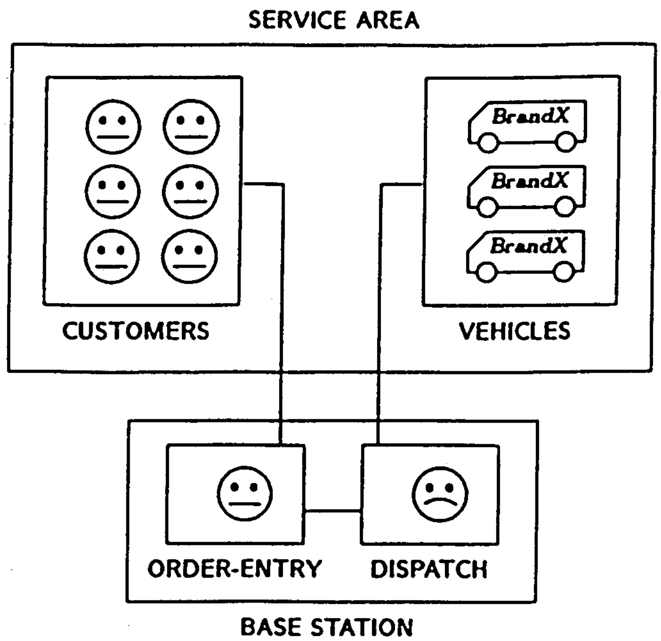

Figure 1: Conventional DART Management Network

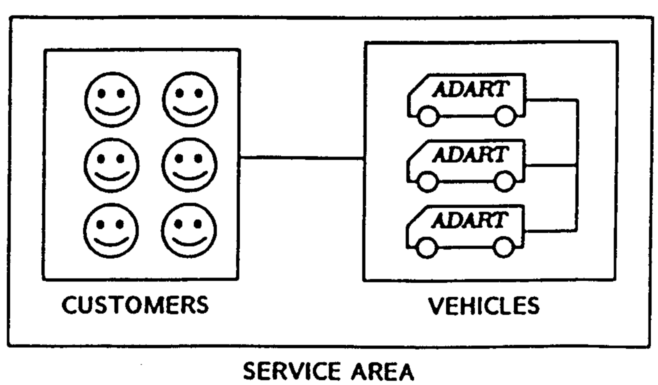

Figure 2: ADART Management Network

1.1.1 Distributed Control

In contrast to a conventionally managed fleet, whose vehicles only communicate with a central base station, ADART vehicles' computers communicate not only with their vehicle's driver, but also with customers requesting service, and computers on board other vehicles. Thus, ADART eliminates the need for a base station. Having no central control, an ADART fleet behaves like a swarm of ants doing their work with no one in charge.

For example, when a customer places a call, a computer on board one vehicle answers the call and its voice unit elicits the customer's trip requirements. Next, an auction ensues among all vehicles (i.e., their computers) to select the best one to serve the trip and assume sole responsibility for it. Later, if circumstances warrant, another auction may reassign the trip. Whichever vehicle finally serves the trip, its computer will just prior to pickup phone ahead to the customer.

This is not to suggest that an ADART operation lacks central management. Vehicle and data maintenance, technical trouble-shooting, service quality control, pricing, hiring, firing, automatic call distribution, billing and accounting are a few examples of functions best served by ADART's central management. Nevertheless, between the time an average customer requests and receives service, centralized intervention---be it mechanical or human---is negligible.

1.1.2 Subscription

Similar to a phone company, ADART requires that its users sign up beforehand. A new ADART customer can subscribe in person, over the phone, or via his personal computer. Having subscribed, he can use ADART for any trip between points in its service area. Unlike some existing DART operations, ADART subscription does not involve registering for a particular trip. ADART subscription merely entails paying subscription fees, providing credit and billinginformation, and furnishing data about routine trips.

1.1.3 Credit and Billing

From order-entry to final billing, ADART accounting is electronic. Payment for service is via electronic funds transfer from banks backing ADART customers' credit cards (e.g., Visa/Master Card). Alternatively, a subscriber may purchase a debit card or a check guarantee card. As we explain later, a passenger submits to an automated credit check with each trip request.

Every ADART subscriber is assigned a personal identification number (PIN) and identification (ID) card. ADART's ID card gains access to ADART vehicles and automatic dispatching machines (ADMs) at ADART terminals. ADART's PIN permits use of the trip reservation system. A customer can obtain multiple PINs and IDs, and may change his PIN at any time.

1.1.4 Routine Trip Making

ADART provides a subscription service that offers several options. Among these is the option to serve routine trips, such as a daily two-way work commute. The customer can sign up for as many of these optional services as desired. Moreover, ADART's fare structure can be designed to offer reduced rates for subscribers signing up for repeated trips, providing incentives for advanced trip scheduling.

Upon subscribing to ADART, the customer registers his personal address list (PAL) of common trip-ends (e.g., home, job, baby sitter, etc.). The subscription process verifies, geocodes, and files these addresses for the customer. Whenever the customer calls for ADART service, he or she can locate his trip-end by keying in a phone number or, alternatively, choosing an address in his PAL. The customer can change his PAL at any time.

Superficially, ADART resembles a minor variation of conventional DART service. Its only apparent difference is that service requests are via touch-tone telephone keys, and ADART can locate trip origins and destinations indirectly via phone numbers or directly via PALs.

1.1.5 The ADART Market

Typical ADART trips include:

- commuting trips between home and fixed route transit stations (subscription service)
- travel by the elderly and people with disabilities
- shopping at a mall or other commercial center (i.e., centers designated for ADART service)
- social visits, with a transfer at a shopping mall or other selected activity center

ADART serves only pre-arranged trips and cannot serve unscheduled pickups, as does a jitney, because such deviations from planned service can cause delays and seating problems.

For all eligible categories of trips, ADART uses PALs and phone numbers to locate trip-ends and customers use:

1. ID and PIN to arrange for travel by phone;
2. phone's touch-tone keys or an ADM to relate their trip requirements:
   origin (destination), earliest departure (latest arrival) time, and passenger count;
3. ID card to board and deboard the vehicle;
4. bank cards to automatically pay for service.

Normally, all these transactions involve only the passenger and a computer.

Every city has several market segments of its traveling public that a many-to-few ADART service can target. Since many trips go from home to some attraction center, many-to-few coverage is sufficient to maintain vehicle load factors that sustain service at moderate cost. Consequently, many-to-few is the most cost-effective form of both ADART and conventional dial-a-ride.

1.2 Vehicle Deployment

The best dial-a-ride systems allow more than one vehicle to pick up passengers within the same service area. In contrast, to simplify dispatching, most demand-responsive systems partition a service area into non-overlapping sub-areas, and assign sub-area coverage exclusively to a single vehicle. Because service reliability is a feature that customers value highly, however, it is dangerous to assign exclusive coverage of a geographic sub-area to one vehicle. Three cases below illustrate this point:

1. *a vehicle is at the left edge of its large service sub-area when it has to pick up a passenger at the right edge;*

2. *a surge of demand in one sub-area overwhelms the capacity of its assigned vehicle;*

3. *a breakdown or accident puts a vehicle out of service.*

By assigning multiple vehicles to the same service area, DART can assign a trip to the vehicle that serves it most efficiently. In this way:

- *another vehicle can pick up a trip otherwise assigned to a vehicle unable to serve it;*

- *fewer vehicles are needed, since their flexible coverage allows them to cover larger areas without risk of service failure, resulting in higher load factors;*

- *vehicle break-downs are handled in a ``fail-soft" manner, since the impacted trips can be redistributed automatically among the remaining vehicles until a replacement vehicle arrives, causing minimal service delay instead of large-scale service failures.*

1.3 Fully Automated Dispatching

A fully automated dispatching (FAD) system is one that can field a customer's request for service, schedule a vehicle to provide that service, and optimally route the vehicle without any human interaction. The vehicle's on-board computer receives a customer request, inserts this request into the vehicle's schedule, and plans an optimal route to accomplish the schedule. Furthermore, if beneficial to do so, the computer may pass the request off to another DART vehicle, without the drivers knowing it.

This process occurs through the following sequence of events.

Order entry: When a customer calls, a computer on board a vehicle answers the phone. Routed to a vehicle by an automated central distribution system, the call arrives with its origin's phone number, which is converted into a street address. An ID number and PIN provide customer data, including credit standing. Touch-tone key input describing trip requirements furnishes the rest. Having the customer's ID and his phone's number, the computer uses the customer's PAL to prompt for the destination's street address (or a phone number that it converts into that street address), makes revisions to its route, and posts data for billing.

Scheduling: Regarding departure or arrival time requirements, the computer knows the vehicle's scheduled whereabouts, as decided from its schedule of all outstanding trips. By inserting the new trip into its vehicle's schedule, the computer estimates the customer's earliest pickup or arrival time and compares it with the request. After conversing briefly with other computers, its voice unit then notifies the customer accordingly.

Call-ahead: To minimize dwell time, the computer schedules itself to call the customer at a specified number of minutes before arriving at the pickup point. At that time, the computer will trigger the phone call and its voice unit to tell the customer the precise time of its imminent pickup.

Pickup and delivery: When the pickup occurs, the computer notes the passenger's arrival from his ID card, read when the passenger boards. When the passenger reaches his destination and swipes his card, the computer initiates the process of billing the customer and receiving payment electronically.

Route optimization: Meanwhile, the computer is working hard to optimize its vehicle's route, while conspiring with other vehicles' computers to minimize operating cost for the entire operation.

Routing-and-scheduling. Using every free computer cycle, the routing-and-scheduling system (RSS) continually works to improve the planned route of the vehicle to fulfill its outstanding trips. The RSS's goal is simply to devise an itinerary for the vehicle to pick up and deliver passengers according to their origin/destination and time-window requirements at minimum cost. In practice, however, accomplishing this goal is not very simple.

Even with off-line computation, routing and scheduling several trips with time-window constraints over a large road network poses a formidable computing challenge. For an on-line operation like ADART, it is much more difficult. The RSS is aiming at a moving target. After composing an excellent route for its vehicle, the RSS might receive a new trip, whose inclusion destroys the viability of the planned route. Furthermore, the computer has limited time to find a *feasible* solution, let alone one that is optimal.

Using dynamic programming, a large fast computer can meet this challenge, provided the number of trips to process is small. In ADART's case, this number is kept small by three algorithmic expedients:

1. *focusing attention on trips needing service in the near future;*

2. *delaying informing the driver of any decision as long as possible;*

3. *considering only trips in the dispatch of a single vehicle.*

The first item discounts the importance of far-future trips, since any early plans for these trips would most likely be upset by new trip demands. The second item permits the RSS to absorb a maximum amount of data and to change its mind several times before committing to a route. The third item needs discussion of ADART straight-forward routing-and-scheduling algorithm.

While vehicle navigation systems are available off-the-shelf, no existing commercial routing-and-scheduling package meets ADART's requirements. Consequently, routing-and-scheduling software must be built. Because efficient algorithm design and reliable real-time code are software engineering's biggest challenges, this software's construction requires a high capital investment. Its cost becomes insignificant, however, when divided by the large number of vehicles that could use the software.

Vehicle assignment: Whenever a user calls the ADART phone number, all ADART vehicles await the call. The first vehicle's computer to receive the call prompts trip data from the customer. This initial vehicle's computer (VC) then initiates an ``auction" for the trip:

1. *It begins by estimating the "marginal cost'" (e.g., expected miles/trip) of including that trip into its vehicle's schedule. Its computer figures this cost by inserting the trip into its vehicle's planned route, or some variation of it, in a way that assures the vehicle meeting all its scheduled arrivals.*

2. *Then it broadcasts this cost and the trip's requirements to every vehicle serving the same sub-area. Each of these latter VCs makes its own estimate of including the trip in its own itinerary. Any VC whose estimate is lower than the initial VC's responds with its own cost. Others remain silent.*

3. *Finally it informs the VC with the lowest cost of its responsibility for the trip. All other VCs ignore the trip. The responsible VC enters the trip into its scheduling system, which grinds away toward an optimal route to serve all its currently assigned trips.*

1.4 Trip-End Geocoding

To ADART, "geocoding" means associating a trip-end with a location on the road network. A key in achieving an effective on-line FAD is the decision to use phone numbers and address menus for geocoding. This decision, admittedly, restricts the service potential of ADART vis-a-vis conventional DART to some degree. However, restricting FAD to phone numbers and address lists precludes getting bogged down in the ever painful and problematic interpretation of random street addresses.

1.5 On-Board Command and Control

ADART's distinguishing feature is having all of its information, command-and-control systems on board the vehicle. On-board command-and-control requires that each vehicle carry all computing and communications hardware and software necessary for FAD. Low prices of fast computers with large RAM and disk storage make this possible.

1.5.1 On-board Hardware

Each vehicle carries a full complement of computing hardware and data. The hardware, all off-the-shelf, includes:

- *general purpose computer for routing and scheduling,*
- *vehicle navigation hardware for monitoring the vehicle's location and communicating it to the driver and the routing-and-scheduling system,*
- *communications equipment for carrying information between customers, vehicles, and computers,*
- *cellular telephone for both routine and emergency communication with the driver.*

1.5.2 On-board data

On-board data is extensive but practical due to inexpensive massive data storage devices, off-the-shelf digital road maps, and robust database software. On-board data files include a trip database, a partial customer database, a complete vectorized road network, and a service log.

1.5.3 Data Acquisition

Inexpensive vectorized road networks are available from several geographical information system (GIS) vendors, who also provide address and place-name geocoding files. The phone company furnishes phone geocoding files. ADART generates the service log automatically.

1.5.4 File Maintenance

All the above files will require maintenance---updating and backup. For example, it is likely that ADART drivers will detect errors in the road network database. The ADART file maintenance system would provide the means for using these driver observations to update the network database in all vehicles.

1.5.5 On-board Software

The on-board ADART software systems fall into five general classes: order-entry, vehicle navigation, routing-and-scheduling, and communications. The functionality of all this software should be clear by now, except perhaps for communications software.

1.6 ADART Benefits

ADART's distributed arsenal of hardware, software and data brings three-fold benefits: technical, operational, and financial.

1.6.1 Technical benefits

Distributed computing and simple vehicle-to-vehicle communications yield efficient dispatching, lower communications traffic, and high reliability:

- *Efficient dispatching.* An ADART fleet's combined computer power permits the implementation of sophisticated parallel decomposition algorithms to approximate globally optimal vehicle itineraries. The principal technical benefit is efficient dispatching---no matter how high the demand.

- *Higher reliability.* The trip-auction algorithm readily handles vehicle failures. ADART has no failure point that can bring down the whole operation---a vulnerability that every centralized system suffers.

- *Lower communications traffic.* Compared to conventional systems, ADART creates less communications traffic. This saving results from ADART's on-board command-and- control, which obviates centralized vehicle tracking. Except for the customer's phone call and trivial PAL downloading, ADART's only major mobile communication is for trip--vehicle assignment auctions.

1.6.2 Operational Benefits

Ease of expansion. ADART brings numerous operational benefits. Most important of these is ease of expansion. Because the cost of running an ADART operation is linear in the number of vehicles, ADART can do something conventional DART cannot---grow to service very large demand efficiently.

For innovative transit service, ease of expansion is crucial: it is difficult to forecast the pace and magnitude of change in demand. Upon the service's introduction, demand is low but eventually ramps up to a stable level, as customers learn the system and develop sufficient confidence in it to modify their travel behavior.

The ideal transit operation expends resources in direct proportion to the demand for service. For a centralized system, however, this ideal is impossible. A centralized system must forecast, budget, and program resources. It has to allocate people, space, and hardware several months in advance, and these allocations once in place resist change. While demand is low, a centralized system is lavishly over-equipped, and when demand increases beyond forecasted levels, it cannot adapt fast enough.

An ADART system, by contrast, grows simply and cheaply. It can start by putting a single vehicle in service. If increases in demand warrant adding a vehicle, another vehicle simply joins the fleet to become a productive member of the team immediately. The new vehicle brings with it all the additional hardware and software needed to guarantee service for the new demand. Of course, these same arguments apply to the routine daily fluctuations in demand that bring vehicles in and out of service.

Better security. Beside the superior passenger security implicit with doorstep service, ADART improves security for people both inside and outside the vehicle. For example, the on-board computer permits the driver to alert the police by only pressing a single key, which automatically dials 911 to report a particular incident type occurring at the LL where the hot key was pressed. This message includes the number of the driver's cell phone, in case the police needed to call back for further clarification.

Extended utility. Being a formidable armada of networked computers on wheels, ADART has potential utility beyond the many-to-few dial-a-ride application that is the subject of this report. Some of its ideas would find good use in route-deviating and interlining buses, local police cruisers, and package delivery vans. Most apply even to driverless systems, such as personal rapid transit and dual mode. Furthermore, the ADART vehicle would be a natural recipient of real-time highway speed information, and would serve well as a "probe" to provide this information to others.

1.6.3 Financial benefits

With its higher productivity, lower manpower, and improved service, ADART promises direct and indirect financial benefits:

- *allows several vehicles to optimally cover the same service area, by using its immense computing power and a massive information base;*

- *needs fewer people than a conventional demand-responsive service, by having no telephone operators, no dispatchers, no driver supervisors, and minimal accounting/clerical support;*

- *reduces driver error and training costs, by monitoring and directing each driver through his entire work day;*

- *creates new revenue for existing transit, by linking low-density residential areas to high-speed fixed-route transit systems.*

The plummeting costs of computer hardware, mobile communications, and vehicle navigation place the cost of ADART vehicles within the budgets of transit operations. Case in point: In Boston, MBTA's "The Ride" uses a van that, with volume discount, costs $32,000, which is about half the fully loaded annual cost of the driver. Of this $32,000, $20,000 is for the base vehicle and the remainder for special equipment. With its computers, an ADART vehicle will cost 10 to 15 per cent more, thus paying for itself as soon as it yielded a one-time reduction in personnel cost or increase in revenue of about $3,000---a tiny fraction of any transit operation's budget.

1.7 Organization of Report

The following chapters of this report address key aspects of ADART service in greater detail. Chapter 2 considers the prospects for ADART implementation in terms of historical precedent, logistics, and costs. Chapters 3 and 4 review the state of the art of the technologies crucial to ADART operations: mobile communications and vehicle navigation hardware and software systems. Chapter 5 presents a summary of the report's conclusions.

2.0 DIAL-A-RIDE TRANSIT STATE OF THE ART

This chapter investigates dial-a-ride transit service in terms of its historical context, current status, and future potential. For the purposes of this report, dial-a-ride transit is defined as any publicly-funded flexible route transit service arranged for by phone. This definition broadens a traditional definition of dial-a-ride (i.e., real-time scheduling) to include rides that are scheduled in advance. The defining service characteristic is the user's need to call for service.

Relevant experience with taxi and jitneys are considered in this review. While both of these types of service share some characteristics in common with dial-a-ride, there are also important differences. Taxis and jitneys, like dial-a-ride, both provide flexible routing. However, unlike dial-a-ride, these services are private sector operations that can be ordered by hailing a vehicle from the curb. Nevertheless, consideration of these services is useful in providing a reference point illustrating relevant characteristics of urban transit demand in a historical context. In addition, current taxi dispatch technology, used primarily for phone orders, provides a useful analog for dial-a-ride dispatching.

2.1 History

The first dial-a-ride services were implemented in the 1960s. The history of dial-a-ride actually has deeper historical roots, however, in technology and politics extending back to the horse-drawn omnibuses that plied the streets of Paris in 1819. Reviewing the technical and political events associated with transformations in public transit service reveals patterns that may provide insights into the future of dial-a-ride.

Four eras can be identified that span the evolution of modern transportation technology:

- the horse 1830 - 1880 50 years;
- electricity 1880 - 1920 40 years;
- the auto 1920 - 1970 50 years; and
- the computer 1970 - 1996 26 years (to date).

The boundaries of these eras correspond to key changes in technology, which led to an expansion of public transportation options. In the first three eras a new source of power served as the agent of broader change, while the current era is characterized by progress in information technology. Judging by the duration of previous eras, the current information-based era may continue for many years.

2.1.1 The Horse Era

The earliest enterprise that made money from transporting passengers in the city was the taxi. In the western hemisphere, this industry made its first appearance in the early 17th century, when hackneys pulled coaches along the streets of London and Paris. Nearly two centuries later, public transit began when horse-drawn omnibuses made their debut in Paris. Omnibuses were introduced to New York in 1831 and soon filled the city's streets. The omnibus quickly was made obsolete, however, by horse-drawn vehicles that ran along iron rails, called "tramways," thus providing a ride far superior to the omnibus, which had to run over rough cobblestones.

An important characteristic of this period is that public transit was a private enterprise. The first company in the world to provide local passenger transportation on rails, the New York and Harlem Railroad company, was formed in 1832 by a group of prominent businessmen who got permission from the state legislature to incorporate. Apparently, this type of service was profitable. By 1880, the world's largest street railway (the West End Street railway in Boston) used about 4,000 cars and 8,000 horses. In 1890, approximately 105,000 horses and mules were engaged in pulling 28,000 streetcars over roughly 6,600 miles of track.

2.1.2 The Electric Era

During the 1890s three technologies were competing to provide urban mass transportation: horse-power, cable-power, and electric power. Cable made inroads into the market dominated by horse-drawn public transportation services, but was later eclipsed by electric-powered vehicles. The difficulties entailed in pulling long, heavy cables underground and engineering reliable cable-grips doomed cable technology. At its height, cable cars ran over 448 track-miles. By 1890, however, electric rail cars had captured one-sixth of the total street rail-miles in the United States.

There were a number of inventions that led to the use of electric power in the cities. In 1825, William Sturgeon created an electromagnet and four short years later Joseph Henry constructed the first electromagnetic motor. In 1859 the lead battery was discovered by Gaston Plante. Most electric-power transportation was powered by batteries until 1873, when Z.T. Gramme and Hippolyte Fontaine demonstrated that an electric motor, if rotated mechanically, would generate electricity. In 1882 Thomas Edison started the first US central station power plant with 59 customers. Edison used direct current, which can only transmit power one or two miles. By 1900 this problem was solved by using alternating current and by 1920 it was possible to transmit current 200 miles.

The first commercial electric railroad was operated by the East Cleveland street railway in 1884. In 1886, the first trolley ran off power from overhead lines, its name a corruption of "troller," which originally described the how the vehicles moved—the overhead contraption reminded people of fishing rods. Chicago installed the first elevated rail line that was powered by electricity in 1895. Boston was the site of the first underground electric rail line in 1897. Electricity was also applied to taxis. The first successful motorized taxi cabs in the United States, the "electrobats," were operated in Philadelphia in 1896 using battery power. Within four years, New York City had some 200 electric cabs plying its streets.

The greatest period of expansion for electric-powered public transportation was from 1902 to 1917. Rail lines were marketed as franchises that had low capital requirements. Each individual line typically was operated by a separate corporation and charged a separate fare. Although the capital cost for a horse-drawn vehicle was lower than that for a vehicle powered by electricity, operating costs were higher. The expanded patronage and faster service provided by electric-powered vehicles was thought to make up for the higher costs and expansion continued at a rapid pace. A period of mergers followed, where services would join together and allow transfers between lines operated by a single owner. While average trip length per fare increased as a result, the economies of scale were still powerful enough for the rail companies to make a profit.

The ability to transmit electrical power over long distances had a huge impact on the structure of the transit industry. Whereas the direct current power industry was characterized by a large number of small highly competitive powerhouses, the long transmission distances possible with alternating current led to significant economies of scale. These economies of scale and a lack of regulation led to consolidations of power and monopolies.

There were instances where a very small minority of stockholders controlled numerous operating companies by pyramiding holding companies and limiting voting stock. In part in reaction to these abuses, the federal government passed the Public Utility Holding Company act in 1935 to regulate and control this industry. In addition to creating the Securities and Exchange Commission to regulate the power industry, this act limited the operations of holding companies to electric power production and required that their assets be geographically contiguous. Thus ended the commingling of electric street railways and power generation [Cook and Barb 1979; Enc. Britannica 1959].

2.1.3 The Auto Era

While Gottlieb Daimler patented his internal combustion engine in 1886, it took 25 years for the automobile to begin to supersede both steam and electric motors for powering transit. The Domination by the new technology was more apparent in the consumer market; between 1910 and 1916, the production of automobiles in the United States grew by nearly an order of magnitude, from 180,000 to 1,500,000.

This new technology had a startling effect on urban mass transportation: it spawned the "jitney craze." People with private automobiles found that there was money for the taking in pirating passengers from the electric streetcar routes. They charged the same fare as the railroad--a jitney (five cents)--but provided faster service, and business boomed. One author estimates that 62,000 jitneys were operating in the United States in 1915, and that Seattle alone had 500 jitneys carrying 49,000 passengers a day.[1]

This boom was short-lived however, as this industry was unregulated, chaotic, and considered a danger to the public. One notable source of opposition was the electric streetcar franchises. These franchises lobbied hard for anti-jitney ordinances and succeeded in getting them passed in most cities. By 1920 jitney service ceased to be a major factor in United States urban transportation.

The streetcar franchises were not able to thwart buses as they did jitneys, however, and instead embraced this new mode. The gas engine, combined with improved roads and tires, gave the buses too many advantages to be outlawed. The adoption of the motor bus by the streetcar franchises signaled not only the end of expansion for electric streetcar lines but also the beginning of the reduction of market share. From 1917 to 1954, electric streetcar track-miles shrank from 45,000 to 5,600.

2.1.4 The Computer Era

The discussion of this era shifts to focus more specifically on dial-a-ride, which first makes its appearance at this time. There were originally a number of different objectives motivating interest in dial-a-ride transit. The first objective was to make transit service more compatible with changing land-use patterns, as people moved to the suburbs. The dispersion of activity and travel produced declining ridership on traditional fixed route transit services. In 1964, the federal government began providing urban mass transit operators with capital, as they could no longer afford the investment. Perhaps one of the earliest proponents of moving towards more flexible and responsive transit service was Richard N. Farmer, who argued in a 1965 paper for a return to the free-wheeling jitneys as a response to the current problems of urban transit: *"The jitney . . . might be a method of making public transit in many areas of low or diffused flow more compatible with what the traveling public clearly wants."*[2]

A second factor that led to the growth of dial-a-ride transit was the "Great Society" program of President Johnson, which provided an infusion of federal funding for human service programs. The Older Americans Act of 1965, as amended, provided grants to states and communities for programs serving the elderly and included transportation. However, federal programs that funded transportation for human services preceded Johnson. The Social Security Act of 1935, as amended, allowed federal funds to be used for transportation expenses of low income and public assistance recipients. In a 1975 paper sponsored by the Transportation Research Board, it was estimated that

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[1]Brian Richards, *The Taxi: Transport for the Future?* In *The Taxi Project: Realistic Solutions for Today*, ed. Emilio Ambasz. New York: The Museum of Modern Art , 1976.

[2]Richard N. Farmer, *Whatever Happened to the Jitney?* Traffic Quarterly, 1965, pp. 263-279.

approximately 2,000 transportation projects were being funded under this Act, nearly four times the number funded by the Urban Mass Transportation Administration under Section 16(b)2.

2.1.5 Application of Technology in the Rochester Dial-a-Ride Demonstration

In the late sixties and seventies, people began to look at computer technology as a tool that had the potential to transform dial-a-ride transit into a large-scale operation with economies of scale. The 1975 Rochester, New York federal demonstration program was an experiment in using computers to schedule and dispatch dial-a-ride service. Many of the approaches and technologies that were used in Rochester are now being implemented across the country under the label of "advanced" systems. For example, Rochester incorporated all of the following:

- *subscription routes;*
- *real-time demand response;*
- *integration of dial-a-ride with fixed-route service;*
- *two-way digital communication between dispatcher and vehicles;*
- *mobile data terminals;*
- *computerized scheduling and dispatching, for both subscription and real-time demand.*

The Rochester work was built on four previous projects. The CARS project at MIT ran from 1969 to 1971 and conducted the initial analysis and design work for dial-a-ride automation. Based on the control system design from the CARS project, the US Department of Transportation and Mitre Corporation implemented a computer-based automated control system for the dial-a-ride demonstration project in Haddonfield, New Jersey between 1972 and 1974. This project was the first to demonstrate that automation was both feasible and effective. There were other projects in Santa Clara, California (1974 - 1975) and Ann Arbor, Michigan.

The Rochester project augmented a local service that had started in August 1973. This service offered same-day door-to-door service to any person in the service area and served intra-community trips as well as feeder service to regular fixed-route bus lines. Three control room personnel managed a 13-vehicle fleet using radio frequency modems to send and receive digital messages to and from the vehicles. The manual dispatching process worked as follows:

1. *Telephone operator receives a request for immediate service.*
2. *Operator gives customer a pickup time, as estimated by the dispatcher.*
3. *Operator keypunches one computer card for pickup and one for drop-off.*
4. *Operator sends cards to dispatcher for inclusion in a subscription tour.*
5. *Dispatcher assigns each demand to a vehicle.*
6. *Dispatcher transmits new tour to vehicle.*
   a. *Feeds card that identifies the vehicle into a card reader.*
   b. *In "tour-order," feeds pickup and drop-off cards into card reader.*
   c. *Control terminal (connected to reader) encodes message digitally.*

d. Control terminal transmits message to vehicle using radio waves.
e. In-vehicle thermal teleprinter prints sequence of stops for driver.

The dispatcher used a six-foot by seven-foot magnetic map of the service area as a decision support system. Each vehicle's location was represented on the map by a uniquely colored magnet. A vehicle's stops were shown with magnets that were the same color as the vehicle's, and origin and destination pairs were differentiated by using magnets of different shapes. Using this system, one dispatcher could handle 10 - 15 vehicles.

In April 1975, the system became part of a federal demonstration project sponsored by the Urban Mass Transportation Administration. The main objective of the demonstration was to investigate the impacts of replacing the manual scheduling with computerized scheduling. The production code that handled the scheduling was operated in Waltham, Massachusetts on five time-shared DEC-10's at First Data Corporation's. A leased line with a bandwidth of 600 characters per second connected Rochester and Waltham.

Once the computer began scheduling trips, it became apparent that the existing digital communication infrastructure was not sufficient. The in-vehicle teleprinters required 25-30 second delay per message and drivers complained that the characters were too small. The vehicle manifests printed by these thermal printers were first replaced by voice communications and finally by in-vehicle cathode ray tubes that had a keyboard and displayed 32 characters on each of eight lines. Using these mobile data terminals, a seven-line message took three seconds to transmit.

The computer dispatched trips for five different types of service:

- *home-to-work subscription;*
- *feed-a-bus;*
- *home-to-school;*
- *many-to-many; and*
- *a more specialized elderly and handicapped service.*

These services carried from 500 to 560 passengers each day, and service productivity typically was in the range from 5.0 to 5.5 passengers per vehicle hour. In the first year of operations, the operating cost was $3.00 per passenger and $16.33 vehicle hour. The cost of transporting each passenger was subsidized by $2.42, on average. Fares were dependent on the type of service and ranged from 25¢ to $1.00, with an average fare of 58¢ per passenger trip. From 65% to 70% of the many-to-many passengers had origins or destinations at one of three activity centers (making it a many-to-few service). Two centers are shopping malls; thus, primary trip purpose was shopping.

In the routing and scheduling algorithms, travel time was computed based on the average vehicle speed and the "as-the-crow-flies" distance between trip origin and destination. The speed and dwell times were estimated using regression to be four minutes per mile of travel, three minutes for a pickup and two minutes for a drop-off.

There were three basic types of passengers: immediate, advanced, and transfers.

Immediate passengers are inserted when booked, advanced passengers are inserted a set time before the scheduled pickup time, and transfer passengers are advanced passengers that have a pickup or drop-off time that corresponds to the fixed bus route schedule. The objective function for optimizing service delivery incorporated a weighted sum of squares of:

- *time between service request and pickup(wait time);*
- *time between a customers pickup and delivery (ride time); and*
- *time between the promised and actual pickup time (pickup deviation).*

The weights for these disutilities were varied by customer type. For example, it was assumed that advanced passengers want to be picked up as close to their scheduled time as possible, whereas transfer passengers prefer to be picked up as soon as possible after they make their request (as their request is made from the fixed-route bus that they are on).

Once the service began operating, the model was "tuned" to more closely correspond to realities. There were a number of changes to the weights in the objective function. One system dynamic that led to parameter changes was that wait times degraded quickly when the system became heavily loaded. In response, the objective function weights for immediate customers were changed so that minimizing wait time became more important. Another dynamic was that the advanced passengers tended to be routed on circuitous trips--to compensate, the weights were changed so that minimizing ride time became was made important and minimizing pickup deviation was made less important.

Transfers of passengers from fixed-route service to dial-a-ride were particularly troublesome. The original implementation assumed that every customer demand was entered into the computer prior to pickup. Thus, the driver of the fixed-route bus was supposed to communicate the demand to the dispatcher. Communication difficulties resulted in few if any of these demands being entered and many customers were stranded. If a van did show up, the waiting customers besieged the vehicle, the driver of which had a small subset of this demand logged on his manifest. The large number of people passing through the transfer point added to the confusion and the service was generally unsatisfactory.

To respond to this problem, the operators decided to relax the requirement of advance booking and simply send an empty bus to the stop every thirty minutes. The driver would then log the demands as the customers boarded. This approach was also not satisfactory, as it took too long to log all the demands and the trip lengths were too long. A third approach was to stop logging demands and to use two vehicles every 30 minutes: one for northbound passengers and one for westbound. This worked until late September of 1976, when direct communication was established between fixed-route drivers and the control room and a new line-haul route, originating at the transfer station, was added.

There were other interesting adjustments. The need for automated reassignment of passengers to other vehicles was apparent when it became clear how unreliable the vehicles and drivers could be. In response, every 20 minutes, each customer that was waiting for service was considered for reassignment to another vehicle. Finally, in late March 1977, a penalty was added to the objective function for tours that "did not make sense" to the drivers. Before this addition, the computer sometimes generated vehicle tours that reversed direction frequently, jeopardizing acceptance of the system by the drivers.

What was apparent from the Rochester demonstration project was that dial-a-ride transit would not be the solution to the decline in the transit industry. What was first conceived of as a high-tech rapid-response transit option for the general public evolved into a manually-scheduled advance-reservation system for selected segments of the population. The economies of scale and the associated high productivity required to support the investment did not materialize as the consumer demand was much lower than expected. The problem of low demand was compounded by the difficulties that transit agencies had in providing reliable service. Vehicle maintenance was a particular sore spot in Rochester. Maintenance crews, trained in and experienced with large diesel buses, were not as handy with the smaller, auto-like, vans. The result was that manually scheduled dial-a-ride services had higher productivity than the automated systems. A 1993 study found that:

> *Manually scheduled and dispatched systems in Michigan and California achieved system productivities of six to eight passengers per vehicle service hour, which exceeded the productivity level of the computerized systems in Rochester and Haddonfield.*[3]

2.1.6 Federal Government Support of Dial-a-Ride

There were a number of strategies used to adapt to the market and technological realities described above, all of which are still being used today:

1. *use of private operators—services operated under contract by the private sector and not-for-profit organizations.*
2. *market restriction—special services limited to the elderly and/or physically handicapped.*
3. *Spatial restriction—operating many to one service in non-overlapping zones with inter-zone transfer required, providing non-doorstep service, or operating on a fixed route but with route deviation on request, as opposed to general many to many service.*

[3]Roger F. Teal. Public Transit 1993 - Bus, Paratransit, and Ridesharing. Transportation Research Record No. 1390. National Academy Press. Washington, DC, 1993.

4. *Temporal restriction—restricting vehicles to some sort of schedule, providing service only during limited periods of the day, and/or requiring advance notification of trips.* [4]

During the 1970s the federal government began supporting dial-a-ride with many and varied programs. Listed below are some selected federal laws having an effect on dial-a-ride transportation.

- *1970: Section 16 added to Urban Mass Transportation Act of 1964. Provides federal grants and loans that fund 80% of the capital cost of new vans that provide service for the elderly and handicapped. Note that local taxi companies protested these grants.*

- *1973: **Federal-Aid Highway Act**, Section 147. Funded 102 demonstration programs ($25 million) for fixed route and/or paratransit for the general public, those with low income, the elderly, and the handicapped. [Cook & Barb, '79, p 12-13]*

- *1974: Urban Mass Transportation Administration begins financial aid for transit operating expenses.*

- *1974: **Emergency Highway Energy Conservation Act**. Demonstration carpool projects authorized as part of response to energy crisis.*

- *1975: **Energy Policy and Conservation Act**, Section 362c(2). Mandated the promotion of carpools as part of a state's energy conservation plan.*

- *1978: **Surface Transportation Assistance Act**, Section 146. Authorized federal funds for projects that encourage ride-sharing.*

- *1978: **Surface Transportation Assistance Act**, added Section 18 to the Urban Mass Transportation Act of 1964. Grants 80% of capital funds and 50% of operating funds for rural transportation.*

Included in this list are only the federal programs that are administered by the US Department of Transportation. In 1977 GAO identified 114 federal programs that provided financial assistance for the transportation of people, administered by eleven federal departments, agencies, and commissions.

Since the beginning of the 1980s there have been three major pieces of federal legislation that have affected the dial-a-ride transit industry.

- *1990: **Americans with Disabilities Act (ADA)** (see below)*

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[4]Nigel H.M. Wilson and Chris Hendrickson. *Models of Flexibly Routed Transportation Services.* Presented at the International Symposium on Transportation Supply Models. Montreal, November 1977, pp. 1-2.

- *1990: **Clean Air Act Amendments**. Required that all sites that employ 25 or more people and that are in cities with severe ozone non-attainment must increase vehicle occupancy rates by 25%.*

- *1991: **Intermodal Surface Transportation Efficiency Act (ISTEA)***

ADA has had by far the largest impact on the provision of dial-a-ride service. Transit authorities were required to comply by January 26, 1997 with the provisions of this act—certainly one motivation for current interest in dial-a-ride. Every transit property with fixed route service must provide a dial-a-ride service that complies with the following provisions:

- ***fares** cannot exceed twice the fixed-route fare for the same trip;*

- ***geographic service area** must parallel, in a 0.75-1.5 mile band, the routes of fixed route service. In urban areas, the geographic service area must fill in any gaps;*

- ***service hours and days** must match those of fixed route service;*

- ***capacity constraints** cannot justify a regular pattern of trip denials, excess in-vehicle time, and pickups or drop-offs that are not within a 15-minute window;*

- ***reservations** of up to two weeks in advance and as soon as next-day must be serviced.*

The impacts of ISTEA on dial-a-ride are starting to become more evident now. In particular, intelligent transportation systems (ITS) technologies are directly applicable to the dial-a-ride industry. Congress authorized $600 million to be spent on these technologies, such as geographical positioning systems, digital communications, computerized control and other electronics. These technologies are being applied today through the Federal Transit Administration's Advanced Public Transportation Systems (APTS) program.

2.1.7 Advances in Computer Hardware and Software

There has been dramatic progress in both the software and hardware industries since the Rochester experiment. When MIT began implementation of automated scheduling in 1975, the RAM chip was only five years old, the microprocessor was four, and the C programming language was a young three years old. The reference manual for C was only one year old!

A primary product of the progress that has occurred in the computer field is vastly improved processing speed. The increase in power of personal computer's central processing units is astounding: in 1971, Intel built the first general purpose microprocessor the 4004. It was a 4-bit chip that ran at 0.108 Megahertz and processed an estimated 60 thousand instructions each second. (An interesting side note is that the world's first microprocessor was built to control traffic signals, not computers.) A contemporary 64-bit chip is produced commercially that runs at 400 Megahertz.

A topic less often discussed is that of software advances. The year that the Rochester experiment began, Bill Gates and Paul Allen made their first sale: a version of BASIC that they sold to Micro Instrumentation and Telemetry Systems (MITS) on a per-copy royalty basis. MITS was the company that produced the Altair, the world's first personal computer. In contrast, sales of Microsoft's Windows 95 were measured in millions of units!

Perhaps the greatest advance in software engineering has been building since Smalltalk-80 was produced by Xerox in 1980. This was the first language that was specifically designed from the ground up to be object-oriented. A fundamental tenet of object-oriented software is the creation of modules or components that can be reused over and over again. The advantage of this approach of particular importance is the ability to re-use code, which allows for improved efficiency in programming. This concept has recently been applied to the operating system itself, the "microkernel" operating system, providing programmers with the ability to port software from one machine type to another with much less trouble.

The number of advances since 1975 extend beyond the hardware and software of personal computers. Chief among them is the world wide web, which was developed from 1978 - 80. The Ethernet (1981) is a standard for local area networks, and Novel Netware (1981) is a common network management system. In recent years, hard drives have increased data density at an annual rate of about 60%. Visual programming, parallel processing, hard disk and CPU caching, software components, microkernel operating systems— the capabilities of a transformed computer environment to address the demands associated with dial-a-ride service are markedly improved.

2.1.8 Advances in Algorithms for Solving Routing and Scheduling

Software and hardware improvements have made it possible to write and run programs much faster, but this is just one aspect of the technological progress that can be applied to dial-a-ride.. The other aspect is the mathematical models that represent vehicle routing and the algorithms that turn these models into problems that a computer can solve. This field of study, known as operations research, has also advanced significantly since Rochester.

The dial-a-ride problem is one variant of the vehicle routing problem:

> *The vehicle routing problem (VRP) involves the design of a set of minimum-cost vehicle routes, originating and terminating at a central depot, for a fleet of vehicles that services a set of customers with known demands. Each customer is serviced exactly once and, furthermore, all the customers must be assigned to vehicles without exceeding vehicle capacities.*[5]

[5]Marius M. Solomon, *Algorithms for the Vehicle Routing and Scheduling Problems Time Window Constraints.* Operations Research. 1987, pp. 254-265.

During the early 1980s, operations research models and algorithms made rapid progress, particularly when applied in commercial applications. Du Pont reduced delivery costs by 15%, Air Products and Chemicals, Incorporated reduced operating costs by 6% to 10%, and Chevron developed a real-time dispatching system for petroleum tankers, thereby reducing transportation costs by 13% while at the same time increasing fleet productivity. These are just a few of the more well know success stories that began appearing during this time.

These successes were fueled by a synergistic dynamic whereby modelers strove to create more realistic models and theoreticians created algorithms that allowed these more realistic models to be solved. While progress was made in algorithms that find exact solutions, it was in the application of heuristics that the great successes were found. Exact solution techniques are hampered by the "NP-hard"[6] nature of routing problems, including the routing of vehicle fleets. In order to solve the larger scale problems that are endemic in real-world problems, researchers have turned to heuristics. Heuristics are approximating algorithms and are not guaranteed to find the optimal solution, but do find a feasible solution in a reasonable amount of time. All of the commercial successes mentioned above were produced using heuristics.

There were two basic types of heuristics used in the 1980s: insertion heuristics and sequential heuristics. Insertion heuristics typically work by inserting new customers into existing routes based on some cost function. The algorithm used in Rochester was an insertion heuristic. Sequential heuristics typically partitions the problem into stages that are solved sequentially. For example, the first stage might be to somehow divide all the customers into groups of 25 and then find the optimal route for each group of customers. While the within-group routes would be optimal, the system-wide solution will only be as good as the technique used to create the original groups.

One component that is critical to the successful modeling of dial-a-ride service is the representation of time windows. A time window is a set period of time in which you can pickup or deliver a passenger. This is an example of the type of real-world complexity that the models began to incorporate in the 1980's. Rochester's objective function is an implementation of "soft" time windows—a customer could be picked up at any time, but the farther the actual pickup was from the desired pickup time, the larger the penalty in the objective function—the so-called "pickup deviation" portion of the objective function.

More recently, modern heuristics have incorporated some randomness in how they move from one feasible solution to the next. The basic concept is that this randomization will help them transcend optima within groups or clusters of customers and improve their chances of reaching a global optimum.

[6] NP-hard means that it is unreasonable to expect that the absolute best solution will be found in an amount of time that is a polynomial function of problem size (for example, the number of customers).

Algorithm research was conducted in tandem with the Winston-Salem APTS projects. This research involved the application of two modern heuristics to one day of data that included 322 clients making about 600 scheduled and subscription trips. One interesting byproduct of this formulation was the generation a pareto frontier of aggregate travel time versus customer utility, which represent competing objectives. This frontier is shown in Figure 3 on the following page, along with the actual schedule run for that day.

The apparent difference in performance between the schedules obtained by the model and the actual schedule, which reflects both longer travel times and greater customer disutility than the simulated solutions, is due in large part to differences in operating policies. In particular, the model did not attempt to represent the policy of maintaining a set of skeleton schedule subscription routes for a some period of time. Nor was the model constrained by the real-world policy of not mixing elderly dialysis patients with grade-school children. It is also interesting to note that the model improved on-time performance more than it reduced total travel time--increasing the former by at least two-thirds and the reducing latter by at least one-fourth.

Looking at simply the reductions in travel time and the improvements in on-time performance do not tell the whole story--fleet size is another important variable. The computer's schedules used from nine to 15 vehicles and the actual schedule was operated using 14. If a computer-generated schedule used ten vehicles instead of 14, was considered satisfactory from a safety and customer service point of view, and served the same number of passenger trips in the same amount of time, the system productivity would be increased by 40%.

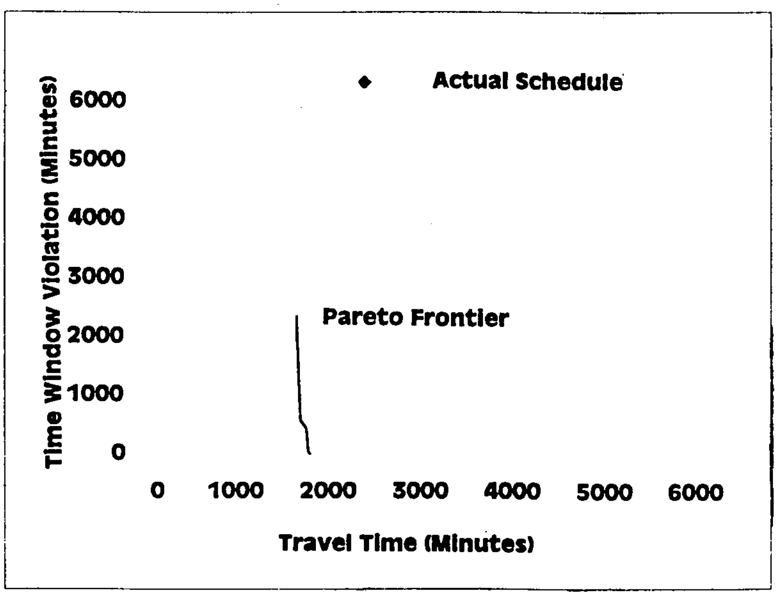

Figure 3. The real-world policies of using skeleton schedules for subscriptions, not mixing the elderly with the young, as well as other constraints not modeled appear to affect time window violation more that travel time.

2.1.9 What Lessons Can We Learn?

This whirlwind review of the history of dial-a-ride and other small-scale shared-ride services suggests a number of lessons.

- ***The impacts of a new technology can take decades to have their full market impact.*** The time interval between invention of the electric motor and the replacement of horse-powered transit. by electric streetcars was sixty years. Thirty years passed from Daimler's patent on a high-speed internal combustion engine until motor buses put a halt to the expansion of the electric streetcar network. If the computer era started in 1970, then we perhaps may be entering the period when transit "powered" by this latest technology begins its ascendance.

- ***Transit users have a strong demand for convenient access between points of origin and destination.*** In the 1910s, this demand fueled the jitney craze. Evidence of the persistence of this demand can be found in the experience of the illegal jitneys in New York City and Miami, where transit agencies first tried to suppress competition but now plan to incorporate jitneys into the transit system. The heaviest-traveled bus route in Brooklyn, the B41, had a pre-enforcement average weekday ridership of 35,000. After a concentrated effort to shut-down the jitneys, ridership increased to 45,200, suggesting that the jitneys had captured over one-fifth market share, despite operating illegally and without subsidy. A significant difference between dial-a-ride and jitney service, however, is the need to call ahead for dial-a-ride. Implications of the jitney experience for dial-a-ride, therefore, is limited, albeit important.

- ***The current dial-a-ride market is shaped by government.*** Both the demand and supply are affected—demand is created by the American with Disabilities Act and the Clean Air Act Amendments, and the supply is subsidized by the large number of federal programs that provide funds for dial-a-ride services.

- ***Institutions with a vested interest in entrenched technologies may resist innovations that will reduce their market share.*** Efforts by electric streetcar franchises to outlaw jitneys and motor buses serve as an example of opposition to technological change. Similarly, taxi drivers objected to Section 16(b)2, which provided federal capital to non-profit agencies for purchasing vans that provide service to the elderly and the handicapped. The broader lesson to be learned from this historical experience may be, however, that institutional opposition can be overcome when technology provides a superior product, as it was in the case of both motor buses and Section 16 services, and to some extent, in the recent experience with jitney services.

2.2 State of Dispatching Technology

This section describes the recent experience of transit agencies and private service providers in implementing technology to automate dispatching and scheduling functions for demand-responsive services. Topics addressed include logistics, operational issues, costs, and the nature and status of current technology applications, the differences in dispatching problems for three types of dial-a-ride service and taxi service.

2.2.1 What is so difficult about dial-a-ride dispatching?

In 1991, taxis carried about the same number of passengers as all the bus transit systems in the United States combined. In 1970, taxis served only half as many passengers as bus transit (and collected more revenue doing so). If taxi service can respond in real time to such a large market segment, why has dial-a-ride restricted its market share to a specific population that must schedule rides in advance? Particularly taking into account the level of support provided through government subsidies, why hasn't dial-a-ride gained more market share? Considering that each dial-a-ride vehicle can carry over ten passengers, while a taxi cab is generally limited to one or two, shouldn't dial-a-ride be at least five times as productive as a taxi cab?

The difficulty in dispatching dial-a-ride is integral to the service concept: shared-rides. A taxi dispatcher must consider only one thing—the place and time of pickup. When you introduce shared-rides into the system, the dispatcher must now consider the place and time of pickup and the place and time of drop-off. This seemingly minor complication has huge ramifications for the dispatching problem.

2.2.1.1 A Small Example of a Large Number of Permutations

Consider the situation where you own a van and have managed to find 20 customers that would like you to pick them up and drop them off in a single day. Half of the trips occur during the a.m. peak and the other half during the p.m. peak. You want to find the solution that turns away the fewest customers, if any at all. You also believe that in order for you to stay in business, you will need to build some tools that will help your business to grow.

You know a little basic programming and decide to write a program to generate a schedule for tomorrow morning. You don't have too much time to write the program, so you decide to write the simplest program you can think of: generate all the possible sequences of customer pickups and drop-offs and pick the route that services all the customers on-time and gives you the most margin for error. Before starting, you wisely decide to give a friend a call, as this friend has had some experience using operations research to create schedules for an airline.

Much to your chagrin, after explaining your heretofore brilliant idea to your friend, he breaks out in laughter. "You have no idea of the number of permutations you are dealing with" he says, and leads you through some computations that show the following:

- *running Pentium 120 (1.2×10^8 clock ticks per second), and*

- *assuming the cost of one possible solution is computed each clock tick, considering all possible ways to share rides,*

- *it would take your program,*

- ***over 12 days to finish.***

If you were to consider the case where you provide taxi-like service and don't share rides, it would take the program **three-hundredths of one second** to complete. The difference in complexity for this simple one-van system is a function of the factorial of the number of passengers. As you consider multiple vehicles, the shared-ride system gets even more complicated.

2.2.1.2 Some Further Complications to Dial-a-Ride Dispatching

Dial-a-ride service generally comes in three flavors:

1. ***subscription service,*** in which all trips are reserved in advance,

2. ***route deviation,*** in which real-time dispatch is mixed into the routes generated by the advance reservations, and

3. ***real-time dispatching,*** in which all trips are scheduled when the customer places an order on the phone.

Clearly the third flavor is the most complicated. As of 1992:

> *real-time shared-ride scheduling remains a goal to be achieved in high-volume everyday service. It is not yet a practical reality.*[7]

The demands associated with serving a population with special needs presents an additional complication for the dispatcher. In this situation all trip requests are not the same; some passengers are in wheelchairs, some have limits for how long they can be on board, and some require drivers with special training.

2.2.1.3 State-of-the-Practice in Dispatching Dial-a-Ride

Due to the lower than expected demand for dial-a-ride services, the expected economies of scale necessary to support the high cost of automated dispatching were never realized in the 1970's. As a

[7]John Stone. *Assessment of Computer Dispatch Technology in the Paratransit Industry.* Office of Technical Assistance and Safety, FTA. Washington, DC, March 1992.

result, between 1975 and 1990, most computers were used to create advanced reservation systems in dial-a-ride services. In fact,

> *With the exception of the Orange County DRT system [which used the system developed at Rochester—MB], the state-of-the-art technology for DRT consists of computerized reservations and scheduling software of varying degrees of sophistication, primarily oriented toward meeting the requirements of advance reservation systems.*[8]

In addition to advance reservations, the other type of function that has generally been computerized is the generation of reports that are required for funding under federal Section 15 reporting regulations. The data required include pick-up and drop-off points of trips, odometer readings to determine distance traveled, and arrival and departure times.

In recent years, software packages that offer some of the functionality installed in Rochester have become commercially available. Currently, there are at least two companies that offer computerized scheduling integrated with computer mapping and mobile data terminals. It is clear that operators want more computer scheduling. In a 1996 survey, 119 dial-a-ride providers that were already using some form of computerization were asked to identify existing software features and potential improvements they considered to be most useful. Five features were mentioned most frequently:[9]

1. ***Automatic retrieval of passenger data*** - Entering a passenger's name on the reservation form causes the passenger record from the passenger database to be retrieved and, in some cases, inserted into the reservation form.

2. ***Tracking recent ride history*** - A record of recent rides is kept that may be useful to speed up making trip reservations, auditing performance, or planning group trips.

3. ***Automatic rider eligibility check*** - Entering the passenger's name on the reservation screen causes the software to check to determine if the person is eligible. This may be just a check to determine if they are registered or a more sophisticated procedure of determining if the person and this trip are eligible for ADA service.

4. ***Trip eligibility check (for ADA trips)*** - Verifies that a patron making a trip request and the trip type have been certified as eligible.

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[8] Teal, Public Transit - *Bus, Paratransit and Ridesharing*

[9] Systan, Inc. And Logitrans, Inc. *A Guide for Acquiring Demand Responsive Transit Software:* Preliminary Draft. Prepared for the Transportation Cooperative Research Program, Transportation Research Board, National Research Council, Washington, DC. 1996.

5. ***Fully computerized scheduling and dispatching*** - The computer software determines the schedule and the trip assignments to vehicles with no human intervention.

Automatic retrieval of passenger data is the feature used more than any other by the operators, and fully computerized scheduling and dispatching is the feature wanted more than any other by the operators.

2.2.1.4 State-of-the-Practice in Dispatching Taxis

While taxi dispatching is an easier task than dial-a-ride dispatching, the taxi industry did not introduce computer control of their operations until the mid 1980s. The late adoption of computer controls by the taxi industry is a direct result of the industry's structure, which is characterized by the presence of a large number of small firms and very few large, multi-city firms. Thus, operations control is frequently uncomplicated. Moreover, many taxi companies generate their revenue by leasing taxis to drivers and thus will only realize significant gains from more efficient dispatching if they lease more vehicles; higher vehicle productivity does not affect their profitability unless their fleet expands.

Notwithstanding these barriers, starting in the late 1980s a number of large taxi companies invested in computerized dispatch systems. These investments have been significant, averaging around $1,000,000 for each of the 30 taxi companies involved. These systems implement "fully-computerized" dispatch, where the computer determines which vehicle is offered first dibs on a trip. This technology has increased dispatcher productivity, with possible staff reductions approaching 40 percent and evidence of increased customer satisfaction and ridership, as a result of reduced response times. Automated dispatching also has boosted revenues by increasing fleet size.[10]

A Typical Automated Dispatch Installation

A typical system in the United States includes eight components:

1. *data-entry terminals*
2. *computer*
3. *switch that routes digital messages between the computer and drivers,*
4. *processor that stores and prioritizes computer/driver messages*
5. *controller that codes and decodes both digital and radio frequency data*
6. *one or more base radio stations that transmit data to drivers*
7. *a mobile data terminal for each driver*
8. *a taximeter that is linked to each in-vehicle data terminal*

The computer uses three databases to help figure out how to dispatch each fare.

[10]Stone, 1992.

1. *a geo-file with address ranges for all streets in the service area,*
2. *an index that links each address range to a "zone," and*
3. *a list of vehicles and their characteristics.*

Each zone is defined by the taxi company and typically covers about four square miles. The system assigns passengers to drivers within zones through an interactive process. When drivers log into the system via the in-vehicle terminal, they query the system for the status of each zone. In response to this query, the terminal displays:

- *how many taxi cabs are currently "posted" and*

- *how many calls are awaiting service in each zone.*

Based on this information, drivers choose the zones in which they would like to do business and posts their selections to the computer. The computer then places each taxi at the end of the queue of taxis that are posted to that zone.

When a customer places an order, the computer finds the zone associated with the address and, absent any special trip requests, such as a need for a station wagon in which the driver allows smoking and takes Visa, the dispatcher offers this fare to the taxi cab that is at the head of the queue for that zone. (If no taxis are posted to the origin zone, the computer begins searching for queues in nearby zones.) When a driver is offered a trip, his/her in-vehicle terminal sounds a beep and displays an abbreviated description of the fare—usually the pickup zone. The driver is given a set time to accept or reject the trip—typically about one minute. If the driver does not respond within this set time, the computer offers the trip to the next driver in the queue and removes the previous driver from the queue. When a driver accepts the trip, his/her terminal displays the full trip information, including map coordinates and a page number reference to the local metropolitan map book.

The computer records a complete trip-- noting when the order was originally placed, when the driver accepted the trip, when the taximeter was turned on, when the taximeter was turned off, and any other transactions that occurred during the servicing.

Some Suggested Improvements to Automated Dispatching

The primary drawback of automated taxi dispatching is the large capital investment required for system purchase and installation. There is a minimum fleet size below which it is not cost-effective to install an automated dispatching systems. Fixed costs constitute a large share of the capital outlay for small operators. According to several taxi company representatives, the minimum fleet size for automated dispatch is about 200 taxicabs or 2,000 daily dispatches.[11]

An important means of boosting productivity is reducing the number of "exceptions," which are calls for which the dispatcher must get directly involved. Exceptions include such circumstances as

[11]Stone, 1992, p.14.

response times that exceed a stipulated criterion, driver rejections, unzoned addresses, customer no-shows, messages to drivers, and system errors. Operators have reported anecdotally that the daily number of exceptions approximately equal the number of dispatches.[12]

2.2.1.5 Cost of computer-aided and automated dispatching systems

Dial-a-ride systems

The cost for dial-a-ride systems can range widely, depending on size of fleet and service area and software features. A package that automates billing and reporting functions will cost far less than one incorporating mobile data terminals. Some features, such as mobile data terminals and automatic vehicle locators, require additional hardware costs that may be included in the price of the software.

Researcher Roger F. Teal calculated in 1993 that a 20-vehicle dial-a-ride fleet could be re-engineered to include automated scheduling and smart fare cards, among other features, at a cost of $130,000. A separate review of 10 different systems by John Stone at approximately the same time suggested that costs can vary from $25,000 to $1,000,000, depending on the size of the scale of operations.

Taxi systems

There are more cost data for automated *taxi* dispatching systems, which began to be installed in the 1980s. A 1993 survey of North American taxi operations conducted by John Stone showed that taxi computer dispatch systems averaged about $1,000,000 for a fleet of 300 taxis. It appears that competition and technological advances may be pushing prices down, as indicated by the following cost estimates, drawn from the survey:

• 150 vehicles	$350,000	$2,333 / vehicle
• 200 vehicles	$415,000	$2,075 / vehicle
• 350 vehicles	$860,000	$2,457 / vehicle

Europe in particular has exhibited strong growth in the automated dispatching of taxis: in 1995 there were 29,949 vehicles controlled by computer; an increase of 276% from 1990 [EcoPlan 1995]. The experience of European operators suggests that automation for a fleet of 500 taxis would require and investments of $300,000 - $400,000 for the control room and communications base and $1.5 - 2 million ($3-4 thousand per taxi) for mobile equipment. Cost data for European automated taxi systems are presented in Table 1.[13]

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[12]Stone, 1992, p.14.

[13]EcoPlan International, Leber Planification 3 Ingenieria S.A., Gardner Consulting . *TaxiCom 95: International Survey of Leading Innovational Taxi Communications and Operations Approaches.* U.S. Department of Transportaton, Federal Transit Administration, Technical Assistance and Technology Sharing Program. Washington, DC, 1995, p.6.

Operator	Taxis	Supplier	System	Date	Cost (US $ thousands)
Taxi Blues (Paris)	2,000	Indelco / Pragmatic	“Basic” w/ GPS	9/95	157,000
Computer Cab Co. (London)	2,500	Computer Cab Co.	self-developed	1989	n/a
Glasgow T.O.A.R.S. Ltd	480	GMSI	MDCS	7/93	800
Hansa Funk Taxi (Hamburg)	600	Indelco AG	“Simple”	1990 to ‘91	3,900
Linkoping Taxi Econ Union	89	Volvo / Ericson	Taxi-80	1984	306
Taxi Asker o Baerum (Hovik)	300	Volvo / Ericson	Taxi-80	1984 1994	145 65
Taxi Gothenburg	615	Volvo / Ericson	Taxi-80	1982	n/a
Taxisentralen Drammen	94	Volvo / Ericson	Taxi-80	1986	1,280
Taxi Zentrale Stuttgart	700	Innova / Unitax	self-configured	1989 1992 1994	375 120 120

Table 1. Taxicab companies in Europe have been continuing to invest in automated scheduling technologies.

2.3 State of Dial-a-Ride

2.3.1 Investing in Technology

Advanced public transportation systems (APTS) are a set of advanced technologies that transit operators are using to improve productivity. In 1996, the Volpe Center surveyed the 1993 Section 15 reporters to ascertain the level of APTS activity. The preliminary results of the survey are summarized below. Responses were received from 464 agencies, some of which reported that they were not using nor planning to use APTS technologies. These agencies were not included in the tabulation.

The APTS technologies presented in Table 2 are a subset of all the technologies included in the survey. Note that this survey covered all Section 15 reporters and was not limited to dial-a-ride providers. The complete list of APTS technologies follows.

- ***advanced communications***: digital radio and/or trunked radio (computer selection of an available frequency, as opposed to a manual selection or use of pre-set frequency)

- ***automated vehicle location***: position determination via an automatic technology or combination of technologies, such as Global Positioning Systems, Signposts, Ground-Based Radio, or Dead-Reckoning, typically including real-time reporting of that location to a dispatcher.

- ***automated passenger counters***

- ***vehicle component monitoring***

- ***automated operations software***

- ***automated transit information***

- ***multimodal traveler information***

- ***automated fare payment***: payment schemes in which riders pay for individual trips using a debit card purchased in advance or a credit card that provides for payment later.

- ***multi-carrier fare integration***

- ***paratransit CAD***: Computer-Aided Dispatching employed on demand-responsive fleets

- ***mobility manager***: a centralized office through which riders or human service agencies may book trips on one of two or more subscribing service providers. Riders or agencies are billed by the Mobility Manager.

- ***transportation management centers***
- ***traffic signal priority***
- ***real-time ridesharing***: ridesharing trips arranged on short notice or on an ad hoc basis, typically in private autos
- ***automated HOV facility monitoring***.

Not only is computer-aided dispatch the most common dial-a-ride APTS technology, it is the most common of all 15 technologies.

Technology	Operating	Imple-menting	Planning	Testing	Total
paratransit CAD	59	16	16	1	92
automated vehicle location	22	32	21	5	80
advanced communications	52	10	7		69
automated fare payment	15	15	15	5	50
mobility manager	4	2	1		7
real-time ridesharing	2	1			3

Table 2. The most common dial-a-ride APTS technology is computer aided dispatching, followed by automatic vehicle location. Ninety-two properties are operating, implementing, planning, or testing computer aided dispatching.

2.3.2 Dial-a-Ride Data in Section 15

Table 3 below shows some basic statistics for dial-a-ride, based on 1996 Section 15 data, compiled under FTA auspices for urban areas. Note that the sample size for the fare revenue statistics is smaller than the other statistics because properties do not have to fill out Form 203, Operating Funding, with mode specific information. However, some properties do provide fare revenue by mode; 32 to be exact. The remaining 31 operators in the sample set were those properties that provide only one mode of transportation, namely dial-a-ride, and reported their operating revenue.

Metric	Value	# of reporting data	Median
Expenses	$805,066,744	435	$612,333
Fare Revenue	$8,661,584	63	$51,249
Pass Trips	54,500,766	434	53,870
Pass Miles	390,940,943	426	312,281
Vehicle Miles	363,080,242	434	295,843
Vehicle Revenue Miles	307,916,048	434	259,122
Vehicle Hours	24,373,006	433	22,440
Vehicle Revenue Hours	21,437,829	433	19,986

Table 3. According to the 1996 Section 15 data, there was over $800 million expended in the provision of dial-a-ride transit.

The Section 15 data can be used to estimate developed by jitney researcher Richard N. Farmer in 1965 to calculate operating profit or loss. The operating statistics were computed by matching directly operated expenses with directly operated service statistics and purchased transportation expenses that had operating statistics reported in the same report with those purchased transportation operating statistics. Those statistics for properties that contracted out their dial-a-ride service to contractors that submitted their own Section 15 were not included, as it was not possible to link the expenses directly to the operating statistics.

Let: R = *revenue per passenger mile*
A = *average passenger-miles per vehicle-mile*
S = *average vehicle-miles per hour*
C = *average cost per vehicle-mile (including depreciation)*

We can then compute the profit margin per hour, M, as

$$M = RAS - CS$$

Using 1995 section 15 data, we can compute the nationwide values for the above four parameters to be:

R = *\$0.13 revenue per passenger mile*
A = *1.00 passenger-miles per vehicle-mile*
S = *13.82 vehicle-miles per hour*
C = *\$1.88 in expenses per vehicle-mile.*

Unlike the cost component of Farmer's model, the Section 15 data incorporate neither interest on loans or depreciation as an operating expense. The computation yields a gross operating balance of -$24.18 per vehicle hour.

2.3.3 Providers' Experience

Academic literature and statistical data provide useful information about the application of technology to demand responsive service, but do not necessarily present a complete picture of actual conditions in the industry at a particular time. In an attempt to capture this perspective, five operators were called to obtain information based on practical experience with dial-a-ride operations.

2.3.3.1 Selection of Provider Contacts

The original approach taken was to focus on the larger dial-a-ride operators, because the potential net benefits of automation are greater in the case of larger fleets. However, contacts representatives of the MBTA in Boston and PACE in Chicago revealed that these large operators provide dial-a-ride service by contracting with multiple vendors. The MBTA had eight separate vendors providing service and PACE has 53 separate dial-a-ride "projects." In addition to having multiple vendors, PACE had multiple service policies. PACE provides the suburban bus service for the Chicago area, and many of its dial-a-ride projects are for different cities in towns in the five collar counties of Chicago. Each city and town can have their own guidelines governing such factors as eligibility and service area boundaries.

The Section 15 data support these observations. Among the operators that provided more than 5,000,000 dollars worth of dial-a-ride transit service in 1996, 80% of their expenses were for purchased transportation. Of the $300 million that these providers spent on purchasing dial-a-ride service, three-quarters was to vendors that did not report their service statistics in separate Section 15 reports, meaning that most of these contract operations are not large enough to be required to submit separate reports.

Instead of continuing to call the larger properties, it was decided to focus on operators with annual expenses between one and five million dollars, based on the expectation that there would be a greater likelihood of speaking with individuals having direct responsibility for managing operations. The Section 15 data from 1994 contains 103 such operators. The set of properties included in the sample are identified below in Table 4. While the sample is small a wide range of operator types are represented. The operators in Illinois and Santa Ana are private vendors that contracts with municipalities. The Winston-Salem operation is directly operated and is one of the most technologically advanced properties in the country. The San Carlos operator provides all of it's dial-a-ride service by contracting with a private vendor. The dial-a-ride operator in Tucson is run by a general manager and an operations manager that are contract employees, while the remainder of the workforce is on the city payroll.

Section 15 ID	Purchased service from a vendor?	Total dial-a-ride expenses	Unlinked passenger trips	Vehicles operated in max. service	City, State
4012	No	$1,021,218	159,208	12	Winston Salem, NC
5150	No	$2,123,525	234,130	61	Oakbrook Terrace, IL
9009	Yes	$2,541,603	144,126	44	San Carlos, CA
9158	No	$3,225,068	592,996	104	Santa Ana, CA
9033	No	$4,256,333	291,469	50	Tucson, AZ

Table 4. The operators ranged in size from 12 to 104 vehicles (as reported in the 1994 Section 15 data) and included two contractors, two direct operators, and one property that purchased all its dial-a-ride transportation.

Information provided by three of the contacts is presented below: the Houston jitney and bus/jitney-hybrid service, and the two most technologically advanced operations, Winston-Salem and Tucson, Arizona. Observations from the other contacts are summarized at the end of this section.

2.3.3.2 Introduction of Jitney Service in Houston

This is not a story about dial-a-ride specifically, but it concerns issues that are relevant to dial-a-ride. For while jitneys are typically hailed from the curb and not reserved in advance, operations are very similar to those of dial-a-ride in terms of flexible routing and vehicle maintenance.

There are actually two jitney programs in the Houston area, both a result of a citizen suing the city to repeal the City's anti-jitney ordinances because he believed that he could run a jitney service at a profit. The City responded to the repeal of the anti-jitney laws by creating a revenue-neutral program in which licenses may be granted to private operators through the branch of the municipal government responsible for licensing charter buses, sightseeing trolleys, limousines and taxi-cabs. The license fee is around $500 for a year. Once licensed, the jitney operator is free to operate without monitoring of passenger loads by the City.

The other Houston service is not really a true jitney operation but rather a hybrid that falls between fixed route bus and taxis. This program, called FasTrak, is administered by the regional transit authority, which accepts potential contractors' proposals at any time. A proposal should identify the corridor in which the entrepreneur would like to operate and provide detailed cost information on the daily cost of the vehicle, the insurance cost, driver cost, and revenue expectations. The City analyzes this information to determine whether the operation is likely to break even. The drivers do not need commercial licenses, but they must pass a drug test and background checks and are required to have held a driver's license for three years. If they operate vehicles with capacities of less than eight passengers, they are exempt from ADA requirements.

There are six bus corridors available for the FasTrak program. One of these corridors is very large—one of the top ten routes in the country in ridership. The driver may deviate from the corridor by up to one-quarter of a mile, with the intent of make drop-off more convenient—not to search for riders. The operators are not allowed to cruise malls. The operator gets to set his fares and keeps the revenue. In addition, if he operates a vehicle six hours in one day (with three-hour minimum segments) he receives a $25 subsidy from the transit authority. There are no restrictions on the number of days in the week he must provide service.

FasTrak has gotten off to a slow start. The first contractor lasted nine weeks. A second contractor was ready to begin service, but Houston withdrew support when municipal personnel learned that the contractors insurance payment had bounced. A third contractor is lined up and should begin service soon. One reason for the difficulty is the high cost of insurance, although requirements don't appear to be onerous:

- $20,000 each person for bodily injury
- $40,000 each accident for bodily injury, and
- $50,000 each accident for property damage.

Costs for this level of coverage are on the order of three to four times the equivalent for a personal automobile.

Based on the City's limited experience with the first contractor, it appeared that there was a market for type of service provided. The contractor operated a fleet of five vehicles and began with a demand of 25 to 30 people per vehicle, which grew quickly to a maximum of 50 people per vehicle per day. The contractor charge $1.25 per trip, while the bus fare was $1.00. At a per-vehicle cost of $25 per day, the average cost per passenger trip to the City was $0.50 at the maximum level of demand. However, with only a small vehicle fleet, ridership was limited to only 250 passenger trips per day, which represents only a small fraction of total transit ridership. The limited experience represented by this example does not support extrapolation to conclusions about the potential scale of jitney or dial-a-ride markets.

2.3.3.3 Automation of Dispatching and Scheduling in Winston-Salem

During 1995, Winston-Salem integrated computer-aided dispatch and scheduling software from On-Line Data Products, mobile data terminals from Gandalf Mobile Systems, and an automatic vehicle locator system from Racon Systems. This was one of only four operational "Mobility Manager[14]" APTS projects in the United States and was funded with an FTA APTS grant.

[14] A mobility manager is a centralized office that books passenger trips on two or more service providers [Volpe 1996].

Winston-Salem has run dial-a-ride service since 1978, when it provided transportation for human service organizations. The transit agency is now a truly integrated service provider, receiving funding from multiple sources and serving a variety of clientele. Currently, the vehicle fleet consists of 190 vehicles and 14 vehicles are required to meet peak-hour demand. These vehicles provide nearly 200,000 passenger trips each year, and cover nearly 500,000 vehicle miles. Demand has doubled since ADA was enacted.

There are three main vehicle types used in the Winston-Salem dial-a-ride service: minibuses, van conversions, and body-on-chassis. These have become quite reliable, now that the implementation of new technologies has been tried and tested. Demand responsive vehicles now conform to ADA, and the manufacturers are focusing on fine-tuning the technologies. For example, lifts has always been a problem so low floor vehicles are getting more attention.

Winston-Salem is one of the more efficient providers in the country, averaging six passenger trips for each vehicle hour and 0.42 passenger trips per each vehicle mile. Computer scheduling is used to assemble routes for approximately 50 percent of the trips served. Roughly 25 percent of the routes are "hand-massaged" the day before, and the final 25 percent are assigned on the fly by the dispatcher on the day of service.

Another impediment to dial-a-ride productivity, in addition to low demand densities, is open-ended return times. Many medical trips are of this type, where the customer requests a ride to and from the doctor's office and does not know exactly when the appointment will be over. The customer calls when the appointment is finished, which makes the scheduling task more difficult. Another constraint results from the integrated nature of the service: experience has shown that rambunctious grade-school children do not mix well with elderly dialysis patients returning home from medical appointments.

As for the future, cost pressures are likely to lead to a modified fixed route type of service—a move away from the standard dial-a-ride. Paying for dial-a-ride was not difficult when the service was small in scale, but now that it has grown, funding has become and will continue to be a problem. Technology can be expected to play a big part in creating future efficiencies in scheduling and dispatching functions.

2.3.3.4 Installation of Mobile Data Terminals in Tucson

The City of Tucson received an FTA grant to upgrade its transit communication network. One piece of this project was to install mobile data terminals in the dial-a-ride fleet. Rockwell is the prime contractor on the project, which will integrate Trapeze software with the mobile data terminals.

While Tucson has had the "PASS" system installed for six years, it has not been used for scheduling, as "they never got it to work right." Scheduling has been done manually by four employees in an operation that runs 54 vehicles in maximum service. Trip requests come in up to seven days in advance and a day's schedule is created two days in advance. A crew comes in at night and calls customers who are scheduled for service two days hence. The schedulers will take trip requests the day of service and fit them in as possible. Real-time changes to a vehicles tour are communicated via two-way radios.

Tucson has operated special needs transport since 1972. In recent years there have not been major changes in demand; this year demand is approximately 10 - 12 percent higher than last year, which is a typical annual increase. Tucson has stood firm on restricting eligibility to those who truly fit the ADA requirements, resisting public relations pressure from organizations representing the elderly. Part of the pressure resulted from confusion over why some people are granted temporary eligibility (until fixed-route buses are lift-equipped) versus full eligibility.

The mobile data terminals, when implemented, will record the time and mileage for every communication, replacing the current onerous and error-prone work of recording trip sheets. Currently, a trip sheet is generated by the computer and given to a driver at the beginning of his tour. As the day progresses, the driver annotates the trip sheet with the actual times of pickup and drop-off, as well as any additional trips added to the tour. When the day's work is complete, the driver submits the trip sheet to data entry personnel, who key punch the information into the computer.

2.3.3.5 Observations from Discussions with Providers

- ***Dial-a-ride scheduling is not yet fully automated—but automation is expected soon.***

None of the providers that were contacted relied entirely on the computer to schedule and dispatch vehicles. Most were computer-assisted, none were automated. John Stone's observation that

> *real-time shared-ride scheduling remains a goal to be achieved in high-volume everyday service. It is not yet a practical reality.*

still seems to be applicable today. All contacts that did use computer assisted scheduling also mentioned having skilled dispatchers that were able to modify the computer's schedules to make more "sense."

The providers also mentioned that automated scheduling is an area that they expect to improve in the future. One contact commented that the key to automated scheduling is real-time feedback from the vehicles. He noted that no-one (to his knowledge) has put all the pieces together in one application.

- ***Contracts are being split in two—the "broker" and the operator.***

The amount of contracting for dial-a-ride service is increasing as more and more municipalities turn to private contractors to help them meet the requirements of ADA. Contracts can run the gamut from simply providing drivers and management to all aspects of service, including labor, vehicles and other equipment, and marketing.

A recent trend is the structuring of dial-a-ride contracts in two parts, where a municipality contracts with one vendor to provide the schedules and dispatching, and contracts with another (or others) to operate the service. This structure is intended to combat the conflict of interest inherent in contracting both pieces through a single vendor. As most vendors are paid a set amount per vehicle hour, if one vendor is both scheduling and operating a service, the corporate incentive of maximizing net income conflicts with the municipalities incentive of serving the most passengers for the same cost.

One private contractor commented that while this approach would remove the possibility of a vendor assigning trips to its own less efficient vehicles, it could also lower efficiency if a single firm is the most productive provider of all required services. The multiple-contractor approach has the added complexity of involving many companies in providing one service. The operations part of the contract generally will be larger than the scheduling/dispatching of "broker" component.

- ***Eligibility is the only control a municipality has for dial-a-ride demand.***

ADA limits fares to twice those of the fixed route service and at the same time does not allow an operator to have a pattern of turning away trip requests because of insufficient capacity. While automated scheduling can help improve efficiency, it does not control demand. In fact, efficient scheduling, and in particular scheduling that allows same-day service, may in fact lead to increased demand as customers realize the service is reliable and operates much like a taxi cab--for only double the price of a bus ride.

The only tool that remains for a municipality to control the growth in cost is to be as strict as possible when determining eligibility. ADA is only supposed to give service to those people that can't use fixed-route buses. This is mainly a functional test, based on such criteria as an individual's ability to get to a bus stop, stay oriented, and determine the stop at which to get off the bus.

Some municipalities that in the past offered dial-a-ride service to the entire elderly population may find their generosity has become more expensive than they had planned, as the demand for the dial-a-ride service has risen. These places now face the unpalatable choice of restricting service further or absorbing the growing expense. One location took the novel approach of offering non-ADA-eligible elderly customers a free ride on any fixed-route bus in an attempt to shift demand away from dial-a-ride. It was cheaper to provide free rides on fixed-route than to collect a fare for the same trip on dial-a-ride.

- ***ADA passengers can present special challenges.***

A final theme that emerged from the discussions with the providers is that ADA customers can present a set of special challenges for the service provider. Some passengers become disoriented once they are on board. One operator related that some customers use dial-a-ride for their mentally disabled children and specifically request that the children are not delivered before a specific time--in other words, they ask the dial-a-ride operator to extend the trip home so that the parents are sure to be home when their child is dropped off. In these instances, the bus ride is used as a very short-term day care service.

There are other challenges that are specific to the provision of dial-a-ride. As noted previously, it is not good policy to mix elderly dialysis patients with young school-age children on the same bus. Taking phone orders can be difficult because it is hard to communicate verbally with some customers. A common problem is determining how to adequately restrain electric scooters with solid wheels, as most restraining devices assume wheels with spokes. The last problem is that there is a significant number of subscription service no shows--one operator estimated the frequency to be as high as 10-20% of all calls. This factor is a significant source of schedule inefficiency.

2.4 Conclusion

The historical perspective and review of recent experience presented in this section provide a number of insights into the challenges and potential applications of ADART. One market dynamic that is clear is that dial-a-ride demand, particularly service for the elderly, will not be declining any time in the near future. The U.S. population is aging and demand will decline only in cases where local governments impose more restrictive eligibility requirements, is if a municipality decides to make their eligibility test more stringent. This is an extremely delicate political issue, however, and is unlikely to occur in too many municipalities unless dial-a-ride service becomes an extreme municipal financial burden.

Given a finite transit budget, expansion of dial-a-ride operations will necessitate reductions in other transit services. However, as shown in Table 5 below, on a national scale, this is not likely to create a major problem, as dial-a-ride trips account for only one percent of all transit trips. There may be pockets where the impact of rising dial-a-ride demand will cause serious fiscal pressure on the provision of fixed route service. It will be interesting to see how municipalities react to this pressure; for example, some may begin raising fixed-route fares or charging more for transfers in order to increase ADA service dial-a-ride fares, which cannot exceed twice the fare for fixed route services. The table also shows that operating costs for dial-a-ride are substantially higher on a per passenger trip basis than for other transit services. While dial-a-ride trips represent only 1 percent of all transit trips, the cost to provide these trips is 6 percent of total transit operating costs.

Certainly, it will not be long until mobile data terminals, automated vehicle locators, and automated scheduling are available to dial-a-ride operators. A commercial product that integrates mobile data terminals and computer-assisted scheduling is available now, and claims two installations. Winston-Salem has three vehicles operating with mobile data terminals, smart card readers, and automatic vehicle locators. Computer-aided dispatching is the most common APTS technology in the field.

The improvements that can be expected from computerized scheduling should be able to bring dial-a-ride costs in line with the rest of the transit industry. Data presented in Table 5 show that on average, it costs around $35 to operate a dial-a-ride vehicle for an hour. Based on this operating cost, Figure 4 presents a plot of the frontier between net profit and loss as a relationship between dial-a-ride productivity, as measured in passenger-trips per hour, and the fare charged per passenger trip. Assuming the fare per passenger to be two dollars without any subsidy, the productivity required to break even would be about 17 passenger trips per hour, which exceeds the capacity of many dial-a-ride vehicles! The level of productivity required to achieve a 40 percent fare recovery rate, which is typical for public transit overall, would be 7 passenger trips per vehicle hour with fares of two dollars per trip, which appears to be within reach. Nearly 10 percent of dial-a-ride operators reported productivities of 5 passenger trips per hour or higher in the 1995 Section 15 data set.

	1988	1994	% change
Operating Expenses (in millions)			
dial-a-ride	$462.60	1,145.70	148%
all transit	$14,287.3	$18,782.3	31%
dial-a-ride percent of total	3.24%	6.10%	
Passenger Trips (in millions)			
dial-a-ride	73	87	19%
all transit	8,666	8,435	-3%
dial-a-ride percent of total	0.84%	1.03%	
Operating expense / passenger trip			
dial-a-ride	$6.34	$13.17	108%
all transit	$1.65	$2.23	35%

Table 5. Comparison of operating costs and usage for different transit services nationwide.

total cost / vehicle-hour	$34.00
operating cost / vehicle hour	$28.00
vehicle miles(millions)	552.7
operating expenses (millions)	$1,145.7
average speed	14
capital cost / vehicle hour	$6.00
chassis on body	$60,000
vehicle life (years)	7
annual mileage	20,000
average speed	14

Table 6. On average, it costs around $35 per hour to operate a dial-a-ride vehicle.

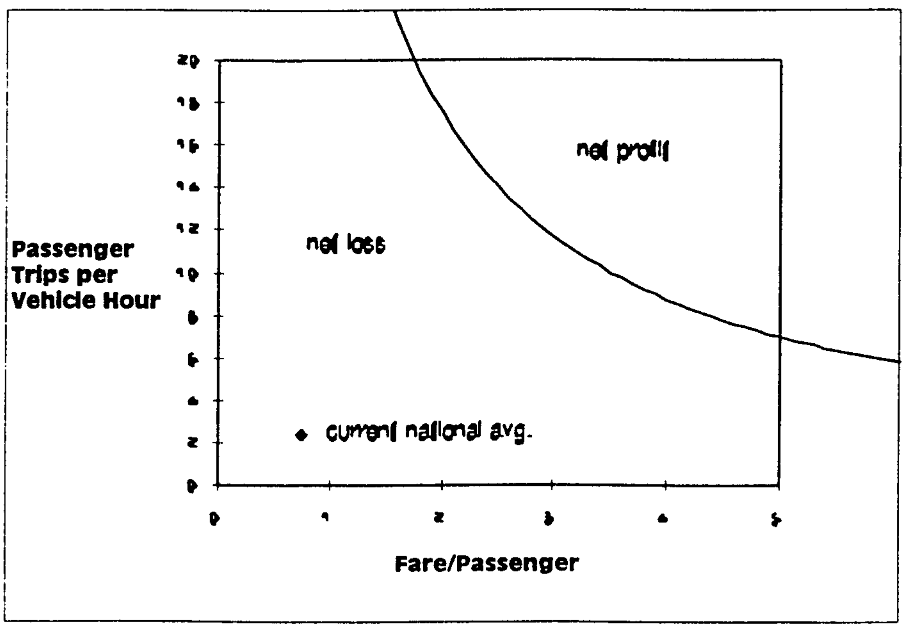

Figure 4. Using a per-hour vehicle cost of $35, we can plot the frontier between net profit and loss as a relationship between dial-a-ride productivity and fare.

Whether or not dial-a-ride ever reaches the break-even frontier is impossible to predict. What is clear is that to reach this frontier, the service will have to serve large numbers of non-ADA trips at premium fares on the order of $4 to $5 dollars per passenger trip. The application of automated scheduling, dispatching, and routing technology is likely to be a prerequisite to achieving the productivity improvements upon which the expansion of dial-a-ride services depends.

3.0 MOBILE COMMUNICATIONS

This chapter reviews the application of mobile communications technology to ADART. Five key topics are covered:

1. Requirements for developing a wireless communications network for ADART.

2. The current state-of-the art of wireless communications services, technologies, and providers, including an analysis of the features/benefits of each available service/technology, each system's/provider's respective advantages and disadvantages, and respective costs.

3. A near term forecast of the status of wireless communications market/technology, including the identification of those technologies/providers likely to emerge as the dominant factors in the wireless industry.

4. Analysis of the various wireless communications' application program interfaces (APIs), where relevant; the services the various APIs provide; and which set of APIs will be most useful in the ADART application. Descriptive technical detail is also provided on how the ADART service can be implemented over a wireless data network.

5. Recommendations for ADART application development and a wireless architecture. Criteria considered include account systems' reliability, development time, systems maintenance and upgrades, and operating costs in a production environment. Also, the computer operating systems that are best suited to support an ADART wireless system will be identified.

3.1 Mobile Communications Framework

The communications hardware and software establish three connections.

1. ***Vehicle--customer***: Under normal conditions, all vehicle--customer communications goes on between a computer and the customer. This takes place within the framework of the mobile communications system as a client-server communication, in which the customer requests service by either calling an Interactive Voice Response (ICR) system or logging onto the server via the Internet or a remote terminal. At a pre-determined time, the vehicle computer automatically calls the customs with the estimated time of arrival (ETA) or an ADART vehicle for the pick-up. Rarely does a driver communicate directly with a calling customer.

2. ***Vehicle--vehicle***: A mobile radio via the modem carries and receives broadcast messages from other vehicles, primarily for allocating customers among vehicles in systems where multiple vehicles operate in the same service area. This form of communication is server-to-server.

3. ***Vehicle--base station***: A radio-modem sends and receives messages to and from the base station, primarily for fetching customer data from the central accounting system (discussed below) and secondarily for vehicle tracking at the base station when desired. A cellular phone provides back-up emergency communications when a vehicle's computer system goes down.

At the first level, this is a wireless, client/server system. Users across a city-sized area will be calling into an automated Computer Telephony/Dispatch Server (CT/DS) to request a service. The CT/DS uses text to speech (TTS) and ICR to communicate with the callers, instead of human operators. Alternatively, users with PCS will dial into a CT/DS server and request a service. Remote dumb terminals will also be scattered throughout a metropolitan-sized area and will be used to dial-up and access the CT/DS. Attached to the CT/DS will be a file server/Data Base Management System(DBMS). All servers will be fault tolerant and run on IBM PC-compatible machines.

The CT/DS server will dispatch a user request for service to client machines, which are located on-board roaming vehicles. The clients will also be based on PC compatible-based systems (laptop machines). The mobile clients will use Global Positioning Systems (GPS) as well as other navigational aids and will communicate back and forth to the CT/DS server. For example, the clients will have on-board credit card-type readers that will scan all user information, and then relay that user data (which is kept secure at all times) back to the CT/DS. The client machines will use TTS to communicate with the vehicle drivers, and also automatically call customers to transmit service status messages (e.g.,"vehicle on the way").

At the second level, this is a peer-to-peer, parallel processing system using digital data wireless communications. The mobile client systems are themselves connected together via a wireless metropolitan wide-area network (WAN). Collectively, the mobile clients will be doing real time parallel processing (the client application – dynamic scheduling – is computationally intensive). For highest application efficiency, the roaming clients would use message passing and dynamic balancing of the computational demand. In effect, the ADART operating/communications system is a mobile, dynamically expandable, network parallel supercomputer. The entire communications system is being designed to run as autonomously as possible, without the need for human operators. The ADART computer will do all the decision making and network self-management. Intelligent software agents will be used to autonomously marshal and logically coordinate resources across the entire network. The entire ADART architecture will be inherently fail-safe and highly resilient to system damage/failure.

3.2 Requirements for Developing a Wireless Application

Every wireless solution has four basic components:

1. *Network* - the physical links connecting here to there
2. ***Devices*** - a user needs something that "talks" to the network

3. ***Connectivity*** - data must get from an application to the device and network layer.
4. ***Applications*** - what does the user (in this case, ADART) want to do?

These four basic components are presented in Figure 5 in the standard Open Systems Interconnection (OSI) reference mode in order to facilitate an understanding of the requirements.

The first of these components is the network, comprising the physical infrastructure (transmitters, receivers, network control logic) that forms the communication backbone used by the other three components. The second component group is the wireless devices that connect to the network. These devices use wireless modems to communicate with the network backbone. The third component is connectivity tools, which are the various software communication programs on each end-station that coordinate messages between devices or between the device and the central server. It is recommended that ADART developers use "off the shelf" commercial software for these tools and that they choose tools that support an API, to ensure that the application software can easily gain access to the capabilities of these tools. The fourth and final component is the application software, that is, the programs that compute routes, dispatch vehicles, generate schedules and reports, and perform other functions intrinsic to ADART. Application software will be used on each of the wireless devices and also at the centralized server when using host routing.

3.2.1 ADART Application Design Considerations

The performance of a wireless data network can be optimized when design criteria are applied that reduce response time to the end-user and minimize costs. One of the primary criteria is to limit the size of messages to below 10 thousand bytes. In the case of ADART, message size between mobile clients is estimated to be about 50 bytes, which is substantially below this threshold. A beneficial design feature is the use of compression software on both client and server ends. It is also advantageous to design for and test exception handling for the times when the wireless device is out of range or "off."

From an operational standpoint, management and prioritization of data transmittal are also crucial. All data sent to the client do not need to be updated wirelessly and in real-time. For instance, updating ADART customer profile files every night using a wireline modem makes sense -- and also enables the mobile vehicle clients to have the latest customer information while in the field.

3.2.2 Cost Considerations

Some primary cost considerations in developing a wireless solution for ADART fall into three major categories:

1. ***Development and Testing Costs***: Training (analysts and programmers), hardware procurement, API procurement, application development/modification, and host connectivity (Dial-Up or Dedicated Line to the wireless network during development and testing). All of these costs will vary depending on the hardware platform selected, the API selected, and

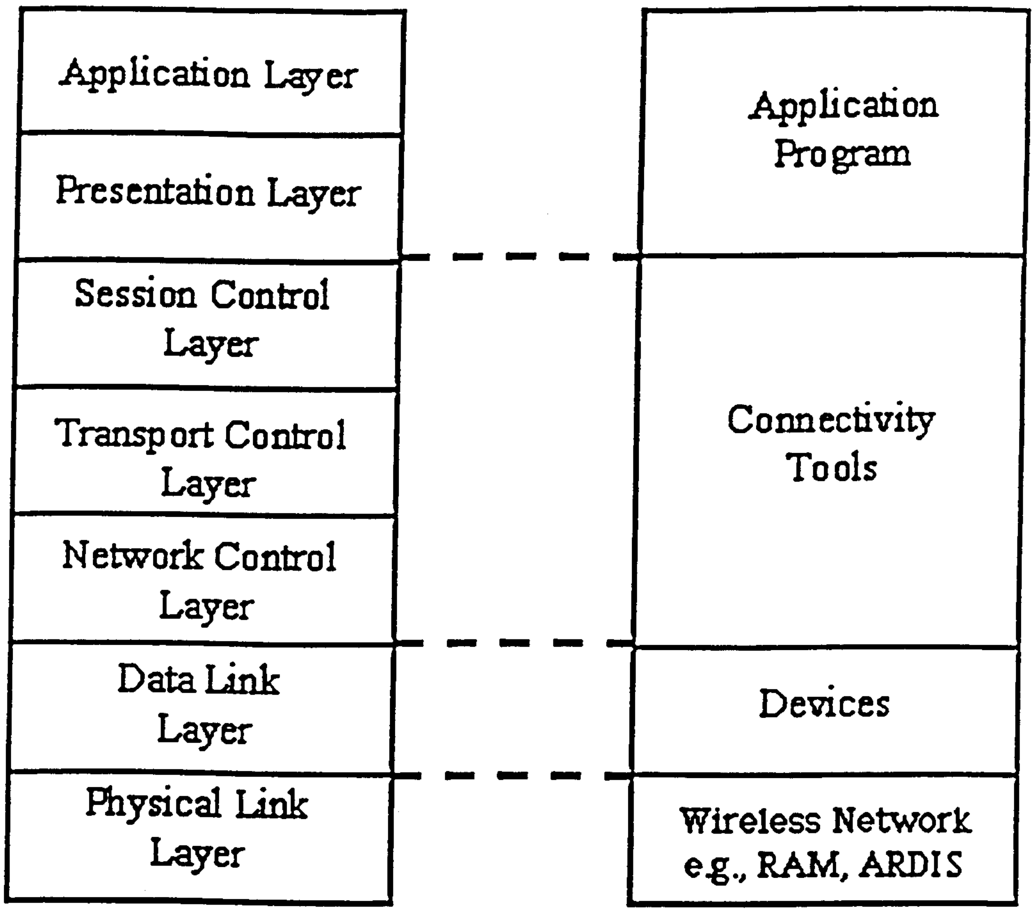

Figure 5 - Wireless System Components

the amount of staffing required to complete the project. The greatest expense--for application development, also will vary greatly among developers based on the analysts' and programmers' level of experience in the development language of choice and in data communications. If modifying an existing wireline application, there can be major costs associated with modifying the software to minimize traffic and handle the exceptions that exist in a wireless environment. The use of APIs can reduce technical set-up requirements.

2. ***Component Start-Up Costs***: Client software, server software, devices/modems, API license fees, dedicated line installation fees, and registration fees.

3. ***Usage/Production Costs*:** Airtime costs per transaction, dedicated line/VAN connection to the wireless network (monthly costs), and cost of hardware/software maintenance. While the packet count between vehicles during the processing of the on-board scheduling algorithm is quite small, operational estimates are required to determine the number of such small transactions that will take place during any given month.

Applying the design criteria discussed earlier will enable ADART operators to estimate the costs entailed in using a service provider's fee-per-packet network. However, an alternative solution is available for ADART that does not require packet-based service charges. This solution involves the use of a wide area, wireless, cellular Ethernet. The air time for this solution is "free," because no service provider is required. This solution is also described in detail in this chapter.

3.3 Current State of the Art: Systems, Technologies, and Vendors

Thanks to a tremendous market surge in wireless products, technologies, and vendors, the ADART project's unique requirements can be fulfilled by several possible mobile data technologies and their associated vendors. These include:

- ***Data Radio Messaging Systems***
- ***Cellular Digital Packet Data (CDPD) over Cellular***
- ***PCS (Personal Communications Services), and***
- ***Wireless, wide area Ethernet***

This section describes each of these four systems and evaluates and presents recommendations for selecting the best system for ADART.

3.3.1 Data Radio Messaging Systems, Wireless Packet Data Networks

There are a number of services and hardware solutions that can enable ADART vehicles and users to communicate data wirelessly, one being wide area packet data radio networks. Packet Data Networks (PDNs) are designed to segment data into packets - much like X.25 international network protocols do for wireline networks. The actual data are broken up into packets of either 240 or 512 bytes and then sent over the network (the modems and network handle this packetization, not the application programmer). The system provides extensive error checking and correction features to ensure data is communicated correctly across the radio waves. What differentiates PDNs from other networks is that users are charged only for the data they actually pass, not for the time they are connected. This allows users to "always be on," in that they can always send and receive data.

There are, nevertheless, certain limitations to Packet Data Networks. The first is that because the data is packetized, on-line sessions are not handled effectively or efficiently without modification. Also, Packet Data Networks are not optimal for handling large file transfers (over 10K). Because the data are broken into packets of 240 or 512 bytes for transmission, the amount of data transferred increases the likelihood that some information must be retransmitted. This results in delays to the user and is an inefficient use of the network. If an application only involves transmitting large files the solution may be better served in a wireline environment. However, because large files are only occasionally needed for ADART and the majority of transmissions are of small data amounts, a Wireless Packet Data Networks can be a good fit.

3.3.2 System Architecture: Routing Information on Wireless Networks

1. ***Host Routing*** (Figure 6) is used when a wireless device sends messages to and receives messages from a fixed host connected to the wireless network. It is suited for applications which require central control functionality or inter-operability with other networks/fixed systems. The centralized host manages the information flow between a central server and many personnel using wireless devices. Host routing is accomplished by running a dedicated private line between the customer/service provider's server and the network.[15] Good examples of host routing within the context of ADART are:

    - ADART applications which allow the servicing vehicles to receive up to the minute information on customers/riders from a centralized server in the main office.

    - Wireless e-mail applications, connected either to a ADART server or to a publicly available gateway, such as RadioMail. All users are connected to RadioMail's gateway, which routes messages between ARDIS users, other wireless networks and the Internet.

2. ***Peer-to-Peer Routing*** (Figure 7) is used when a wireless device sends messages to and receives messages from another wireless device. This is the case when ADART vehicles communicate with each other. These messages are directed to other wireless devices via the ARDIS network. The peer-to-peer configuration works well for communication only between ARDIS users - and

[15] During development, an organization typically uses a dial-up connection to the wireless network instead of a dedicated private line. Once a customer is committed to using the network and the number of potential users has been defined, a leased line can be established.

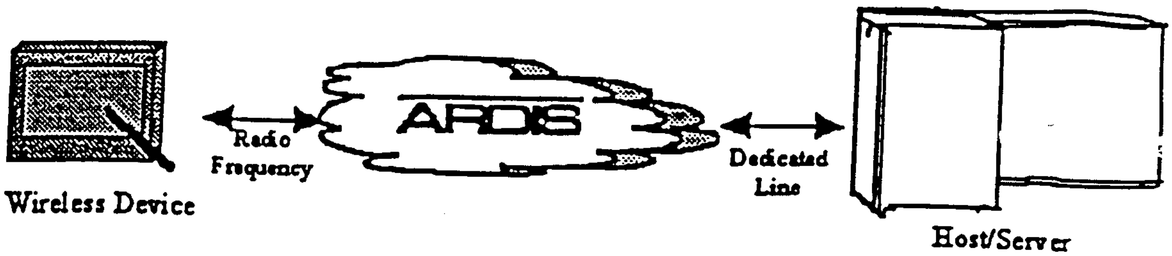

Figure 6 - Host Routing

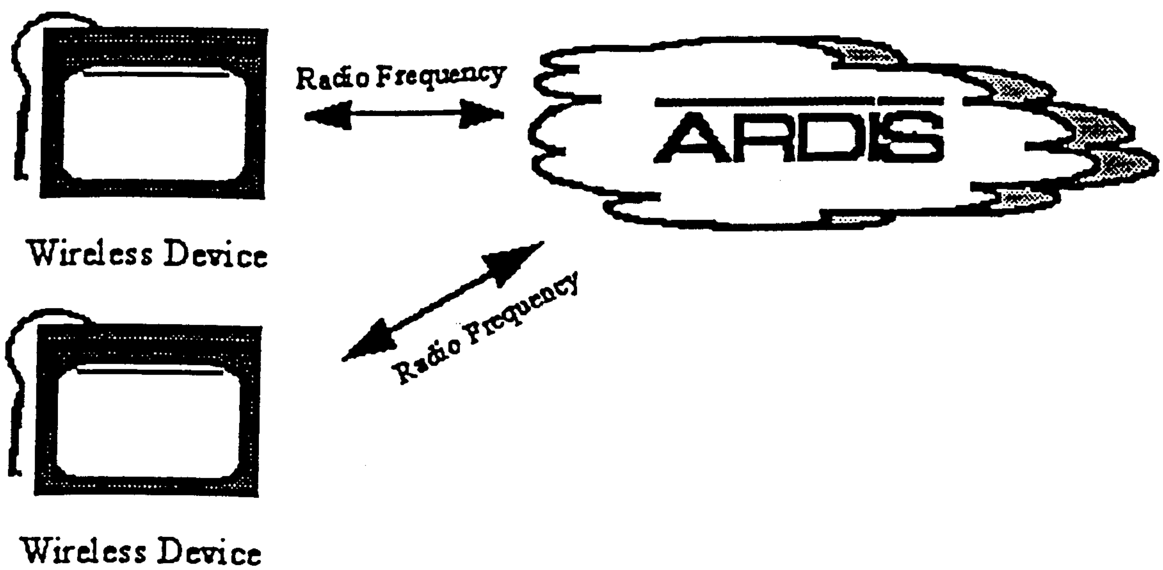

Figure 7 - Peer-to-Peer Routing

therefore, eliminates the need to have a connection outside of the ARDIS network to a host computer. Thus, ADART vehicles can communicate between each other, without first going back to a central server.[16]

3. ***Hybrids***: Depending on the application, both methods of routing (host and peer-to-peer routing) are available to ADART users. The routing method selected depends on the functions the users need to perform and the size of the wireless user base.

3.3.3 RAM Mobile Data

Currently, RAM Mobile Data and Advanced Radio Data Information Services (ARDIS) are the most well known and established of all the national data radio messaging systems. RAM uses the packet switched Mobitex Digital Wireless Network from either Ericsson GE or Motorola. In addition to the usual store-and-forward features, RAM offers software to build interactive, packetized messages for use in other applications, such as those to be found in ADART. In addition, there are no 'long distance' charges for RAM or ARDIS users. The cost per packet is the same whether it is sent across the country or across the street.

RAM serves the top U.S. metropolitan areas, covering over 7,700 cities, plus airports and major transportation corridors. It was also the Official Mobile Data Service Provider of the 1996 Atlanta Olympic Games. RAM's service is based on Mobitex technology, which was initially developed by Ericsson in Sweden in 1986. Since then, advances in technology have allowed improved performance, flexibility, and economy in deployment. In addition, all upgrades are fully backward compatible. RAM's system was designed for shared use. Its creation included such advanced features as broadcast, store-and-forward messaging and transparent roaming, which provides for the intact preservation of messages interrupted by momentary loss of contact with the network.

3.3.3.1 Mobitex

The RAM Mobitex wireless communications network includes the following key features:

1. ***Transparent and seamless roaming***
2. ***Store-and-forward features***
3. ***Increased dependability***

---

[16] Peer-to-peer routing works well for applications that do not have particularly high traffic to their host server -- a wireless modem can be connected to the host server, allowing the remote wireless devices to communicate to the server within the network. However, such a configuration has very definite capacity limitations, since a wireless modem connected to the server cannot handle as much traffic as a dedicated X.25 connection from the network. In addition, such a configuration can increase monthly air time fees since both "legs" of the transmission are over RF (Radio Frequency). This issue is of no concern to ADART, which has minimal data passing requirements between vehicles.

4. ***Modem support***
5. ***System connectivity***

Mobitex also has several important security features. Mobitex networks incorporate advanced digital radio technology that distinguish them from traditional communication systems. The combination of digital technology and packet data switching has produced a high degree of inherent security to safeguard the privacy of users' data. The additional use of sophisticated protocols and unique radio modem designs make it extremely difficult to tap into Mobitex networks. Specific security features include:

> ***Radio Signaling Protocol (Rosi):*** The MOBITEX network uses a unique algorithm to transmit data efficiently over the airlink in short bursts, encoded and interleaved for error correction, and then scrambled.
>
> ***Code Number***: A unique eight-digit MOBITEX Access Number (MAN) is stored within the radio modem and can only be changed by RAM authorized personnel. A security number is hard-coded into each radio modem and is validated by the base station during login. This feature prevents radio modems from unauthorized use and can greatly facilitate the location and identification of stolen mobile equipment.
>
> ***PMAN***: The PMAN (Personal MOBITEX Access Number) subscription provides additional data security to the user. A PMAN, which must be used in conjunction with a password, is associated with an equipment-independent personal subscription.
>
> ***Closed User Group Service***: Subscribers within a closed user group cannot receive messages from, or send messages to, subscribers outside their group. This service prevents users from accidentally or intentionally transferring messages to other users in the network. Closed User Group also prevents hackers from gaining access to customer's terminals and host computers outside of the group.
>
> ***Status Messages:*** For security reasons, sensitive information, such as an ADART customer's PIN ID, can be coded into STATUS messages for transmission instead of sending the actual information over the air.
>
> ***End To End Data Encryption:*** Data encryption at the user application level provides the best protection of user data. The same encryption algorithm is used by the applications at both ends of the communication path, thus securing the entire communications path. On the other hand, each customer, like ADART, has the flexibility to select the most suitable encryption algorithm to meet its own security requirement.

How elaborate do the security measures of an ADART data communication system need to be? Protecting propriety information and preventing unauthorized access to ADART's computer systems is essential. The combination of end-to-end encryption and the network's inherent security capabilities would appear to provide the highest level of security to ADART data on the MOBITEX networks.

3.3.2.2 ARDIS

ARDIS offers similar coverage to RAM at comparable expense, with modems for both systems costing roughly between $300 and $1,000. Both the RAM and ARDIS modems also come in PCMCIA (PC Card) format. ARDIS features message store-and-forward and provides message acknowledgment services. ARDIS also offers a link into America On Line. A remote ARDIS user can thus use any of AOL's services, including the Internet and e-mail. ARDIS also has its own mobile terminal offerings based on Personal Digital Assistants (PDAs). Lastly, ARDIS offers RadioMail, a wireless e-mail service with national coverage.

ARDIS offers several features that are not available on RAM:

- ***Deep In-Building Coverage***: A mobile unit operator can automatically send and receive messages simply by turning on the modem virtually anywhere in the U.S. However, hilly terrain can be a range-limiting factor of ARDIS.

- ***Guaranteed Delivery of Messages***: guaranteed in 14 seconds, with the average being less than 5 seconds. It is the only network that guarantees the response time for delivery of messages to customers.

- ***Guaranteed Uptime of the Network***: No other network guarantees the time periods when the network is available. In practice, however, both RAM and ARDIS appear to offer the same level of reliability.

3.3.2.3 Comparison Between RAM & ARDIS

A study conducted by the University of Massachusetts provides a comparative analysis of the coverage and performance of RAM Mobile Data's and ARDIS' networks. This study evaluated both networks in an identical automated data collection application using the same hardware and software platforms:

Results of the study suggested that RAM and ARDIS had virtually identical success rates for in-building coverage. Even though the RAM and ARDIS systems performed similarly for packets under 240 bytes in length, RAM surpassed ARDIS in having a 40% faster response time for packets that were between 256 to 512 bytes in length. Because ADART messages generally will be shorter than the 240-byte threshold, both RAM and ARDIS would be equally suited to ADART applications, in terms of response time.

3.3.3 Cellular Digital Packet Data

In addition to using digital techniques for adding more voice calling capacity, cellular providers are also giving their users special data-only channels. This new cellular data domain is called Cellular Digital Packet Data (CDPD). CDPD is a direct market competitor to the data radio messaging services offered by RAM and ARDIS. CDPD uses User Datagram Protocol (UDP) to effect data transmission. UDP, which is part of the standard Transmission Control Protocol(TCP)/Internet Protocol(IP) suite, is a connectionless-oriented protocol and is very "lightweight, " i.e. streamlined, and thus, efficient. However UDP, unlike TCP, does not guarantee data delivery of transmitted packets. In the instance of CDPD, guaranteed packet delivery is left to the wireless service provider. The price range for CDPD modems is $450 - $1600 and the software (TCP/IP-based) to send data over the cellular network is required. The host computer system needs to be connected to a network that provides IP routing.

CDPD piggybacks onto existing analog cellular systems. When no one is talking, CDPD slips in a few data packets, 19.2 Kbs at a time. CDPD is thus a packet data service overlaid on the existing analog cellular telephone system. The system uses the temporarily idle channels in the cellular telephones systems to transmit data. This architecture, making data communication subordinate to voice, exposes critical data applications to potential delays and congestion. Advanced features such as broadcast, store and forward have been left for individual operators to provide. Sniffing out idle air time to transmit CDPD packets is no mean feat. One company has developed a unique radio system that can scan any range of frequency spectrum, and in real time, instantly detect channels that are free. A new messaging IP-based protocol, called the Limited Size Messaging protocol, has been added to the CDPD Forum. LSM addresses a glaring previous deficiency within CDPD, providing CDPD the ability to store and forward data packet by efficiently moving shorter messages. CDPD is now being deployed by a number of cellular companies, including Bell Atlantic, Ameritech, GTE, and AT&T (McCaw Cellular).

3.3.3.1 CDPD and the Web

An industry communications alliance has been organized to deploy CDPD, which requires TCP/IP, as the basis for Internet/Web wireless communications. Cellular phones and personal digital assistants would use the new Handheld Device Markup Language (HDML). HDML encodes text-based Web pages in such a way that they can ride over wireless networks that use CDPD (although any packet data network, such as RAM or ARDIS, could also use HDML). A non-CDPD version for circuit switched cellular (which can also transmit data via regular modems) will also be available.

3.3.3.2 CDPD Evaluation

Cellular's CDPD is seen by many as a short sighted, interim solution. The rapid rate of technological change may soon wipe out any future digital cellular market advantage. Even with more efficient digital use of limited bandwidth, cellular requires costly towers and relatively high channel costs, rental fees, and equipment outlays. Cellular equipment is difficult to modify to meet new user demands, or to implement new services.

3.3.4 Evaluation of RAM Mobitex versus CDPD

An evaluation of data transmission services offered by CDPD cellular telephone providers versus pure data-only services offered by companies like RAM and ARDIS are presented here (for a price comparison of ARDIS, RAM and CDPD services, refer to the Appendix). Because RAM and ARDIS have similar features, RAM will be considered to represent both of the Data Radio Messaging Systems. The results are as follows:

***Speed and Capacity*:** While RAM currently supports a raw data rate of 8 thousand bits per second (Kbps) and CDPD supports 19.2Kbps, RAM has produced a system that is dedicated to data transmission. CDPD, in comparison, transmits data when voice channels are idle; thus actual throughput depends on how busy the voice network is. This situation prevails except in cases where special data channels have been implemented. CDPD has implemented dedicated data channels in some markets and some tests have indicated its performance exceeds RAM's. However, this is the exception, since dedicated channels will not be the norm in system implementations.

***Features*:** RAM's service was developed specifically to support wireless data. Transparent nationwide roaming and store-and-forward are examples of important features not provided by CDPD.

***Coverage*:** The cost per square mile of deploying CDPD exceeds that of RAM. CDPD's initial deployment was in targeted metropolitan areas, and service is currently only available in a handful of locales. Coverage varies in those areas and does not extend over long distances. The expansion of CDPD to outlying areas will require substantial additional investment. Comprehensive nationwide coverage is dependent on cooperation by many carriers. It is unlikely that all CDPD carriers will invest in extending coverage to outlying areas for quite some time. Today, the service area for either RAM and ARDIS vastly exceeds CDPD's, and RAM is expanding at approximately 20 percent per year. Development is customer driven.

In summary, the wireless network technologies are in a state of flux. It is unlikely that any clear-cut winner will emerge any time soon. In the meanwhile, service providers such as RAM, ARDIS, and CDPD are offering reliable solutions. CDPD was proposed as a technology that all the cellular operators could deploy to make use of the unused voice capacity. It has progressed from the specification stage to initial deployment in a number of markets. However, CDPD has been endorsed by only half of the cellular industry, leading to a number of cities where deployment is unlikely. Furthermore, the rate of deployment has fallen far behind the original announcements, which promised full deployment by the end of 1994. The introduction of digital cellular is also causing some operators to pass over CDPD. Therefore, RAM or ARDIS Data Radio Message Systems seems to be the better of the two data transmission technologies.

3.3.5 Wide Area, Wireless Ethernet

The major deficiency of the ARDIS, Mobitex, and CDPD networks is that they are not universal and can be used only by paid subscribers. Universal outdoors networks are planned through the use of satellites. All these networks are expensive, both to implement and to operate. All wireless services (RAM, ARDIS, CDPD, or PCS) involve user access fees based on the amount of bytes transmitted per month. In the context of ADART operations, using a wireless wide area solution would avoid all such service provider fees and would obviously represent tremendous cost savings. However, such a non-fee, "free" airtime service would have to offer, at the very least, the same robustness, security, wide-area scalability (i.e., adaptability to areas varying in scale), and ease of application implementation as offered by commercial service providers. In addition, to be viable within the ADART context, such a non-fee based wireless system would have to adhere to some type of well-defined industry standard.

Fortunately, a wireless service that meets all of these stringent criteria exists. It is a wide area, wireless network that, for all intents and purposes, behaves just like an Ethernet, which is the protocol used in most Local Area Networks (LAN). That is, attaching a remote ADART mobile node to this wide area wireless network is no more complicated than adding a workstation or PC to an Ethernet-based local area network in one's office. This solution, being Ethernet-based, also means that developer packages and third party applications are readily available off-the shelf. The product and application comes from a company called Wi-LAN.

3.3.5.1 Wi-LAN

Wi-LAN has launched products to address the needs of two broad market segments: wireless networking and wireless data collection.[17] Of the two markets, the primary interest lies in wireless wide-area networking, the main thrust of which is wireless Internet access. Wi-LAN designed a Wireless Ethernet Bridge for this market. This and other Wi-LAN products share the same basic features:

- ***License exempt operation***
- ***Connect to non-proprietary IEEE standard interfaces***
- ***Self-contained***
- ***Software independent***
- ***Application independent***
- ***Platform independent***
- ***Software***

[17] Wi-LAN Inc. owns the rights to a patent for Multicode Direct Sequence Spread Spectrum which is the highest speed (data rate) spread spectrum technology in the world. Wi-LAN researchers also hold numerous patents in digital communications and signal processing which have formed the keystone for a new generation of wireless products and services.

The Wi-LAN Hopper Plus has unique features that make it ideal for the ADART application under consideration:

- ***Packet Filtering***: The Hopper Plus filters packets such that only those packets intended for transmission are sent on the air or the ethernet wire. This prevents unnecessary congestion and enhances efficiency. The unit adaptively learns the IP addresses of the units to which it is connected and updates these addresses on an ongoing basis.

- ***Speed***: Throughput efficiency is the highest available on the market and further improvements are under development.

- ***Networking***: The Hopper Plus is designed with a polling protocol that guarantees that each unit will have equal network access. The priority for the units also could be modified so as to deviate from equal access.

- ***Simplicity***: The unit operates as a terminal device and hence if connected to another terminal device it requires a cross-over cable. The units could connect to the wired network within less than a minute. Furthermore, currently there is only one type of unit and it can be configured to be a remote unit, a master unit, or a repeater.

- ***Availability of Repeaters***: The same Hopper Plus unit could act as a repeater for particular IP addresses while dropping off traffic for particular IP addresses. This functionality reduces the costs of reaching units that are hidden from the master unit.

In conclusion, Wi-LAN would appear to offer all the necessary structural elements for successful operation within ADART. Moreover, the Wi-LAN products can provide significant costs savings advantages over the life of the ADART system. A system based on Wi-LAN's products could pay for itself in a very short period of time. Consequently, the Wi-LAN product, and in particular, the Hopper Plus, is strongly recommended as the first wireless choice for ADART, before RAM, ARDIS, CDPD, and PCS.

3.4 Near Term Wireless Forecast

3.4.1 Personal Communications Services (PCS)

Users of Personal Communications Services (PCS) have the telephone equivalent of their lifetime social security number. This personal access code (called a Universal Personal Telecommunication Number) follows the user around anywhere in the world. The 1.9 GHz PCS micro-cell promises lower overall costs, even though three to five times as many cells are needed to cover the same area as one macro-cellular system. Because the new hierarchically-deployed micro-cell structures require less power, are more flexible, and need much smaller antennas, the cost to implement a PCS cell is much less than that for cellular systems. Unlike cellular systems, PCS micro-cells will also be going inside buildings.

PCS systems mean much greater access, lower cost, lighter weight, and longer battery life for users' phones. PCS will initially transmit data at the same rate as CDPD, and will likely go much higher in the future. Moreover, PCS phones will support simultaneous data/voice transmission.

In what will evolve into a complete family of PCS products, AT&T's has introduced a series of PCS systems designed for use with the AUTOPLEX(R) System 1000 Series II Cell Site - the most widely-deployed cellular system in North America. With Series II cell sites operating in virtually every major market in the United States, cellular carriers have a platform for PCS in place.

3.4.2 Code Division Multiple Access (CDMA)/Time Division Multiple Access (TDMA)

PCS, like cellular systems, now has two primary competing standards, one of which is CDMA-based and the other TDMA-based. The previous drawback to CDMA was that it had only one equipment supplier backing the technology. Recently, however, AT&T, Goldstar, Hyundai, Northern Telecom, Samsung, Sony, OKI, and others, are now building PCS gear that supports CDMA. CDMA provides at least double the area of coverage over rival technology DCS-1900 in the PCS frequency range of 1.8-2.0 GHz for a typical cell site.[18] This increased coverage allows operators deploying CDMA-based PCS systems to use less than one-half the number of cell sites than an operator using DCS-1900. Fewer cell sites translates into faster time-to-market and significantly decreased deployment and maintenance cost. CDMA has proved to be inherently better than analog or TDMA systems for PCS applications in terms of both capacity and coverage, according to AT&T Network Wireless Systems.

PCS is now being marketed to the public. In the next few months (by mid-1998) it is expected that PCS will emerge as a major player in wireless communications. RAM, ARDIS, the CDPD vendors, et al, will likely find a way to coexist with-- or perhaps even co-opt -- PCS. The wireless market situation may become quite chaotic as all these services and technologies converge or collide. Therefore, any wireless application written for ADART should be as platform and network-neutral as possible. By doing so, ADART can readily move from one type of system/service to another, without compatibility problems.

[18] DCS-1900 is a European-based TDMA technology that is a derivative of the GSM (Global System Mobile) system which has recently been deployed in several European cities. CDMA is the U.S. Cellular Digital Standard, embodied in IS-95 through IS-99, that has been adopted by many U.S. and international carriers for their evolution from analog to digital systems. AT&T manufactures both CDMA and DCS/GSM equipment. Qualcomm manufactures only wireless communications products based on CDMA.

3.5 ADART Applications Development

3.5.1 The Internet + Web = a Wireless Intranet

Making the Internet/Web a fundamental part of ADART will yield important benefits: radically streamlining system operations; providing platform neutral user interfaces; offering far greater application portability, and significantly increasing ADART's productivity, both for operators and customers of the system. Therefore, it is proposed that ADART develop a wireless Intranet that is "blocked off" from the general public and available only for an organization's private, internal use.

3.5.1.1 Intranet Rationale

The Internet is a fault-tolerant, globe spanning mechanism that offers near real time multi-media connectivity, with varying amounts of bandwidth. These powerful features are typically available at a fixed, relatively low price, with easily decipherable user up-front charges. ADART system cost savings increase with Intranet + Wi-LAN network deployment use. This is in marked contrast to the case of ADART's using a radio messaging system like RAM or ARDIS that would charge ADART operators per each and every packet transaction. There is, thus, a strong economic case for actively seeking out ways to develop ADART into an Intranet + Wi-LAN network. The Internet/Web and its associated protocols constitute an independent and complete operating system with a client server environment. The Internet + Web distributed model can offer ADART a standardized client interface, means for multimedia data representation, a way of creating a network among heterogeneous legacy systems, and a set of protocols for transmitting and receiving diverse data.

3.5.1.2 ADART Client Side Development

Netscape, Spyglass, and Microsoft now let developers have access to their web browser's API. Via the browser API, specialized applications or functions can be integrated into the browser client. The native capabilities of the Web browser are thus readily enhanced. These new browser features are then triggered when a tag or tag attribute from a Web file calls for a particular service, if it is present. Within the past few years, the HDML has appeared for Web browser clients. HDML encodes text-based Web pages so they can use wireless services.

These rapidly arriving Web client enhancements are intended for cross-platform use. Therefore, once an interactive browser client is fully deployed, ADART has immediate and consistent portability to any computing device that supports the Internet and the Web. Upgrades to the Web client and ADART's Web servers can be implemented easily and distributed rapidly across a heterogeneous network. Moreover, ADART operators have the comfort of knowing that what they see on their PC-based clients is exactly what their customers on the other end are seeing on their PC, Mac, or UNIX Web browsers. There is no need for ADART operators to worry about what new operating systems its customers will be using in the future.

3.5.1.3 ADART Web Server

One important key for accelerating ADART development of its own Intranet is the Web server CGI (Common Gateway Interface).[19] The CGI is the all important specification for passing data between ADART's Web server and an external program. The CGI thus opens the door to integration of a Web server with the rest of ADART's systems, and in particular, with its database management system (DBMS). For example, when a user fills out one of those ubiquitous registration forms on a Web server, a CGI script, or some other type of CGI program, passes the entered data to a DBMS. Flexible, customized, interactive Web browsers, working together with Web Server-to-legacy applications, can produce easily accessible on-line product documentation, marketing reports, customer analysis, and product shipment tracking.

3.5.1.4 Java Limitations for ADART

If ADART is to allow its customers system access via their PCS (as well as telephones), it will face some severe incompatibility problems if some systems are based on 16 bit MS Windows systems and others are based on 32 bit systems. The main problem is that Java, which can provide the needed compatibility between systems, reduces efficiency and thus requires more powerful processors to achieve the same response time. The minimum amount of RAM for a PC running Java must be at least 32MB, and preferably 64MB. Moreover, the client CPU requires a fast -- and expensive -- PC. From the ADART mobile client side, these Java requirements obviously drive up the system implementation costs. From the ADART customer side, the use of Java similarly drives up costs and will exclude many potential customers who might prefer to use a PC, rather than a phone, to interface with ADART.

Finally, within the context of ADART, which views the world in terms of small packet size transmissions of less than 100 bytes, the not-often-discussed enormous size of Java programs (i.e., applets) will come as a shock. Java programs make onerous demands on network bandwidth when downloading. Early anecdotal evidence indicates that even a 128KBs ISDN line is too slow for downloading many Java programs. Regardless, the appeal of such a cross-platform applet development tool is obvious, and is difficult to ignore. Moreover, one of the avowed goals of ADART is to be as autonomous ("operator-less") as possible. As such, ADART would require some

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[19] The Common Gateway Interface (CGI) is a standard for interfacing external applications with information servers, such as HTTP or Web servers. A plain HTML document that the Web daemon retrieves is static, which means it exists in a constant state: a text file that doesn't change. A CGI program, on the other hand, is executed in real-time, so that it can output dynamic information. A CGI script can trigger most any type of application or service, but DBMS actions are among the most common. For example, let's say that you wanted to "hook up" your ADART database to the Web to allow your mobile vehicles all over the city to query it. Basically, one needs to create a CGI program that the Web daemon will execute to transmit information to the database engine, and receive the results back again and display them to the client. This is an example of a gateway, and this is where CGI originated.

type of intelligent Internet applet facility that, like Java, can be used to create intelligent software agents.[20] A possible solution is the VXM SILK.

3.5.2 VXM SILK

VXM SILK does not have Java's CPU/memory/bandwidth overhead. It is a robust, proven system, and has already been used in some very advanced telecommunications environments. The main points to understand about the VXM SILK system are as follows:

- *SILK transforms dissimilar Internet-attached systems into independent, logically standardized machines.*
- *SILK-enabled machines can take autonomous, intelligent, cooperative action, across different generations and types of computer systems, applications, and networks.*
- *SILK can logically transform data formats, protocols, and messaging systems and unite them under a common user interface (in the process, nothing is displaced via SILK).*
- *SILK is completely cooperative and coexists with all applications, operating systems, etc.*
- *SILK programs can be quite small, just a few hundred bytes in size, and can do a lot of work (unlike Java programs, which are typically many thousands of bytes in size and requiring much more (expensive) system memory).*[21]
- *True network parallel processing support is also available.*

Thus, many new types of ADART applications are made possible by the combination of SILK and wireless systems. SILK system applications are written in ASCII and are machine independent. Being ASCII text files, executable SILK applications can be readily sent over both wireless systems and landline to ADART customers. Wireless data service systems such as ADART's can now be expanded to include interactive messaging, shared work group activities, distributed decision support, and autonomous network management.

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[20] A software agent is typically characterized by its ability to take an autonomous action, such as operating a communications link or reading a file, and then transmitting information. A truly autonomous agent is also intelligent, i.e., it can take an action based on what it "reads" in the file. A good example is diagnostic data. Rather than have a human being at a console read pages of mind-numbing data, this task is better delegated to "agents." Moreover, properly designed agents can also take corrective or proactive actions to avert systems failure.

[21] The SILK System presently encompasses MS/Intel platforms, UNIX System V, SPARC Sun OS 4.1.X, RISC ULTRIX, MIPS-based UNIX (e.g., SGI), and VAX VMS. Mainframe VM and MVS, NT, and Macintosh support is also planned in the near future. Both TCP/IP and Netware protocols are supported by SILK. The complete VXM Silk system is only 128KB in size, and can run on 8/16 bit processors (Java is limited to 32 bit systems).

3.5.2.1 ADART Benefits and Capabilities with SILK

SILK has the ability to provide benefits and added capabilities to ADART. Such benefits and capabilities include:

- *The highly intelligent agents created with SILK scripts take the place of skilled human operators. This lowers ADART's operating costs and operational complexity.*
- *Distributed Silk agents, from a few to several hundred (even thousands) can create a massive parallel network that is highly intelligent. This SILK feature complements ADART's own structure, which incorporates a peer-to-peer mobile system for processing the vehicle's scheduling algorithm.*
- *Ability to collect diagnostic data from around an ADART network, analyze it, reformat it, and bring it back to a central station for review.*
- *Execution of autonomous intelligent action(s) based on the gathered data, thus, obviating the need for centralized ADART management. This ability can significantly cut ADART system downtime and reduce operational costs and complexity.*
- *Superior reformatting capabilities, making different "types" of systems talk to each other and uniting different systems under a common command interface.*
- *Provides ADART developers with the capability to create their own custom programming or command language.*
- *Enables the exchange and integration of data among different database systems. This capability can be utilized at the mobile user/consumer level as it will work with any system that can represent its data in print file format.*
- *SILK macros can be used to encapsulate and orchestrate complex SQL commands at the Web Server. Data driven, rules-based, e-mail workflow, or consumer purchasing systems for ADART services can be quickly developed via these SILK application macros.*
- *Automated packaging of complex data for network transmission as a unit message object.*
- *Capability to extend and exceed what is available in present OSI application layer services.*
- *Rearranges and recodes headers from one messaging system, e.g. Internet MCI Mail AT&T Easy Link, to another. Also does the translation of messages, including headers, from TCP/IP, Netware, and Netbios networks to OSI networks, and in the reverse direction, as well.*

The SILK System thus establishes a new and unique category of software and can bring ADART to a new operational level that is greatly simplified, yet highly automated.

3.6 A Computer Operating System for ADART

The use of the Intranet as the foundation for ADART software development presents many new application development possibilities. Given that the vehicle scheduling code is written in a high level, relatively portable language, like C, the rest of the software issues such as user interfaces, database access, and communications can all be handled via the systems independent Intranet model. In addition, VXM SILK frees the developers from having to worry about how to handle complex, system-specific diagnostics and management. The Intranet model means that software execution efficiency can easily be increased via better and faster systems, without becoming entangled in the "guts" of an operating system's peculiarities. Most fundamentally, the Intranet approach translates to operating system independence for ADART, both at the client side and at the server side.

ADART developers will want to select an operating system that can support peer-to-peer message passing to facilitate the processing of the scheduling algorithm, including VXM Silk operation, without adding coding complexities. The messaging system should mask the underlying communications network from the application. Also, the developers should be able to select only the subset of functions within an operating system needed for application execution. This ability reduces costs, coding complexity, and systems maintenance requirements. Finally, the operating system should offer load balancing in the peer-to-peer network to expedite and facilitate the execution of the scheduling algorithm. None of these operating system features should be application-obvious or "developer-visible," such that they destroy the software independence promised by the Intranet model. To the extent that these parts are native to the operating system, the application portability increases. Such an operating system exists, and QNX (from QNX Software, Ltd.) offers features that make it ideal for the ADART application.[22]

3.6.1 QNX

Scalability is QNX's strength. By combining various modules, developers can scale QNX down for lean embedded systems, scale it up for large development workstations, or scale it out for vast fault-tolerant networks, which are capable of rerouting messages in the event of a network link failure. Like QNX itself, the pricing for QNX components is modular. QNX is also small and fast. This means that ADART can use cost-effective CPUs on board the vehicles, without incurring a performance penalty. As a modular system, QNX is easy to extend, giving great design flexibility. Developers can use any of the many modules QNX provides, or extend the OS with their own modules. QNX also has a robust protected-mode environment, so developers are always free to test their extensions and try new approaches.

[22] The QNX real time operating system first appeared on the market in 1981. QNX is now the leading real-time OS for PCS. QNX states that it has hundreds of thousands of installations in over 60 countries, at work in everything from critical healthcare applications to fast-food services. QNX customers include such diverse corporations as DuPont, GE, General Mills, Sony, Motorola, and Texaco. Over 100 of the Fortune 500 are QNX users. Consisting of a 10K microkernel and a team of optional modules, QNX provides priority-driven scheduling and responsive context switching (3.9 used on a Pentium 100. QNX also offers comprehensive network support - from FDDI to low-cost serial - and can run multiple networks simultaneously, with fault-tolerance and load-balancing already built in. Modules are available for TCP/IP with NFS, the X Window System, the Photon microGUI, data acquisition, and more.

3.6.1.1 Networking

QNX offers some special features in the area of networking that can significantly assist ADART application execution. Chief among these is the ability to implement QNX's FLEET network facility, which supports multiple network file links per machine and performs traffic load-balancing across those links for greater throughput and fault-tolerance. This feature means greater speed in processing ADART's scheduling algorithm across multiple CPUs on board different vehicles.

QNX's FLEET builds upon the operating system's message-passing architecture. The QNX FLEET network facility seamlessly turns a bunch of isolated machines into a supercomputer. In the case of ADART, this would apply to the scheduling algorithm running in distributed parallel network.

3.6.1.2 Message Passing

Via QNX's network-transparent message passing, a process can run on any CPU and use any resource on the ADART network, including disks, modems, and data acquisition ports. Like VXM's Silk, QNX turns ADART's entire LAN into a single logical machine (at the system level). Even embedded systems can become part of a single logical computer network. ADART could also run multiple networks simultaneously. Most importantly, the QNX message passing scheme can be used as the high level API to an ADART wireless network. The QNX message simply talks to an Ethernet interface, which, in this case, is actually a Wi-LAN wide area wireless network. There is also no need to buy additional third party software tools for wireless application development. In all, QNX and its message passing scheme makes everything much simpler for ADART.

3.6.1.3 Fault-Tolerant Networking

When nodes are connected by two or more networks, there is more than a single path for communication. If a cable or wireless network card in one network fails in a way that prevents any communication on that network, QNX will automatically re-route data through another network. This feature is critical to ADART applications.

3.6.1.4 Load-Balancing on the Fly

With FLEET technology ADART can practically double throughput. For example, on the vehicle's computer, one Wi-LAN PC card could be used as the wireless network interface to remote ADART servers and be employed for accessing customer profile data off a file server. The second PC card could be used to enable peer-to-peer communications between mobile vehicles as they execute in parallel the scheduling application. This is a feature unique to QNX and can be of great benefit to ADART. Furthermore, since QNX is a multitasking OS, ADART developers can easily put two or more client/server pairs to work to deliver even greater throughput.

3.6.1.5 TCP/IP and QNX

Besides FLEET, which is its own high-speed networking protocol, QNX supports full implementation of the standard TCP/IP protocol suite and utilities, including the Network File System (NFS). As a result, QNX can operate as a full peer on TCP/IP networks, using Ethernet (such as Wi-LAN's), or other connections. The built-in TCP/IP protocols make creating an ADART Intranet quite straightforward, and cost effective. QNX TCP/IP supplies all the following capabilities:

- ***Log in to remote systems***
- ***Transfer files***
- ***Exchange mail***
- ***Write socket applications***
- ***Run remote user interfaces***
- ***Merge filesystems with both client and server NFS services***

QNX also provides remote-display processes for X, Windows 95, Windows NT, and other desktop environments. Graphics drivers can run on any node in a network and handle multiple graphics drivers running on one or more nodes. Therefore, a user can drag an application window from one node to another or have a single application stretch across multiple screens. In ADART's example, an operator of a mobile ADART unit sitting in a vehicle can drag a window from the screen of his or her lap-top system onto the screen of another mobile lap-top user in another vehicle, then "board" the other vehicle, and "remotely interact" with the live application. For ADART's mobile devices, this is a core, enabling capability.

For all the above reasons, this report strongly recommends that ADART select QNX for the mobile client side operating system, and should also carefully consider using QNX on the server side, as well.

3.6.2 Implementing ADART via QNX

3.6.2.1 QNX Wireless API

ADART should use a high level message passing API like QNX. The QNX message passing application program interface is network/protocol independent, an important feature for an ADART operation. Wireless services have already been supported with QNX using TCP/IP over CDPD. This allows for an IP protocol and IP-based services to be used. The same will apply to Wi-LAN's wireless systems, which, to QNX, appear to be just an ordinary Ethernet interface.

3.6.2.2 QNX Message Passing API Limitations In Wireless

Because QNX's native network protocol is based on positive acknowledgments of packets, which adds time to message transmittal, it is not the optimal protocol to use if there are significant turnaround times involved. However, ADART's scheduling algorithm is expected to require only about 50 bytes to be transmitted between nodes, and turnaround times become problematic only when messages exceed 100 bytes. The protocol, therefore, should meet ADART requirements. Moreover, Wi-LAN's unique data transmission system could raise the "byte barrier" for effective data delivery to several hundred, and possibly thousand, bytes, without significant problems. However, all these performance expectations are subject to rigorous testing by ADART developers.

3.6.2.3 Implementing the QNX message passing scheme under an HTTPd server

TCP/IP and the Internet/Web software model allow ADART to reach the goal of communications with all types of systems, including between a QNX and non-QNX platform. This would be done to request and send data back and forth between a QNX Web browser and a Web server; or between a Web-aware DBMS/file server. This is readily accomplished via standard HTTPd (Web protocol), and is supported under QNX.

At the ADART Server end, there will also be servers connections to the wireline telephone system. A review of the available telephony products found that there were no text to speech, automatic call distribution and predictive dialer applications. Telephony hardware vendors supporting QNX include:

- *Rhetorex, Voice*
- *Pika, Voice*
- *Linkon, Voice*
- *Brooktrout, Fax*
- *DataKinetics, E1/T1/SS7/C7*
- *Aculabo, Some European signaling standards, Amtelco, Telephony switch matrix card*
- *Xircom, primry/basic-rate ISDN*

Overall, QNX offers a number of significant features, many of them unique to QNX, which will significantly enhance performance, operation, ease of coding, and maintainability of the ADART software.

3.7 Proposed Wireless Architecture for ADART

3.7.1 A Wireless ADART Network

Via Wi-LAN's products, a metropolitan area can be served from a number of service centers strategically positioned on high buildings or electricity towers distributed throughout the city. A Service Center (SC) will have a wireless modem together with a personal computer for dispatch processing. For optimal operation, the SCs will have to be placed every 2 miles, serving a hexagon of radius 1 mile. They will be connected to the centrally located (or distributed, if need be) ADART system servers through another set of wireless modems operating in a different frequency band.

Each SC will have a unique frequency channel at which to operate. In total, a seven channel reuse pattern, similar to the original AMPS cellular telephones, will be used.

The advantage of deploying for using SCs as described is that they minimize the number of users per SC which is the most effective polling protocol for data communications with a large number of users. Other systems, such as carrier sense multiple access (CSMA) as used in wired IEEE 802.3 ethernet, ALOHA and Slotted ALOHA, have lower efficiencies when the number of users increases. Token ring, such as in IEEE 802.5, is very ineffective in wireless (RF) multipoint to multipoint communications since the hidden terminal problem could cause a unit to miss the token as it attempts to reinitialize or restart the token. However, the SC arrangement is an improvement over peer equal communications because the SC can be a sophisticated unit that has higher transmit power and a better sensitivity than the remote user units, and this improves the range of communications.

3.7.2 ADART and Wi-LAN Operation

A newcomer - an ADART vehicle - into the service area of a SC will register with the SC during a polling process that the SC establishes. The newcomer will first check the signal strength it receives from the adjacent codes, and once it determines the strongest code, it will search for the strongest frequency channel. It will wait for the "new comer registration invitation" and then register its IP address. Polling is done to ensure that every user will get an equal opportunity to deliver its message to the network. A client user - the ADART vehicle - will monitor other channels during the time the SC polls other users. It will establish a data base of its alternative choices for communications (ranked according to the signal strength) and attempt to establish communications with the new SC before it breaks its existing link. Breaking a link will occur in one of two cases:

- *If a client user does not respond to the ADART vehicle's poll four consecutive times*
- *If a client user notifies the SC that it is switching to another SC*

All attempts will be made at "make before break" in establishing communications links, thus ensuring that data/message packets will not be lost. However, breaking a link without notifying the SC is acceptable, since the underlying software will request a re-transmission of the packet if the packets do not reach their ultimate destination. However, breaking a link without notifying the SC is acceptable since the underlying software will request a re-transmission of the packet if the packets does not reach its ultimate destination.

3.7.2.1 Multiple Access Scheme

The proposed ADART access scheme will be a mix of CDMA, TDMA, and Frequency Division Multiple Access (FDA). Within the same service area all users will use the same code and frequency channel in a TDMA manner. Adjacent SCs will use different frequency channels in a FDA manner. A cluster of seven SCs will use the same set of codes across selected frequency channels in use; the six adjacent clusters will use different codes to ensure some separation among the clusters.

3.7.2.2 Functions of a Service Center

The following are the functions of SC:

- ***Registering all mobile client users within its service area;***
- ***Sending IP addresses of client users to the ADART servers;***
- ***Determine if the traffic is local or not (local traffic will be directed to local users and will not leave the service area of the SC);***
- ***Communicate traffic that is not local to the ADART Servers;***
- ***Page a user if a message (or packet) is destined to it from the ADART servers.***

3.7.2.3 Security

There will be many levels of security with the ADART/Wi-LAN system:

- ***The entire system design will eventually be unique such that the products are not available for sale to anybody else. This provides a technological barrier against eavesdropping on the system.***
- ***Packet synchronization will be achieved through the use of a unique 5 Octet (40 bit) code. This means that there are over 10^{12} codes to choose from.***
- ***Packet filtering will ensure that only the unit with the correct IP address will receive the transmission.***
- ***End-to-end encryption is recommended for implementation in the remote users units.***

3.7.3 ADART Test Bed Implementation

For ADART Test Bed prototype purposes, a first trial composed of 2 SCs, one server, and as few as two to four remote mobile units will suffice. However, the greater the number of remote mobile clients, the more realistic will be the evaluation of the ADART system. The purpose of this test bed would be to demonstrate:

- *The capability of the SC to register the remote units;*
- *The capability of the SC to develop a data base for the remote units within its service area;*
- *The capability of the remote unit to determine the base station to which it is closest;*
- *Two-way cap communications between two remote, and a remote and the outside world.*

The ADART server unit will communicate to the SC units via a 2.4GHz link while the SC units will communicate to the remote units via 915MHz links. The reason for this set-up is that the ADART Server/DS links are fixed and could be optimized upon installation, whereas the SC-remote units links are mobile and require the most resilient product. A list of recommended ADART software components include:

1. *TCP/IP & Web Protocols*
2. *CGI and HTTPd Web Servers*
3. *ODBC or SQL for DBMS*
4. *QNX Operating System*
5. *Spyglass Web Browser*
6. *VXM Silk*

3.8 Conclusions

In conclusion, Wi-LAN would appear to offer all the necessary structural elements for successful operation within ADART. Moreover, the Wi-LAN products can provide significant costs savings advantages over the life of the ADART system. A system based on Wi-LAN's products could pay for itself in a very short period of time. Consequently, the Wi-LAN product, and in particular, the Hopper Plus, is strongly recommended as the first wireless choice for ADART, before RAM, ARDIS, CDPD, and PCS. The combination of Wi-LAN, plus the recommended software components, will provide ADART with a system that provides:

- ***Minimal wireless data communications costs***
- ***Minimal staffing costs and relatively inexpensive overall operation***
- ***Adherence to well established standards***
- ***Rapid application development***
- ***Reusable code across multiple platforms***
- ***Peer to peer, high performance parallel processing***
- ***Heterogeneous systems interconnectivity***
- ***Very high reliability and robustness***
- ***Autonomous operation***
- ***Ease of network migration***

Finally, the use of standard TCP/IP and Internet/Web protocols will provide ADART with a significant technology/product buffer zone. In the event that Wi-LAN should not work out, or a more desirable technology comes along, network portability and system adaptability would allow ADART to shift over to another system quite rapidly (for example, to CDPD or to another TCP/IP-based wireless system). The SILK System has established a new and unique category of software and can bring ADART to a new operational level that is greatly simplified, yet highly automated.

The use of the TCP/IP protocol suite, the Internet/Web as an Intranet, and VXM Silk will significantly decrease ADART's software development expense and time. They will also provide ADART with a means to buffer and isolate its applications from changing technical specification, as well as provide ADART with near complete platform/network independence. Also, the use of standard Internet protocols will allow ADART to interface its systems to the public easily, thus increasing subscriber satisfaction, and providing greater ease of use. Finally, these Internet software systems, especially Silk, will allow ADART to achieve its stated goals of autonomous systems operation and highly automated maintenance/management. ADART can thereby decrease its manpower operational requirements, along with its overall operational costs.

4.0 REVIEW OF VEHICLE NAVIGATION HARDWARE AND SOFTWARE SYSTEMS

Vehicle navigation systems perform several key functions:

- ***monitoring vehicle location***
- ***communicating vehicle location to the driver***
- ***routing the vehicle, automatically or by manual means.***

This chapter reviews the features of commercially available vehicle navigation hardware and software systems in terms of their capabilities to meet ADART requirements. Six software systems were selected for review that are all off-the-shelf and run on PC notebook computers[23]:

1. Atlas Speaks and Strider from **Arkenstone**
2. Automap Streets from **Microsoft**
3. City Street For Windows from **Road Scholar**
4. GPS MapKit CD from **DeLorme**
5. Retki GPS Land Navigation System for Windows from **Likkuva Systems**
6. Streets on a Disk from **Klynas**

The hardware products reviewed are[24]:
1. **Rockwell/Siemens/Zentek/Navigation Technologies** vehicle navigation system
2. NVX-F160 from **Sony** (Note: the new NVX-F30 system was not reviewed.)

4.1 Vehicle Navigation Systems Defined

The vehicle's navigation system (VNS) consists of a computer and other special purpose hardware on board the vehicle. The VNS tracks a vehicle's current location in reference to latitude and longitude (LL) and the road network. It gets this knowledge by receiving a periodic LL fix from Global Positioning Satellites (GPS) and locating it on a digital vectorized model of the road network stored as data on the vehicle. For purposes of precision and reliability, ADART uses both GPS and dead-reckoning to track the vehicle's position on the road network.

The GPS system consists of 24-plus satellites, continuously emitting their location in space. Their orbits provide visibility of four satellites from anywhere in the earth's biosphere at any time.

[23] The **TeleType Company** has released a GPS mapping software for the *Apple Newton MessagePad.* This product was not covered in this review.

[24] The *Telepath 100* from **Delco** also was not reviewed. It is a simple distance and bearing-to-destination-type device.

Knowing the location of four satellites, it is possible to determine with the location of a receiver of this information. Theoretically, then a vehicle with an on-board GPS receiver always knows its location. In practice, unfortunately, this is not the case. A GPS satellite can temporarily go out of service, and more importantly, a GPS receiver must be visible to the satellites. Therefore, even if the GPS system were completely reliable, its signal would not reach a vehicle indoors, nor in a tunnel, nor under trees, nor on street flanked by high buildings, etc.

Dead reckoning involves a vehicle tracking itself with only on-board equipment. Wheel sensors act as a differential odometer, and a magnetic flux reader relays its compass orientation. Along with a clock, these items provide the vehicle's direction and speed. When the GPS signal is blocked or inoperative, dead reckoning works alone. When the GPS signal is present and visible, it corrects any accumulated dead reckoning error.

The road network's description resides in the vehicle as a digital map, which is merely a file of street segments. Two adjacent intersections define each street segment. These intersections depict the network's connectivity, or topology. Besides the LL's of its intersections, each street segment has an estimate of the expected speed at which a vehicle may traverse that segment. With these data, the computer can decide the best path between any two points in the network, and figure out the time the path would require.

Vehicle tracking and data logging. The VNS continuously outputs position updates to a display monitor in the vehicle that shows the vehicle moving along a map of the roads in its vicinity. Because road names also appear on the monitor, the driver always knows his exact location. This display also informs the driver of the path he is to follow, and, when appropriate, shows the location of his next pickup and expected time of arrival. In addition, the vehicle's computer continually logs its location history to a disk file, which provides data to analyze the driver's performance and to help improve future system performance.

Command-and-control. Knowing the vehicle's location, the FAD can plan the vehicle's itinerary from any point in time, give the driver directions, and monitor his compliance. In effect, the vehicle---and its driver---is merely a device under the control of its routing-and-scheduling system.

4.2 Description of Software Products Reviewed

Atlas Speaks and **Strider** from **Arkenstone:** Atlas Speaks is the first "talking map" software. Strider incorporates the features of Atlas Speaks with a GPS receiver. It accepts GPS input and when installed on a "talking" notebook computer, becomes a personal orientation tool for people that are blind or visually impaired. Using GPS satellites, Strider can direct the user on a path plotted ahead of time, help determine the course while in motion, or simply keep the user apprised of the current location. At around 11 pounds, Strider is lightweight and easy to handle. Atlas Speaks and Strider are designed for "eyes-off" operation that does not require the user to monitor or operate the software visually. Strider comes with a complete "talking" user interface. With some practice, it can be used without a display. The voice quality is good, depending upon the speech synthesizer used. (DECtalk™ from **Digital Equipment Corporation** was used for this review.) It uses synthesized text-to-speech hardware and software products to reproduce speech. Strider can also be used as a vehicle navigation system. Atlas Speaks and Strider use **ETAK** as the road system database provider. Road network editing and maintenance is performed with an editing program.

Automap Streets from **Microsoft:** Automap Streets is a street atlas product primarily intended for use in the home. The software includes more than six-million miles of roads with 280,000 points of interest. It lets the user quickly locate an address or place in the contiguous 48 states or Hawaii by zip code or telephone number and easily print out a detailed map of that area. An "Enabler" software is available that allows the street atlas to be used with a GPS receiver, and **Microsoft** is starting to position it as a vehicle navigation system. **ETAK** is the road network database provider.[25]

City Streets for Windows from **Road Scholar:** City Streets for Windows is positioned as the first affordable electronic mapping and streetwise personal navigator program that incorporates highly accurate GPS satellite tracking. It includes an address finder, route planner, distance calculator, personal navigator, desktop marketing tool and custom map maker. It is marketed as a customer locator for the mobile business professional and has the ability to import lists of names, addresses and phone numbers from external databases and geocode their position. It does not support any style of abstract "turn-by-turn" direction presentation nor any kind of dead reckoning capability. Differential GPS is supported if the GPS receiver used supports it. **ETAK** is the road network database provider and comes with just one **ETAK** coverage area.[26] Additional coverage areas are available at additional cost and come with an optional Developer's Software Toolkit for developing drivers for GPS receivers.

GPS MapKit™ SV CD from **DeLorme:** The GPS MapKit™ is a software and hardware bundle. It includes MapExpert™ Digital Maps and GPS Link II software. It functions as a basic moving map, allowing the user to have a constant visual reference of location. **DeLorme** is the road network database provider. It is difficult to do a direct comparison of map accuracy with **ETAK**'s road network. In general, it does not appear to be more accurate or have more details. There are a couple of variations among hardware packages available from **DeLorme**; however, these packages are not required if the notebook PC has a built in CD-ROM drive.

Retki GPS Land Navigation System for Windows from **Likkuva Systems:** The Land Navigation System is a general purpose Windows 3.X vehicle navigation system. It also uses **ETAK** as the road

[25] *Automap Streets Plus* no longer uses **ETAK** maps. The new map provider is **GDT (Global Data Technologies)**.

[26] There are 200+ coverage areas making up the United States.

network provider.[27] It has auto-center/auto-rotate map display capabilities, which allow the maps to automatically center and rotate, but the user must specify the ranges to determine where the center and rotations will occur. The program seems clumsy to use, but it reduces the number of times street grids have to be re-drawn and makes the maps somewhat easier to read than maps with a fixed orientation.

Streets on a Disk from **Klynas:** Streets on a Disk is a DOS program with a Windows- style interface. It is a general purpose map presentation program with some GPS capability. The GPS interface is designed to easily display moving vehicles or track any group of moving objects on the map. Powerful point search and display features can be used on GPS-generated targets created by the user. The downside to this DOS package is that it requires operation under Windows to use the GPS package. The user must have a windows GPS package capable of creating ASCII files containing latitude and longitude coordinates. This would have to be a custom software package, as none is provided, although **Klynas** will provide all the necessary tools. To operate the system, the PC must be running Windows, with the GPS software running in one window and Streets on a Disk running in the MS-DOS "box". Streets on a Disk is interesting because it has extensive macro capability that allows easy interfacing with other applications or custom software. Unfortunately, the macros are not industry standards. However, Streets on a Disk does have complete road network editing and maintenance capability.

4.3 General Description of Each Hardware Product Reviewed

ONIS from Rockwell/Zentek/Navigation Technology: ONIS appears to be the current universal standard Original Equipment Manufacturer (OEM) platform. It is an easy-to-use system and may have the largest installed base - Avis and National rental cars. ONIS has GPS and dead reckoning capabilities, with "turn-by-turn" route guidance and map matching. The Avis car system was tested and has "audio navigation" with a speech synthesizer giving voice prompts, directions and warnings. The system proved easy to use once it was initialized. Its "turn-by-turn" route presentation used large colored arrows to indicate navigation instructions, barographs to indicate distance to the next maneuver and some text to indicate important feature names (like name of the next street to turn on) with sometimes confusing voice prompts. Testing conducted as part of this study showed that this type of display is good for a single navigation instruction, but when two or three instructions must be executed in sequence on closely spaced streets, it is very easy to miss the second and third instructions.

NVX-F160 from **Sony:** This is Sony's first generation vehicle navigation system to combine GPS technology, digital mapping and travel and tourist information. The system has a suggested retail

[27] **ETAK** is the road network database provider for many of the products, but its maps are not interchangeable. **ETAK** requires that each manufacturer uniquely encrypt the data it distributes. This means that the **ETAK** maps distributed with Microsoft Automap Streets cannot be used with Likkuva's Retki.

price of $2,995 and is available at major car stereo dealers throughout California, Nevada, Florida and Georgia. It has nice graphics, with basic navigation functions indicating bearing and distance to a selected way point or destination.

4.4 Requirements and Desirable Features for an ADART Vehicle Navigation Hardware and Software System

This section identifies required or beneficial features that can incorporated in an ADART vehicle navigation hardware and software system.

4.4.1 System Compatibility

The hardware and software systems must be compatible with most common operating platforms. Note: Only **Microsoft** Window 3.X versions were tested.

4.4.2 General Data Access Features

To make the system flexible and give the user the ability to customize, the software and hardware must support sophisticated data access and communications features. For example: if a latitude and longitude generated by software responsible for trip-end geocoding is to be used by the VNS, it must be transferred under program control using interprocess communications or manually entered by the vehicle operator. If it is to be transferred automatically, then the data access layer in any vehicle navigation program must be responsible for getting information from various sources such as external databases or another local application and making it available to the program to use automatically. All general data access features must meet the PC software industry standards for Dynamic Data Exchange (DDE),[28] Object Linking and Embedding (OLE),[29] and Open Database

[28] **DDE send and receive:** Microsoft data exchange standards for communications between two applications. DDE was superseded by OLE Automation (see below).

[29] **OLE 2.0 client/server**: OLE has many features. OLE uses standard objects to achieve integration among different applications. OLE associates two major types of data with an object, i.e., presentation data and native data. An object's presentation data is the information needed to render the object on a display device, while its native data is all the information needed for an application to edit the object. The simplest application of OLE would be to pass latitude and longitude between two applications for the calculation of a trip-end. Or OLE could be used in file maintenance of all on-board data.

Connectivity (ODBC).[30] If there are other data exchange specification(s) unique to the manufacturer, they should be listed in the review.

4.4.3 GPS/DGPS/Dead Reckoning

A vehicle navigation system that utilizes GPS, DGPS or dead reckoning must be able to provide latitude and longitude accuracy to ten meters or less for navigation in dense urban areas. The GPS receiver must also be able to support industry standard communication protocols. DGPS must be capable of supporting most GPS receivers and providing the necessary accuracy in most major metropolitan areas. The application must also support dead reckoning devices, including odometer counter, differential wheel counters, single axis gyro, flux gate compass, electronic magnetometers, or inclinometers. A review of navigational systems must consider whether manufacturers will support the independent development of hardware drivers and whether new drivers can be written to support new GPS, DGPS and dead reckoning devices without having to modify the core application.

4.4.4 Navigation

The vehicle navigation system should provide the following categories of information covering the presentation of basic position information relative to a map:

- ***GPS Position***: Represented on the screen with a unique vehicle symbol

- ***GPS Heading***: Represented by the heading/orientation of the vehicle symbol

- ***GPS Speed***: Numerical display of the speed

- ***GPS Information Display***: Status of all available satellites and ability to select GPS settings to improve reception in urban canyons and areas of dense foliage

- ***Dead Reckoning***: Ensure that the system can accept sensor data from various possible dead reckoning sensors (differential odometer, vehicle odometer, compass, gyroscope, inclinometer) and combine this information with position history information to produce a new vehicle location from a previous location. This can be used to supplement and complement GPS information.

- ***Map Matching - Automatic***: Determine whether the navigation package tests for obvious errors generated from the GPS and dead-reckoning hardware. Map matching compares the

[30] **ODBC**: ODBC allows applications to easily access data stored within a wide range of corporate databases, e.g. dBase, ORACLE, Informix and others. This feature can make it easy to use existing databases of bus stops and points of interests with the vehicle navigation system.

previous position and the new position and checks to see if it is a logical position on the map. For example, if you are traveling north on the Golden Gate Bridge in California and only GPS is being used, does the system correct or compensate for a GPS-generated latitude and longitude that indicates that you have driven off the bridge and are currently traveling parallel to its center, 60 meters to the right?

- ***Map Matching - Manual***: Using a mouse or other pointing device, determine whether the user can manually insert a correction to compensate for obvious errors, by manually moving the symbol for the vehicle to the position determined by the user to be correct. This is useful during start-up. If the vehicle was moved without the system being turned on, the last position in the history log would be incorrect. Allowing the user to correct the position would reduce potential position errors and the latitude and longitude provided by the road network would reduce the time required to first-position fix using some GPS receivers.

- ***Virtual Navigation***: Determine whether the user can explore the map independent of the current vehicle position. This can be used to determine a route if automatic routing-and-scheduling are not generating a feasible solution, as determined by the vehicle operator.

4.4.5 Road network support

The application should provide the following information or as much information as possible:

Complete Highway/Street Details: The list of features necessary include:

Major Freeway	Minor Freeway
Limited Access	Arterial
Collector	Major Residential
Minor Residential	Slow Ramp
Fast Ramp	Rail Road

- *Bodies of water*: Shorelines of large bodies of water, rivers and streams are valuable landmarks that should be shown on the map that can aid the driver's orientation to the map display.
- *Railroads*: Railroads are valuable when used as landmarks.
- *Points of Interest* [31]
- *Urban/Rural Parks*
- *One-Way Streets*
- *Overpasses*

[31] Different providers have different databases of points of interest. All products have a database as standard. The number included and their usefulness for ADART was not evaluated.

- ***Elevations***: Provide elevation information through the use of contour maps or changes in color.
- ***Speed Limits***
- ***Address Ranges***
- ***Zip Codes***
- ***Political Boundaries***: City, county, state and national boundaries

4.4.6 Map Presentation

When traveling toward a specified destination along a predetermined route, it is desirable to have two types of presentations. One is "detailed information", in the form of a local area map indicating key details such as the current address, the name of the next street intersection, or other user-selected details. The other is "wide area information" in the form of a global map that covers the entire route, so that drivers know the path to their destination in advance. The following list identifies potential features that are recommended for inclusion in an ADART in-vehicle navigation system.

- ***Normal or Plane View***: This is the traditional map presentation - as if the driver were in a plane looking straight down. The view is from some specified altitude, looking perpendicular to the surface. The traditional mechanism for switching between detailed and wide area information is to change the map scale or zoom in/zoom out using a mouse or specified keys on a keyboard.

- ***Variable Detail View***: This is a variation of a plane view. There are three tiles presented. Two windows, showing detailed information, present a specified area around the vehicle's current position and around the selected destination. The third window shows wide area information that connects the two detailed tiles and the major road network connector that links the current position window and the destination window. This view requires a physically large display to show adequate levels of detail.

- ***Bird's Eye View***: The map is shown in perspective, with two vanishing points and a horizon. The current position is represented by a icon or token on the bottom of the screen, with the destination shown by an icon or token on the horizon. The path to the destination is highlighted. The map scrolls towards the destination as the current position changes.

- ***Street Level View (or "worm's-eye" view)***: This presentation is not a very practical visual presentation. The altitude of the view point would be zero, or very low, and it would not be possible to get enough information.

- ***North-Up Orientation***: This is a traditional map presentation with magnetic or true north being on the top of the display or a selected direction designated as "up."

- ***User-Specified Direction-Up Orientation***: The user can select the vertical or direction-up orientation up using the degrees or cardinal points of the compass.

- ***Heading-Up Orientation***: This requires that the position of a map point relative to the viewer's eye be "up." With the map point being the current position represented by an icon or a pointer, the map rotates, keeping the driver's current heading always represented as going up the screen. This requires a high performance graphical display to perform smooth rotation of the map.

- ***Destination-Up Orientation***: This is the typical presentation when the current distance-to-destination is the only mechanism to determine a path.

- ***Minimum/Maximum Scale***: This is a display of maximum and minimum sizes of areas and a measure of spread between wide area information and detailed area information.

- ***Voice Presentation***: The system can be operated in an "eyes-off" manner.

- ***Smooth Pan and Scroll***: Map scrolls smoothly to keep the vehicle symbol centered on the map when an "up is north"style presentation is used.

- ***Smooth Rotation***: When the orientation is "destination up" or "heading up," the map has smooth rotation, along with smooth panning and scrolling to keep the vehicle symbol centered on the map.

- ***Printed Map***: Includes basic printed copy of a user-selected area.

4.4.7 Road Network Editing and Maintenance

Since most maps are out-of-date the moment they are published and are constantly changing, some editing is always required. To maintain the practicality of route-finding and scheduling functions, it should be possible to edit the road system and share this information with all vehicles in the ADART system. A potential ADART vehicle navigation system should include the following road network editing and maintenance features:

- ***Add, Delete, or Subtract Features***: The ability to add, delete, or move features in the road network, including points of interest such as local landmarks.

- ***New/Custom Features Pertaining to Route Finding***: The road system database is dynamic. Are edits initiated by users incorporated into routing algorithms? Are user-initiated changes in routing stored the same way as road systems or treated as an exception? Route calculation is compromised when corrections or additions originated by the user are not incorporated routinely.

- ***Real-Time Traffic/Weather***: The classification of roadway, speed limit and direction of traffic can be changed or downgraded dynamically to match traffic and weather conditions. For example, if a traffic accident on a interstate freeway has all but one traffic lane blocked, can a segment be downgraded to a one-way local street?

- ***Base Map Edit Integration***: Are edits treated as cosmetic overlays to the map or are they now part of the road network? If they are overlays and if the number of edits becomes a significant portion of the road network, system performance can decline.

4.4.8 Map Cosmetics

An important feature is the ability to alter the presentation of any map feature and the colors used for map presentation. Each manufacturer has supplied each product with a standard set of defaults for presentation. Tests performed as part of this study, however, show a wide variation among users with regard to their ability to see and understand the presentation of information. Complete flexibility in this area is desirable. It is also useful to have the capability to add additional information to the map that may not be present in the standard road network database. An example might be to color coordinate road features to the speed limit. The following are desirable map-changing or override features to include in a potential software package.

- ***Change Feature Color, Label Fonts, Font Colors, Feature Styles***

- ***Custom Icons/Symbols***: The user can customize or personalize the icons used to represent points of interest and/or end-trips (destinations).

- ***Custom On-Screen Vehicle Symbol***: The user can customize or personalize the icon used for the on-screen vehicle to maximize legibility.

- ***Annotations Supported***: The ability to add a voice, text or drawing annotation make it easy to enrich the map. Adding notes about a place or a road, like warnings about construction or traffic congestion at specific times can improve driver and system performance.

4.4.9 Routes

The following is a list of features that would provide desirable route-finding capabilities in an ADART navigation system:

- ***Automatic Route Finding***: Does the system generate recommended routes to a destination?

- ***Open Architecture***: Can an alternative route finding module be substituted for a standard one shipped with the product? The product must support DLL or COM-style route finding modules if Windows-based.

- ***Selectable Travel Preferences***: Can the user designate a preference for travel on specific classifications of roadway? For example, can the user select local streets rather than major highways?

- ***Real Time Updates***: Is the system capable of accepting real-time traffic and weather information to upgrade or downgrade the classification of a road system feature for consideration in route calculations and for warning prompts to the driver?

- ***Manual Overrides***: Can the vehicle operator force a re-calculation of a route after a specific road segment has been eliminated from consideration?

- ***Route Editing***: After recording, can the user edit the route to eliminate unnecessary way points and turn-instructions and add any necessary text/speech annotations to improve system performance and ease of use?

4.4.10 Custom Features/Manual Routes

Tools that adjust the roadway network and routes to incorporate additions or changes:

- ***Virtual/Manual Trail-of-Bread Crumbs***: Using a pointing device or keyboard the user virtually creates a route by having each keyboard action recorded. Useful for creating a route when the automatic route finding algorithms fail completely.

- ***Automatic Trail-of-Bread Crumbs***: Automatic route creation, started by the user. The navigation system automatically records a route while the vehicle is moving.

- ***Distance Interval***: Automatically establishes way points at a user-specified distance interval until the trip-end is reached.

- ***Time Interval***: Automatically establishes way points at a user-specified time interval until the trip-end is reached.

- ***Time and Distance***: The user can select this mode to minimize the number of way-points that can be created when recording a route. This mode ensures that way-points are not being added if the vehicle is stopped waiting for traffic or a stop light. It can dramatically reduce the amount of editing required.

- ***Multi-Stop Capability***: Ability to select multiple stops and have the systems optimize a single route to service all stops.

- ***Scheduling***: If the system has multi-stop capability, determine whether it can estimate a schedule and estimated time of arrival (ETA) for each stop, given departure and waiting times.

4.4.11 Route presentation

The common ways of presenting routes visually on-screen are listed here. Choices that allow for personal preferences are very useful. The ability to edit and annotate directions is an advantage providing the capability to correct errors and make the directions easier to understand. Some forms of route presentation may be more suited than others for ADART use.

- ***Abstract Turn-by-Turn***: This route presentation uses large colored arrows to indicate navigation instructions, barographs to indicate distance to the next maneuver and some text to indicate important feature names (like name of the next street to turn on). This type of presentation is easy to understand with just a glance from the driver of the vehicle. Tests have shown that this type of display is good for a single navigation instruction, but when two or three instructions must be executed in sequence, on closely spaced streets, it is very easy to miss the second and third instructions.

- ***Modified Turn-by-Turn***: This route presentation method uses large abstract color arrows overlaid on top of the street grid to display navigation instructions. The scale automatically changes to ensure all necessary instructions are displayed.

- ***High-Lighted Street Grid***: The calculated route is shown on screen by a highlighted color with a special feature style.

- ***Bird's Eye View***: With a bird's eye view presentation, the segments that are designated as the selected route to the destination are highlighted by color and with a special feature style. The destination is shown as a special symbol.

- ***Variable Detail***: With a variable detail view presentation, the segments that are designated as the selected route to the destination are highlighted by color with a special feature style.

- ***ETA***: Based upon current position and distance from destination, estimated time of arrival is calculated.

4.4.12 Directions

In addition to visual route display, directions communicated through voice presentation and hard copy printouts are important navigation aids. Voice presentation involves the use of synthesized speech to provide turn-by-turn instructions for following a specified route. The ability to edit and annotate directions is an advantage providing the capability to correct errors and simplify directions.

4.4.13 Destination (trip-end) Selection

Providing the user with alternative means of selecting a destination (trip-end) is advantageous. The current level of accuracy of address ranges, historical legacy vs. current street name, zip code areas and the quality of the geo-coder used with each product varies greatly. The more ways that a user can select a destination, the better. Some of the features that should be included are:

- ***Specific Street Address***: Entry of street number, street name, city, state and zip code to select a destination.

- ***Intersection of Two Streets***: Entry of two intersecting streets by name.

- ***Point of Interest***: Select the destination from an existing list provided with the road network or from a user-defined list.

- ***Stored Location***: Allows the user to store a specific street address in a defined list for selection as a destination.

- ***Phone Number***: Allow phone number matching to a specific address. The result gets you to the general area specified by the area code and first three digits. (Only one system - GPS MapKit from DeLorme - currently accepts the input of a phone number.)

- ***Latitude/Longitude***: A latitude and longitude generated from geocoded data, or from the user, can define a destination.

- ***Mouse Position***: After moving the display to view the desired area, this feature allows the user to select the destination with a pointing device. This is useful when all other methods of destination selection fail.

4.4.14 Data Logging

This is the recording and storing of actual vehicle travel. There should be a feature that allows the program to record Logs of Location Histories. This is useful for evaluating driver and system performance and for system analysis. It can be used to enrich the base map, with multiple vehicles collecting data on routes and roads not in the road network. An example might be mapping out shopping center entrances, exits and parking areas. In the case of a rural area, this feature can be used to map the entrance to private roads and driveways.

4.4.15 General

Other features that may be useful for ADART:

- ***User Interface Voice Presentation***: All packages reviewed have a Windows or "Windows-like" user interface. The ability to use a speech synthesizer for the presentation of the user interface is required for complete "eyes-off" operation.

- ***Voice Recognition Ready*** - Command & Control: This feature is a function of the platforms in use. If the application tested was **Microsoft** Windows 3.X-based, it should work using keyboard emulation with the majority of voice recognition command and control packages that are currently available. (Actual functionality with a speech recognition package was not tested.)

4.5 Evaluation Results and Conclusions

The currently available vehicle navigation products are all clearly first generation or new products. No one product stands out and none appears to meet all the needs of ADART's requirements without significant customization and integration.

4.5.1 General Data Access Features

Most of the vehicle navigation software products reviewed, with the exception of Retki GPS Land Navigation System and Streets on a Disk, support general data access. The Retki GPS Land Navigation System allows DDE send and receive, while Streets on a Disk had other macro capabilities. Neither of the two vehicle navigation hardware products reviewed supported general data access.

4.5.2 GPS/DGPS/Dead Reckoning Support

While vehicle and navigation experiments show that 10-meter accuracy matches the detail of road network databases and is necessary for navigation in dense urban areas, 60-meter accuracy is typical for most of the products reviewed. Thus, DGPS and/or dead reckoning augmentation to the GPS-generated latitude and longitude is necessary to improve accuracy to ten meters or less. Dead reckoning augmentation is provided in the AVIS/Rockwell hardware but none of the software systems reviewed.

4.5.3 Navigation

All of the software and hardware products reviewed included GPS features such as GPS position, heading, speed and information display. None, with the exception of AVIS/Rockwell, included dead reckoning. Most also did not support map matching and virtual navigation.

4.5.4 Road Network Support

Most software systems and hardware reviewed had complete details for highways, streets, bodies of water, railroad, parks and popular points of interest. None of the software systems identifies one-way streets, overpasses, freeway exits, or elevations. The absence of one-way street information in particular can make automatic route finding hazardous. Only Streets on a Disk from Klymas supports the user entering one-way street information.

4.5.5 Map Presentation

Different products have different types of presentation schemes. At this time, no single product supports both "detailed information" and "wide area information," which is desirable in ADART's case. Only Atlas Speaks and Strider have voice presentation, which supports an "eyes-off" operation.

4.5.6 Road Network Editing and Maintenance:

Of all the software reviewed, Atlas Speaks & Strider and Streets on a Disk provide the most features that would allow the user to edit the road network. Most package providers prepare yearly updates for maps, with the exception of Streets on a Disk, which provides map updates only once every four years.

4.5.7 Map Cosmetics

Streets on a Disk and, to a lesser degree, GPS Mapkit/MapExpert, provide the most features allowing users to change cosmetic features of the map display. Atlas Speaks & Strider did not permit any changes or modifications. Both the hardware products reviewed did not allow for many changes to map display.

4.5.8 Routes

Only Retki GPS Land Navigation System, Streets on a Disk and AVIS/Rockwell hardware include automatic route finding features. Only Streets on a Disk allows route editing.

4.5.9 Custom Features/Manual Routes

Only Atlas Speaks & Strider has multiple features that allow some degree of customization, including virtual/manual trail-of-bread crumbs and automatic trail-of-bread crumbs displays, and distance and time interval displays. None of the software systems has scheduling capabilities. Only Streets on a Disk has multiple stop capabilities that would be of importance to ADART.

4.5.10 Route Presentation

Few of the software products have elaborate route presentation capabilities. A few allow for high-lighted street grids for better viewing. Only Atlas Speaks & Strider have voice presentation capability, and only Retki GPS Land Navigation System can estimate ETA to a destination. For the hardware systems, AVIS/Rockwell allows for highlighted street grids and voice presentation.

4.5.11 Directions

Atlas Speaks & Strider, Retki GPS Land Navigation System and Streets on a Disk provide turn-by-turn instructions. This is important for ADART drivers when picking up or dropping off a passenger. However, only Atlas Speaks & Strider has voice presentation capability that allows for "eyes-off" operation.

4.5.12 Destination (trip-end) Selection

All hardware products and most software, with the exception of Automap Streets and City Streets for Windows, allow for input of specific street addresses, stored locations, points of interest or intersections. In the case of ADART subscription service, most origin and destinations would be stored and, therefore, would work with most of the products. However, if a customer calls from a location that is not in the stored address list, only the GPS Mapkit/MapExpert would be able to locate the general area using a telephone number from which the pick-up (or drop-off) were to be initiated. None of the products reviewed has the capability of identifying an exact destination with telephone numbers.

4.5.13 Data Logging

This is important to provide for information gathering used in ADART performance evaluation. So far, only City Streets for Windows would support the logging of location histories.

While existing hardware and software products appear to lack the full range of capabilities needed in an ADART navigation system, new products are under development that may be better suited to meeting ADART requirements. Caliper Corporation has announced that the next version of its Maptitude software will include GPS capabilities, although the software was not available to be included in this review. Other announced products are:

- Route Planner by **Magneti Marelli**, with similar general specifications to the ONIS/PathMaster system from **Rockwell.**

- GPX-5 from **Sony**: Portable, compact version of the NVX-F30 vehicle navigation system intended for car, home, hiking or boating. The NVX-F30 will have dead reckoning, automatic route finding, voice guidance and wireless communications capability for information services such as real-time traffic updates.

5.0 SUMMARY AND CONCLUSIONS

ADART is a demand-responsive transit service that has fully automated dispatching and autonomously managed vehicles carrying all of their command-and-control facilities on board. By combining available technology with an autonomous dial-a-ride vehicle, ADART should raise reliability and productivity levels while reducing labor requirements. Applicable to public, private, or quasi-public operation of a variety of service types, autonomous dial-a-ride is a flexible system that may be the answer for transit service to low-density areas, serving a substantial market at a satisfactory cost to consumer and supplier alike. Determination of ADART's ability to fulfill these objectives will require location-specific demand studies, simulations, and service demonstrations. The advent of technologies needed to produce greater economies in dial-a-ride operations suggests that ADART is "an idea whose time has come."

Dial-a-ride services, whether automated or not, present a number of challenges as well as opportunities. The productivity of conventional dial-a-ride is substantially lower than that of most fixed route services and ADART must increase cost-effectiveness significantly to be viable as a transit service for the general public. Demand for dial-a-ride services to meet the needs of ADA customers is increasing and will continue to grow along with the number of older Americans. The integration of ADA customers with large numbers of other passengers in an automated service will affect productivity and will require adaptation of procedures to accommodate people who may have difficulty with computerized voice recognition systems, for example. There is evidence, however, that local dial-a-ride operators recognize the value of computerized scheduling and dispatching and have taken some initial steps towards automation. Dial-a-ride operators also appear to be receptive to management and administrative innovations, creating an environment conducive to adaptation in response to technological change.

From a technical standpoint, a key component of ADART is the wireless communication system that will connect customers directly with in-vehicle computers that control dispatching, scheduling, and navigation. A number of available technologies can be used to fulfill ADART mobile communications requirements. A private wireless wide area network using standard Internet protocols is proposed. This system, in conjunction with recommended compatible software, would provide a high level of performance, reliability, security, and economy.

Review of available vehicle navigation software and hardware systems reveals much promise but substantial shortcomings. Significant adaptation of available products would be required to provide navigation capabilities at a scale sufficiently detailed for ADART use, identifying such critical features as one-way streets and freeway exists. The presentation of information in a form that would be useful to drivers also is deficient and none of the software systems reviewed has scheduling capabilities. Rapid improvement can be expected in these fledgling technologies, however, and customization may be a realistic option for accelerating the application of commercial products to meet ADART requirements.

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Appendix: Key ADART Vendor/Supplier Contact Information

__Mobile Communications__

QNX Software Systems
175 Terence Matthews
Crescent, Kanata, ON, Canada
Tel: 613-591-0931
Fax: 613-591-3579

VXM Technologies, Inc.
P.O. Box 41
Boston, MA 02199
Tel. 617 267 286
Fax: 617 267 8920

Wi-LAN, Inc.
300-801 Manning Road NE
Calgary, Alberta, T2E 8J5
Tel. 403 273 9133

__Vehicle Navigation Hardware and Software__

Arkenstone Inc.
555 Oakmead Parkway
Sunnyvale CA 94086-4023
(800) 444-4443
Internet: www.arkenstone.org

DeLorme Mapping
Lower Main Street
P.O. Box 298
Freeport, ME 04032
(800) 452-5931
Internet: www.delorme.com

Klynas Engineering
P.O. Box 499
Simi Valley CA 93062
(805) 583-1133
Internet: www.klynas.com

Likkuva Systems International Inc.
3330 Cameron Park Drive, Suite 400
Cameron Park, CA 95682
(800) 997-3854
Internet: www.likkuva.com

Microsoft Corporation
1 Microsoft Way
Redmond, WA
(800) 426-9400
Internet: www.microsoft.com

Rhode Scholar Inc.
2603 Augusta, Suite 1000
Houston, TX 77057-4525
(800) 426-7623

Rockwell Automotive
2135 West Maple Road
Troy, MI 48084
(800) 823-2547
Internet: www.rockwell.com

Sony Electronics, Inc.
1 Sony Drive
Park Ridge, NJ 07656
(800)222-7669
Internet: www.sony.com