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16. ABSTRACT

This project provides a state-of-the-art review of AVL technologies which highlights King County METRO Transit's AVL System. This project further demonstrated the use of real-time transit information derived from the Metro AVL system to produce a prototypical display of real-time transit coach locations suitable for wide area Advanced Traveler Information (ATIS) use. This project demonstrated the viability of combining multi-agency data with different technology roots in a single development environment that encourages interagency collaboration in the creation of ITS applications and services. This was accomplished in a rich and flexible development environment, created at the University of Washington and used to leverage a proprietary AVL system to a public ATIS prototype.

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Research Project T9903, Task 7
Automatic Transit Location System

AUTOMATIC TRANSIT LOCATION SYSTEM

by

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1. INTRODUCTION

The Automatic Transit Location System project had two goals: (1) to perform a state-of-the-art review of Automatic Vehicle Location (AVL) technologies and (2) to create an Advanced Public Transportation System (APTS) prototype using King County Metro AVL data. At the time of this proposal, Metro used AVL data solely for internal fleet management. With the completion of this project, we have demonstrated that the same source data that drives Metro's management system can be repackaged for traveler information services, without affecting Metro's existing use of the data. This model is one which, if pursued as a regional strategy, will lead to significantly enhanced regional cooperation through a rich, open network of ITS resources.

2. BACKGROUND AND STATE-OF-THE-ART REVIEW

Public transit systems have been an effective mode of transportation, especially in urban areas, since the 1920s. (Grolier "Bus") A renewed interest in developing better transit services began in the 1960s when the effects of congestion caused by urban transportation, i.e., damage to road surfaces and air pollution, were realized. (Grolier "Transportation") Today, urban congestion is still at high levels, while transit systems operate with a ridership below full capacity. If transit services are to play a key role in reducing urban congestion and reducing the problems caused by congestion, more people must use these services. The challenge is to make mass transit transportation a desirable option for a larger percentage of the public. To meet this challenge, transit officials are working to improve the perceived and actual reliability and convenience of service by minimizing schedule problems while better informing customers of travel options.

To improve service, the managers of transit fleets must have feedback on the performance of their transit systems. They need to be able to identify and locate specific vehicles while the vehicles are enroute. Modern Automatic Vehicle Location (AVL) systems can provide real-time location information in a consistent, reliable, and timely manner, allowing managers to improve both reliability and the service of their transit systems. For example, reliability is improved if managers can respond in real time to an extremely late or disabled bus by sending assistance and dispatching another bus to take over the route. In addition, service can be improved by monitoring over a period of time the adherence of transit vehicles to existing schedules and updating those schedules to reflect actual performance.

Before there were automatic vehicle location systems, transit system authorities used a manual system to monitor their fleets. Individuals would stand at critical points on the service route to monitor the performance of the buses or streetcars. These men, known as point men, needed some way to communicate their observations back to a central control. One common solution was to set up outdoor phone stations at the observers' positions, providing point men with the means to call in the information as they saw it. This method of tracking transit vehicles slowly faded after World War II because the demand for transit transportation declined and labor costs rose (Roth 1977).

The need for an accurate system of monitoring transit fleets remained, and in 1968 the Department of Housing and Urban Development sponsored the Public Urban Locator Service (PULSE) conference to discuss technologies and applications of Automatic Vehicle Monitoring (AVM). This meeting served as a catalyst to spark interest in AVM for a diverse field of users, such as transit fleets, police departments, ambulance services, trucking fleets, and high value carriers.

An AVM system - or Automatic Vehicle Location (AVL) system, as it is known today - actually consists of three subsystems: positioning, communication, and data management. The positioning subsystem is concerned with determining the vehicle's location; the communication subsystem relays the position information to a central control station; and the data management subsystem is responsible for collecting all the position information and displaying it in a format that is meaningful to the system managers. This introductory section focuses only on the positioning technologies that are available for AVL systems. The principal authors have also written a report on wireless communication. (Dailey et al. 1995)

Prior to the PULSE conference, some positioning technologies had already been developed and were being applied in both aviation and marine applications navigation. The equipment required to determine position, such as receivers and on-board computers, was very costly, but the navigation benefits were sufficient to justify the cost for many marine and aviation operations. Since the ability to locate and monitor vehicles is a desirable option for land transportation systems but is not necessary for vehicle navigation, hardly any land organizations chose to invest money in positioning technologies for navigation or monitoring systems. However, by the time of the PULSE conference, computing power had increased, and the price of positioning equipment had decreased enough that positioning techniques were economically feasible for use in monitoring land vehicles. The attendees at the PULSE conference were able to identify three main categories of positioning technology that should be explored for AVM, namely radionavigation, dead reckoning systems, and proximity sensing systems. (Roth 1977)

Twenty-seven years later, this AVM research and development continues under the names of Automatic Vehicle Identification (AVI) and Automatic Vehicle Location (AVL). A newer positioning technology, the Global Positioning System (GPS), is now the dominant method being researched and applied AVL. The remainder of this section explores the four main types of AVL positioning technology - how they work, where they are used, and their advantages and disadvantages for managing transit operations.

2.1 PROXIMITY SENSING

Proximity based positioning systems geolocate vehicles using beacons at local, fixed reference points. The proximity devices are often called "signposts" and can be either passive or active. (Leong 1989) An active signpost transmits a signal that uniquely identifies itself, and this signal can be picked up by any vehicle that is close to the signpost and outfitted with the proper receiver. After the in-vehicle receiver has detected the signal, an on-board computer stores it along with the time it was received. When polled by a central control station, the vehicle's computer uses the radio to transmit the code and time of the last signpost signal that was received. (Riter 1977) At the control station, the AVL system is updated to reflect the information that at the time the vehicle received the signpost signal, the vehicle's location was approximately equal to the signpost's location.

Alternatively, a proximity signpost can be passive and receive transmissions from vehicles. Vehicles participating in this type of proximity AVL transmit a signal that is uniquely coded for each vehicle. The signpost that is closest to the vehicle captures that signal and relays the information to a control center. Once again, the control center assigns an approximate location to the vehicle based on the location of the signpost. (Riter 1977)

Several transit managers have chosen proximity sensing as the positioning technique for their AVL systems. One of the first transit fleet AVL systems, implemented by the Chicago Transit Authority in the late 1960s, used an active proximity sensing system. This proximity AVL system monitored Chicago's transit fleet using active, fixed signposts along the transit routes. (Roth 1977) More recently, in 1989 the OC Transpo transit system in Ontario, Canada, completed the construction of a network of proximity sensors. These signposts function simultaneously as active and passive sensors, both receiving and transmitting radio frequency (RF) signals. Each transit vehicle has a transponder (or tag) attached to it and has a receiver that can detect the signal being transmitted by a nearby signpost. A circuit within the vehicle transponder modulates the RF signal from the signpost, using a technique known as modulated backscattering; the modulated signal then serves as a unique code that identifies the transit vehicle to which the transponder is attached. The modified signal is sent back to the signpost, where the identity of the vehicle is decoded. The signpost passes the information along to a central control station to indicate which vehicle is near. (Leong 1989)

During the early stages of AVL research and development, the proximity sensing technique was the most advantageous positioning technique in terms of both implementation and performance criteria. At that time, the technology required to implement a signpost system was more readily available than the technology for any other technique. During 1971 and 1972, researchers conducted a test in Philadelphia, Pennsylvania, that compared the location accuracy of proximity sensors to radionavigation techniques. (Roth 1977) The goal of this test was to obtain position accuracy within 500 feet for 95 percent of all locations. The proximity sensing system successfully satisfied this condition, while radionavigation techniques could not perform with an accuracy any better than 1000 ft. (Roth 1977) Because of the immediate advantages of proximity systems, many transit systems began using signposts to implement their own AVL systems.

There are at least four disadvantages to using proximity sensing for position location. The primary disadvantage is the expense of installing proximity sensors wherever vehicles need to be located. It is extremely costly to place static sensing devices everywhere that a vehicle may drive. For vehicles that travel over wide areas on unpredictable and varied routes, a proximity sensing AVL system is inadequate. The second problem is that even if a signpost is present, the signal may not always be detected. For example, obstacles such as other vehicles may block the signal, and signposts may be damaged. In addition, continual maintenance must be performed to keep the system operating properly. Last, signposts require environmental approval from the responsible agencies in the region. (Ledwitz 1992)

Since transit vehicles generally travel fixed routes, transit operators can take advantage of a signpost system for AVL positioning more readily than most other AVL users. However, although transit vehicles travel fixed routes for the majority of their operations, exceptions do occur. Buses on special assignment or forced to take a detour will be off the standard route. Signposts may not be present on these alternative paths, and therefore, the control center will be unable to locate the bus. When buses travel from the end of their route to the beginning of another (called deadheading), they often take a variable route. During this time, the bus also cannot be tracked. Thus, while the bulk of transit services can use proximity sensors for AVL, there are many instances in which proximity sensors cannot provide AVL.

2.2 DEAD RECKONING AND MAP MATCHING

Dead reckoning has been used in position location for hundreds of years. It is a navigational term first used by shipmasters charting the oceans in the eighteenth century. Navigators would determine their current position by calculating the ship's bearing and speed since its last known position. (This method was known as deduced reckoning and abbreviated as ded reckoning. From the pronunciation of the abbreviation, the term gradually became known in both written and oral forms as dead reckoning.) The United States Navy and Coast Guard define dead reckoning as " . . . the process of determining a ship's approximate position by applying to the last well-determined position a vector or a series of consecutive vectors representing the run that has since been made, using only the 'true courses' steered and the distance steamed, as determined by the ordered engine speed, without considering current or leeway." (Shufeldt 1970, 71)

Dead reckoning techniques are also used for calculating the position of motor vehicles. The distance traveled is calculated by subtracting the odometer reading at the last known position from the current odometer reading. The bearing of the vehicle is determined by using some type of compass device or by knowing a pre-determined route.

Locating vehicles with dead reckoning can be difficult because many uncontrollable factors can skew the validity of the position calculation. To be successful, the odometers must be very precise and initially calibrated, but other factors, such as tire pressure and road conditions, can affect the measurements. Since positions are calculated from the previous position, errors can accumulate rapidly and cause gross miscalculation. (Riter 1977)

These problems can be mitigated by pairing AVL dead reckoning with computer map matching. In this combination, dead reckoning is used to project where the vehicle has traveled, and map matching is used to determine where the vehicle was capable of traveling or, in the case of a vehicle traveling a fixed route, to compare the odometer data with the planned route. As a result, even though the odometer and compass readings may be biased, the computer software can match the data to the closest possible location. Even more sophisticated map databases can compare "map matched vehicle trajectories with dead reckoning trajectories and build up a history of discrepancies to filter out systematic errors." (Collier 1990, 362)

Map matching uses sophisticated computer algorithms to aid in the location of a vehicle. From the vehicle's odometer and compass readings, a computer algorithm constructs a "historical track" to determine the location of the vehicle. The historical track is a logic tree whose root is the last location known with a high degree of certainty. The computer checks small segments of travel determined by the dead reckoning measurements with the corresponding segments in the map database and adds all possible vehicle locations to the historical track. As the vehicle travels away from the last known location, a function of these two segments describes an enlarging bubble of uncertainty in the position of the vehicle and creates a historical track with increasing breadth and depth. The uncertainty is resolved when the vehicle executes a 90-degree turn. Turns are highly distinctive, and the vehicle can then be precisely located on the map. This location becomes the last known location with high certainty and is the new root of the logic tree. (Collier 1990)

Transit systems and other commercial users have successfully used dead reckoning and map matching as the positioning technique for their AVL systems. One of the first implementations of a dead reckoning system was by the St. Louis, Missouri, police in 1972. (Roth 1977) The Municipality of Metropolitan Seattle (Metro) provides an excellent example of the use of dead reckoning and map matching for AVL positioning by a transit system. Metro began setting up its system in the spring of 1992, and it is currently active for a fleet of 1250 transit vehicles.

Dead reckoning plus map matching, as used for the positioning subsystem in AVL, has two main advantages. First, similar to proximity sensing, the technologies for odometer sensing equipment and map matching algorithms have been available since the 1970s, when AVL projects were first undertaken. Therefore users have not had to wait for technology and protocols (e.g., nationally standardized transmitters or satellite networks) to be developed and deployed. Second, dead reckoning can be used in rural areas and congested cities with equal reliability. Since the technology to find distance and direction traveled is associated with the vehicle itself, high buildings or vast expanses of open land do not affect the technique. In addition, dead reckoning and map matching work particularly well for transit systems. Since the routes of the transit vehicles are generally known, matching the collected data to a map is simplified.

Unfortunately, a margin of position error always exists with dead reckoning and map matching because of unavoidable factors such as tire wear, wheel alignment, and road condition. Since the current position is calculated on the basis of the last known position, these errors can rapidly accumulate and result in sizable location errors. The only reliable way to correct this problem is to use proximity devices to check position, (Riter 1977) but this method, as discussed in the previous section, has several drawbacks as well.

2.3 RADIONAVIGATION

Like the proximity sensing technique, radionavigation relies on fixed reference points; however, the use of radio signals allows information from multiple sites to be integrated into a more accurate determination of position. In radionavigation, the constant speed of light and the propagation delays of radio signals are used to find the ranges from a vehicle to fixed sites. Radionavigation has been used for many years to aid in aviation and marine navigation, but it was not considered for use in land AVL systems until the 1970s, when it became economically feasible. (Roth 1977)

There are several ways to use radio signals to determine the location of a vehicle; they can be used either at the vehicle or at fixed stations to calculate vehicle location. When a vehicle's position is found at a fixed station, the system measures the absolute time the signal takes to travel from that fixed station to the vehicle and back. The absolute times found by a minimum of three stations are sent to a central control station where the times are used to calculate the distance from each fixed station to the vehicle. These distances are treated as the radii of circles with the stations at the center. The intersection of all the circles described by the stations gives the location of the vehicle. When measurements from just three stations are used, the technique is called trilateration; if more than three fixed stations are used, the technique is called multilateration, and the increased number of stations decreases the estimate error in the measurements. (Riter 1977)

With the second radionavigation technique, the vehicle location is calculated at the vehicle. This technique "measure[s] the differences between the arrival times of the various received signals rather than trying to measure the absolute time required for the signal to traverse each path. The time differences define hyperbolas with focal points at the stations. The intersection of the hyperbolas define the vehicle's location." (Riter 1977, 8) This technique, called hyperbolic trilateration, requires less expensive on-board equipment than does regular trilateration because the vehicle does not need to retransmit a radio signal. Similarly to the first trilateration technique described, measurements for hyperbolic trilateration must be taken from a minimum of three stations; when radio signals from more than three stations are used, this technique is called hyperbolic multilateration.

Whether the absolute time of the signal's journey or the time differential of the signal's arrival is measured, the measurement can be made with either pulse or phase ranging. Phase ranging is achieved by sending a low frequency tone over a channel with conventional frequency modulation. To find the signal's travel time, the phase difference between the original tone and the received tone is measured. This technique requires that the phase of the reference tone be synchronized among all fixed stations and the vehicle. A difficulty with phase ranging is the effect of multipath propagation on the tone when it travels either to or from the vehicle. Multipath propagation occurs whenever a tone is reflected off other objects and does not travel in a direct path to the receiver. (Riter 1977)

Part of the problem encountered in using phase ranging can be overcome by employing radio frequency pulses to obtain the necessary measurements. The fixed stations emit radio pulses at assigned intervals, and the time between the emission and the detection of the pulse is used to calculate distance. Pulses reduce the effects of multipath propagation because the first pulse to arrive is the pulse that has not been reflected. There is no phase reference to be established, relaxing the strict requirement for synchronization among the fixed stations and the vehicle; therefore the equipment necessary for measuring radio pulses is less costly than the equipment for measuring phase differences. (Riter 1977)

One of the most extensive radionavigation systems for aviation, marine, and land use is Loran-C. Loran-C was developed to give the military increased radionavigation capability over Loran-C's predecessor, Loran-A. Loran-C is a hyperbolic trilateration system that uses radio pulses. In 1974, the federal government provided it for civil use in naval and air navigation. (Olsen 1991) At that time, chains of Loran-C stations existed in North America, Europe, and the Far East; (Bell 1989) however, Loran-C could not be used to locate vehicles in large sections of North America because of a mid-continent gap in the chain of transceivers. By 1991, the Federal Aviation Association had worked with the Coast Guard to close the coverage gap and build a comprehensive Loran-C navigation system for the United States. (Sedlock 1986, Shirer 1992) Although this mid-continent gap was eliminated to improve air traffic control, it also enabled land AVL systems to consider Loran-C as a viable radionavigation system.

In England, a few transit systems are taking advantage of a radionavigation system known as Datatrak. Datatrak is a hyperbolic trilateration system that is specifically designed for automatic vehicle location on land. Low frequency transmitters are set up every 100 miles, and each vehicle is equipped with a low frequency receiver and a computer to calculate its location. From the time difference between the arrival of signals, the computer finds three hyperbolas, and the intersection of the hyperbolas describes the vehicle's location. Each vehicle using the Datatrak system is assigned a time slot to transmit its location coordinates, speed, and bearing. The vehicle transmission is intercepted by a regional base station, and all base stations send their composite data to one of five regional headquarters. The headquarters have control rooms that are partitioned off to accommodate each of Datatrak's customers. From there, managers of transit systems can monitor the performance of their fleets. (Banks 1991)

One advantage of radionavigation is that it can be used for applications on land, in the air, and on the water. This wide application means that the cost of maintaining such a system can be distributed among many interested users. For some national systems, such as Loran-C, maintenance of equipment falls under the jurisdiction of the federal government, further reducing the costs required for a user to employ the system.. Utilizing a position location system that is funded and maintained by another agency is especially beneficial for transit carriers with restricted budgets. Another advantage of a national radionavigation system is that it offers automatic vehicle location anywhere in the United States, 24 hours a day. Thus, it eliminates restrictions that other systems impose on where vehicles may travel and still be tracked. These advantages are similar to the advantages found with the Global Positioning System (see the following section). However, when GPS was still in the planning stages, radionavigation systems had already been implemented and were producing satisfactory results in aviation and marine applications.

Radionavigation has its disadvantages as well. For instance, radionavigation can provide global coverage only if the stations that transmit radio signals are maintained. The Department of Defense, which has built and maintained the Loran-C chain of stations, is phasing out its use of Loran-C as a navigation tool. The Loran-C chains that are utilized in the United States and Europe will now be maintained by other agencies, but there is no guarantee that there will always be interested parties willing to maintain the system. (Olsen 1991) In addition, radio signals can be lost or distorted, especially in urban areas. Tall urban structures can block a radio signal and keep it from being received. Also, multipath propagation, while mitigated somewhat by radio frequency pulses, is still a limitation in radionavigation systems. (Riter 1977) The final disadvantage for radionavigation systems is that they are less accurate than the Global Positioning System. A study in 1993 proved that GPS signals were more consistently accurate than Loran-C signals. (Melgard 1994) (See the following section for more information on GPS.) The expense of radionavigation receivers and the problems with position location in urban areas make the implementation of radionavigation for a transit fleet AVL system difficult.

2.4 GLOBAL POSITIONING SYSTEM

The Global Positioning System (GPS) provides the newest positioning method for AVL. In April of 1973 the Deputy Secretary of Defense assigned the Air Force the task of implementing one comprehensive Global Positioning System for the Department of Defense. In his words, a GPS should be "designed to give precise position, velocity, and time data world wide in all weather conditions." (Pelc 1986, 27) The Air Force proceeded with a plan to develop and launch a complete network of satellites to realize world-wide GPS coverage. This network currently consists of 32 Navstar satellites in 12-hour orbits at an altitude of 20,200 km above the earth. (Ananda 1990, Dailey 1994, Dork 1986) From any position on earth and at any time, the network is designed to ensure that at least four satellites are high enough above the horizon to be detected. In addition, the Air Force has built a selective availability safeguard into the system. During times of national emergency, the Department of Defense can purposely degrade the accuracy of the satellite signals that are in widespread civilian use, preventing unauthorized personnel from using the signals to target sites in the United States or elsewhere. (Olsen 1991)

GPS enables any observer with a GPS receiver to measure his or her location anywhere on Earth. (Hayden 1994) The receiver's position is found by calculating the range from the known locations of the satellites to the receiver. The underlying premise is that, given *N* ranges from known points, a position in *N* space can be calculated. (Dailey 1994, 25) Each satellite transmits its ephemeris information on two L-band frequencies, L_1 at 1575.42 MHz and L_2 at 1227.60 MHz. In addition to its position information, each satellite transmits a unique pseudo-random P and C/A code. The P code is precise and known only by authorized military users, whereas the C/A code is known to all GPS users. Once the signal has been obtained, the receiver measures the time delay necessary to align the copy of the code generated in the receiver with the code received from the satellite. C_i, the product of the time delay and the speed of light, added to the product of the C/A code wavelength (Λ) and the number of wavelengths from the satellite to the receiver (n_i) gives the pseudo range to the *i*th satellite (r_i):

$$r_i = C_i + n_i\Lambda$$

Pseudo range estimates from three satellites would be sufficient to estimate position if the satellite and the receiver clocks were perfectly aligned. The satellite clocks can be aligned in GPS time using the ephemeris information; however, the accuracy of the clock used in commercial receivers is inadequate for this alignment. (Dailey 1994) By using the pseudo range from a fourth satellite, the clock bias can be eliminated from the calculations because the bias is the same between each satellite and the receiver. (Dork 1986) The satellite network was designed to ensure that at least four satellites are visible well above the horizon at any given moment, allowing receivers to use clocks of lower precision than those used on the satellites. (Hayden 1994) Because receivers passively detect signals from the established satellite network, an unlimited number of users can utilize the Global Positioning System.

Since the accuracy of the satellite data degrades as a function of time, the total GPS system includes a master control station and six monitoring stations positioned around the globe, with the location of each station known precisely. (Pelc 1986) These stations monitor the data stream from each satellite as it passes overhead. Each station calculates its position from the satellites' data and uses the difference between the known location and the calculated location to determine the error in each satellite's estimated position. The monitoring stations also compare each satellite's atomic clock with the official GPS time. The satellite position and time errors are corrected, and the compensated data are uploaded to the satellite by a microwave data link. (Dork 1986)

Currently, new satellites are being built that will be able to function with reasonable accuracy for 180 days without control center contact. Satellites will check and correct their own location information by following three steps: (1) taking pseudo range measurements to all visible satellites, (2) receiving and sending location data to all visible satellites, and (3) processing the measurements to calculate a new estimation for location. Each satellite will also have a failure detection override. If a satellite detects that it is failing to accurately calculate its own position, it sends a poor health flag to Earth receivers and the other satellites. This enables ground users and satellites to disregard data from that particular satellite, preventing the calculation of an incorrect position and avoiding contamination of the entire satellite constellation. (Ananda 1990)

An improvement, known as Differential Global Positioning System (DGPS), increases the accuracy of vehicle location. In addition to errors in the satellite location estimation and the satellite clock, propagation delays through the ionosphere and the troposphere also affect position calculation. DGPS helps correct these errors by taking the known station positions and comparing them with the satellite ranges found using GPS. The stations can then broadcast the difference between real and GPS calculated satellite ranges to other ground users. Since the ionospheric and tropospheric effects, as well as the satellite time and position errors, are the same for receivers, the control station differential can be used by local GPS receivers to correct the measured range.

There is a limit to the effectiveness of differential position correction. Satellite ephemeris and atmospheric errors are spatially correlated to the receivers. The accuracy of control station differential corrections for the pseudo range of receivers decreases as a function of distance from the station. (Harkleroad 1990, Hunter 1990) In other words, the farther away a vehicle with a GPS receiver is from a control station, the more the ephemeris and atmospheric error differs for that receiver.

Despite this limitation, DGPS has been proven to significantly increase the accuracy of the Global Positioning System. In 1989, the Ashtech corporation in Santa Clara, California, compared the accuracy of GPS versus DGPS. Using only GPS, the testers obtained position locations accurate within 10 to 26 meters. With DGPS, they found positions accurate within 1 to 2 meters with selective availability turned on. (Hunter 1990)

Because of the potential for the Global Positioning System to accurately locate vehicles worldwide, most of the recent research effort on AVL positioning methods has focused on improving GPS. While it is possible to locate a position with data from four satellites, researchers have found that it is not practical to restrict a GPS receiver to use only the minimum amount of data necessary. As a result, GPS receivers are being built with six to ten channels to instantaneously receive data from as many satellites as can be detected. However, studies at the University of Calgary have found a practical limit to the number of satellites that should be used in position calculations. They discovered that applying data from the six satellites with the strongest signals results in nearly the same position accuracy as that produced by data from all visible satellites. (Melgard 1994)

Some proponents believe that using GPS technology as the positioning technique in AVL systems will greatly benefit a host of ground transportation users, including transit systems. Paul Ledwitz says that GPS is "affordable, available, and should be seriously considered for all transit applications." (Ledwitz 1992) GPS-based AVL is currently used in both Denver, Colorado, and Milwaukee, Wisconsin, for their transit systems. In Milwaukee, the AVL system is deployed for over 650 transit vehicles; in Denver, over 1000 transit vehicles are monitored and tracked with GPS technology. (Hrut 1994)

GPS as the positioning technology for AVL has three distinct advantages for transit vehicles, as well as for any other ground-based vehicle; these advantages are accuracy, comprehensive coverage, and cost efficiency. GPS has proven to be the most accurate of any positioning method. For instance, researchers compared the location accuracy of map-matched dead reckoning with GPS and found that dead reckoning with map matching was only accurate to within 250 to 280 feet. GPS performed far better, yielding an accuracy of 10 to 26 meters. (Hunter 1990) In a test conducted by researchers at the University of Calgary, GPS was compared to Loran-C for accuracy in AVL in urban areas. In 1991, Loran-C proved to be the more accurate method. However, the full GPS satellite constellation was not deployed at that time. In 1993 when the same researchers performed the comparison test again, the complete satellite network was in position, and they used a GPS receiver with the latest improvements, namely C/A code matching capabilities and 10 channels. This test showed that the accuracy and "the availability of GPS was superior to Loran-C for each street." (Melgard 1994, 487)

A second advantage with GPS is that it offers the flexibility of locating a vehicle wherever it may travel. This kind of comprehensive coverage is the only type of AVL positioning method that will suffice for a vehicle that does not travel a fixed route. Even transit systems, which do travel fixed routes and can use fixed locators such as signposts, occasionally need to locate vehicles that are not on a fixed route, such as buses on detours or special assignments. With new and pending legislation, transit systems may soon be required to pick up handicapped individuals on demand. (Ledwitz 1992) Some paratransit systems, like the Kitsap Paratransit System in Bremerton, Washington, are already providing door-to-door service for individuals who cannot use the fixed-route transit service. (Haselkorn 1994) Because of the unpredictable nature of such "on demand" routes, signposts would be inadequate for continuous AVL, but GPS can provide constant position information to aid in both vehicle location and dynamic scheduling.

The third advantage with GPS is its cost efficiency. The government supplies the GPS signal for free, and the unit cost per GPS receiver is comparable to the cost of equipment for the other AVL positioning methods. (Ledwtiz 1992) GPS is also cost-efficient in terms of maintenance costs. A GPS receiver stays with the vehicle, significantly reducing the amount of damage from weather and vandalization.

GPS is not without its disadvantages. Its two main problems, multipath propagation and signal blocking, are both prevalent in urban settings. For transit systems, which operate mostly in urban areas, these difficulties can be serious obstacles to proper AVL operation. With multipath propagation, the signals from the satellites may be reflected off skyscrapers and other urban structures before reaching the GPS receiver. Since the time the signal takes to travel from the satellite to the receiver is the most important measurement in determining vehicle location, delays caused by multipath propagation can lead to severe position errors. Researchers are working to develop GPS receivers with the capability to reject multipath propagated signals and to use only those signals that travel directly to the receiver. (Melgard 1994)

The second disadvantage, signal blocking, occurs when the satellite signal is blocked and never reaches the GPS receiver. This happens when the vehicle is inside a solid structure, such as a parking garage or a tunnel. Moreover, vehicles operated in cities where the streets are lined with tall buildings often cannot receive all the satellite signals. These vehicles are effectively in an "urban canyon," where the buildings create walls that hinder many incoming signals. Again, researchers are working to improve signal acquisition in urban canyons. (Melgard 1994)

2.5 STATE-OF-THE-ART SUMMARY

In conclusion, there are four different types of positioning techniques for AVL systems that managers of transit systems may use to monitor their fleets, each with advantages and disadvantages. Proximity sensing is viable for position location in transit AVL systems because it utilizes the fixed route characteristic of transit routes. However, signposts require constant maintenance and are unable to provide continuous vehicle location whenever transit vehicles deviate from normal routes.

The advantage of the dead reckoning and map matching technique, like proximity sensing, is that it can use the fixed route information available with transit fleets to improve the technique's ability to locate vehicles. The performance of dead reckoning and map matching is also unaffected by congested urban conditions, which can be a significant advantage for transit fleets that operate in cities. Unfortunately, the accuracy and reliability of vehicle location with this technique are inferior to other positioning techniques.

Radionavigation and GPS have similar advantages and disadvantages. In both cases, a third party is responsible for the installation and maintenance of the signal-emitting equipment. To use either positioning method, managers of transit systems purchase only the receiver. In addition, both techniques are capable of locating vehicles wherever they travel and at any time of the day. However, both radionavigation and GPS have a disadvantage in urban settings in that signals may be blocked or reflected, producing erroneous results.

Each of the positioning techniques have strengths and weaknesses when used in AVL systems for transit operations. The ideal positioning system would combine all positioning techniques to leverage the best feature of each. However, since transit managers must balance the accuracy of vehicle positioning against cost, there will always be trade offs in choosing a positioning technology or combination of technologies to use for transit system AVL applications.

3. FINDINGS/DISCUSSION

The second, primary objective of this project was to create an Advanced Public Transportation System (APTS) prototype using King County Metro AVL data. In this section, we present (1) an overview of King County Metro's AVL system, (2) a discussion of our ITS network, which provides the infrastructure for the AVL-based APTS prototype, and (3) a detailed description of the APTS prototype and the subsystems that make it work.

3.1 THE KING COUNTY METRO AVL MANAGEMENT SYSTEM

In the spring of 1992, the King County Department of Metropolitan Services (Metro) implemented an Automatic Vehicle Location (AVL) system for its transit fleet.

3.1.1 AVL System Components

Like all AVL systems, Metro's system is composed of three subsystems: positioning, communication, and data management. For their positioning subsystem, the managers chose dead reckoning and map matching to the predetermined transit routes. (See section 2.2 for more information on dead reckoning.) To enhance the accuracy and reliability of the dead reckoning positioning system, Metro is using proximity sensors, also called signposts. These signposts are not used to locate vehicle position; they are used to indicate whether a transit vehicle is on the correct route.

For the communication subsystem, Metro has equipped its transit vehicles with a wireless communication system - a radio system - that sends sensor data from the vehicles to Metro's central control station. The control station polls each vehicle for its data approximately once a minute.

Metro's AVL data management subsystem is controlled by a central computer system, the Data Acquisition and Control System (DACS). The DACS includes a database

Signposts are used to alert the control center when a vehicle is "off route." The off-route condition can occur for one of two reasons. First, a transit vehicle is considered off route if it receives a signpost signal from a signpost that is not on its itinerary. Second, a transit vehicle is off route when it misses four consecutive signposts on its route. Once a transit vehicle is determined to be off route, the data from the odometry equipment are no longer used to determine the vehicle's location, and that vehicle is in "off route processing." The location of the vehicle continues to be unknown and untracked until the vehicle receives a signal from a signpost that is on its route. (Oovergard 1994)

After the transit vehicle gathers the information needed to determine position location (signpost signals and odometry data), it passes this information on to Metro's control station. However, the transit vehicle does not transmit its information at random and unscheduled times; the vehicle waits until it is polled by the DACS. The DACS polls the transit vehicles approximately once a minute, and when polled, each vehicle radios back to headquarters its unique vehicle identification number, the number of clicks that have been recorded since the last polling, the last signpost signal detected, and the time that the signpost signal was detected.

Once the position location data are at the control station, the central computer system can determine the vehicle location and display this information in a meaningful format. First, the DACS accesses the file containing the route pattern that the vehicle is traveling. The DACS has approximately 3,000 pattern files describing the various transit routes, and when the transit vehicle starts its route, or "logs in," the DACS matches that vehicle with the pattern file for the route it is traveling. When the information is received from the transit vehicle, the DACS uses the vehicle identification number to determine what pattern file is needed. Second, the DACS calculates the distance traveled using the number of "clicks" recorded by the odometry equipment and matches this distance to the pattern of the route. Third, the computer system identifies the signposts that are located on the transit providing access to information previously unavailable to them, and (5) a system that functions in a geographically distributed computing environment.

The components of our ITS infrastructure include (1) "instance servers" that bridge data sources to a communication network, (2) "fusion servers" that gather and operate on various data types, and (3) presentation systems for delivery of management and traveler information. Each client or server process exists in a distributed computing environment so that all might be present on one computer or distributed over a set of computers. This distributed architecture allows for "scaling" of the system, as well as the migration of any process to any computer. Similarly, the number and type of data sources or display applications can easily be extended.

The framework is based on a communication backbone - an underlying medium that supports communication among ITS client applications, intermediate processes, and data sources without regard to physical location. Figure 1 presents the central nature of the

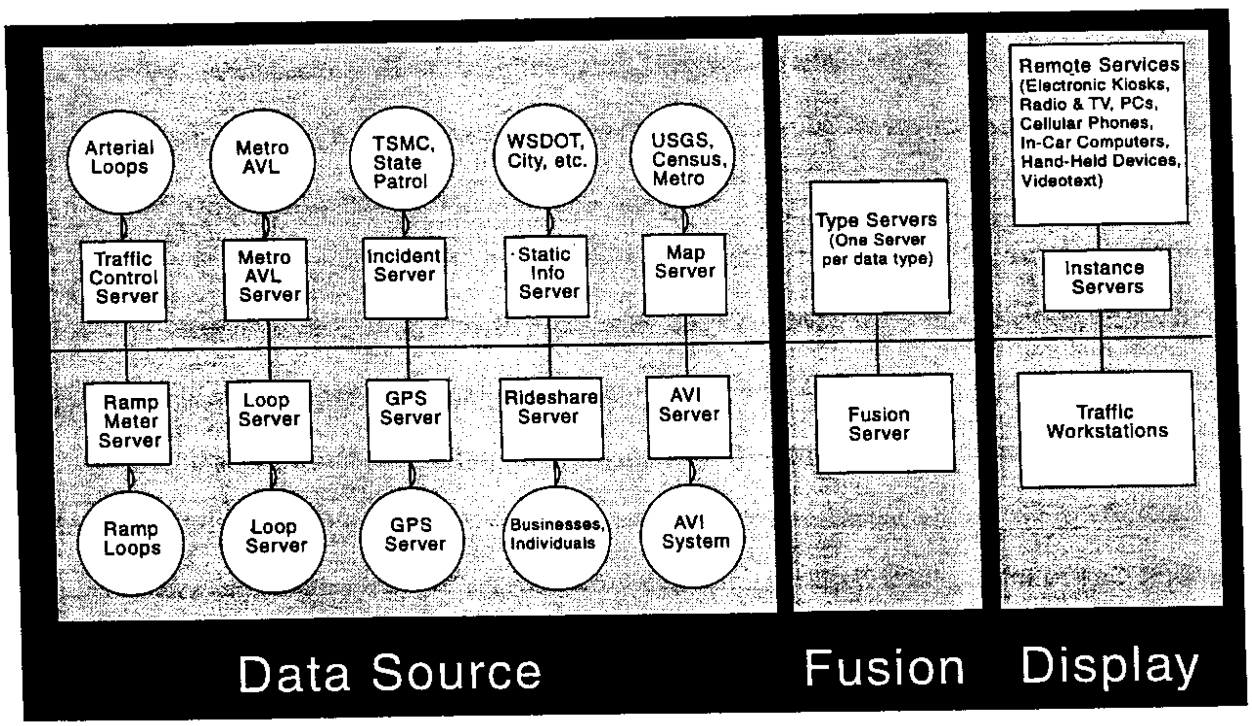

Figure 1. Overall ITS Communication Architecture

backbone pictorially. This backbone meets both system and higher-level needs. For example, while the backbone is necessary for distributed computing applications, it also promotes interagency and inter-jurisdictional cooperation by making it easier for an agency to share its data, and access the data of others, without disruption of that agency's current operations.

Our communication backbone is based on the protocols and standards used by the worldwide Internet community. Our selection of standard Internet protocols not only leverages the vast investment already made by the U.S. government, but also allows the use of standard network interface hardware and software. This allows ITS application and sensor developers to focus on ITS issues rather than communication issues. In addition, this style of network model allows the concepts layered on top of such a backbone to work equally well at the local, regional, and national levels.

A second key aspect of this network model is peer-to-peer communication. This paradigm is often used to share data in a distributed computing environment, and it inherently supports the notion of geographic independence for ITS data sources and applications. In our framework, each process on the network is capable, with some adjudication, of communication with any other process, without regard to its status as a source, intermediary process, or consumer of data. Thus in Figure 1, each of the client/server processes represented by rectangles can communicate with any other.

The peer-to-peer concept implements a network-wide mechanism for intercommunication. Peers exist independently of agency and jurisdictional boundaries. This allows ITS applications developers to access data at any level of complexity, from raw sensor data to information resulting from data fusion. In addition, applications can access data from any agency or organization willing to share all or some portion of the data they use internally. Since the reward for sharing data is access to everyone else's (as well as to fusion processes and user applications on the network), and since data can be shared the network. In system terms, this provides a layer in which data structures for interprocess communication are defined. In terms of higher-level goals, new sensors and applications can easily be added. Innovative development is also encouraged, as developers have a clear model of how to get data and what that data will look like, without severe limitations on what they are allowed to do.

We conclude this general description of our ITS network infrastructure by reviewing some of the higher-level goals that are central to its design. The framework supports existing investments in ITS infrastructure by providing a clear mechanism for integrating past, current, and future development efforts with new ones. Additional sensors or applications, both existing and to be developed, can either implement a network interface internally or use the instance server abstraction to provide a bridge to the ITS backbone.

Our framework also encourages interagency and multi-jurisdictional sharing of data by providing in return the benefits of a global view of traffic and access to numerous other resources and applications. Equally important, a mechanism is provided for agencies to add themselves to the network with minimum cost and no disruption of internal operations. Thus the cost of joining this ITS network is far smaller than the value received, thereby providing incentive for voluntarily membership in the ITS environment.

This framework is also compatible with the national direction for information flow. That direction is toward a computing environment that is fully interconnected by a national data highway. Our framework recognizes this trend and proposes to explicitly take advantage of existing resources in this area by providing a clear distributed-computing framework for development of networked ITS applications. In addition, the use of Internet protocols leverages the huge investment the government has made in this network technology.

makes Metro's AVL data generally available for additional uses such as traveler information, but it also demonstrates that this bus location information can be displayed on a single screen with loop-based freeway congestion information from another agency (WSDOT). The prototype consists of Metro's odometery-based AVL system; WSDOT's loop-based freeway system; an AVL *instance server*, which puts the AVL odometery data on the ITS network; a loop *instance server*,which puts the freeway loop data on the ITS network (constructed under another project); an AVL *fusion server*, called the positioning server, which converts the AVL odometery data to latitude and longitude pairs; and a GIS application that displays, in real time, both bus locations and freeway congestion on a digital map. (See Figure 2)

This prototype is a good example of the development strategy described above. We obtain real-time transit vehicle locations by interfacing with an existing automatic vehicle location system (AVL) owned and operated by King County Metro, and we obtain freeway congestion information by interfacing with an existing loop-data system owned and operated by the Washington State Department of Transportation (WSDOT). The operations of neither agency are disturbed by our use of their data, and any agency on the Internet has the potential to repackage these two data streams for new applications and services.

The remainder of this section presents the details of the APTS prototype. We first provide an overview of the data flow and then supply the implementation details.

3.3.1 Data Flow Perspective

The prototype data flow begins with the acquisition of Metro AVL data; this is accomplished by placing an instance server at a strategic location within the AVL system. (The acquisition of loop data is omitted from this description because it was accomplished under a separate project and is described elsewhere.) As described above, Metro's system consists of several components, including a data acquisition control system (DACS) and a set of GIS command and control consoles. It is at the juncture of the DACS and the

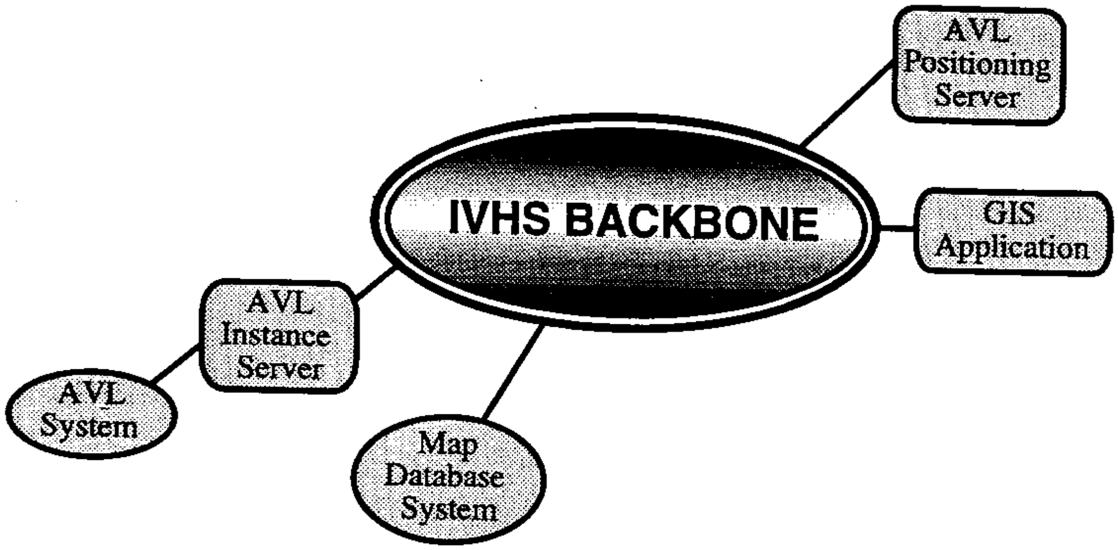

Figure 3. Communication Backbone Support for AVL Project

To present the probe vehicle location information in a useful way, our implementation includes a traffic management-type display of traffic information. In our example implementation, a locally developed GIS display application accesses a set of map data derived from TIGER files, theUSGS 1:100,000 scale digital maps (augmented by local measurements). These maps can be displayed on X-terminals located anywhere on the backbone. These maps are used to give context to the probe vehicle information just developed. Access to vehicle location data, vehicle information (implemented as a network data base), and congestion data (implemented by the Loop Instance Server) is handled in the same client/server way used to establish communication between the AVL fusion server and instance server. The GIS application makes a request for data from the server and then uses these data to build the display.

3.3.2 Implementation Details

Five different processes compose the prototype system architecture. These processes are performed on several different computers that are located in different physical areas and connected by the Internet. Within these computers exist dedicated servers that handle each specific process. Thus, the prototype AVL system architecture consists of the broadcast server, the rebroadcast server, the position server, the hash table, and the Intelligent Transportation System (ITS) server (See Figure 4).

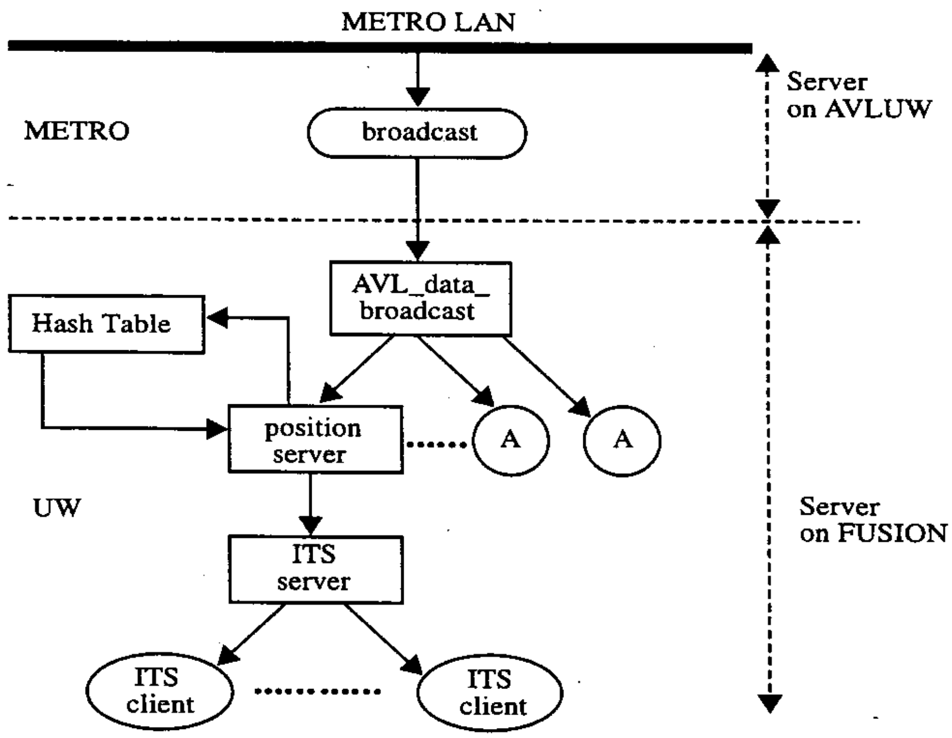

Figure 4. AVL System Architecture

Each server is responsible for one step in the overall process that transforms Metro AVL data. The primary functions of the servers are as follows:

- The first server is the broadcast server, which is on AVLUW, a computer located at Metro. The server is connected directly to Metro's local area network (LAN), and through this connection, the server grabs AVL data that are broadcast across the LAN. This server also listens to the rebroadcast server and determines whether it currently needs the Metro data. If the rebroadcast server is on and has made a request for AVL data, the broadcast server sends it data immediately after retrieving data from the Metro LAN. In other words, the broadcast server will send the AVL data to the rebroadcast server in real time.

- The rebroadcast server, known as AVL_DATA_BROADCAST, is running on the computer called FUSION that is physically located at the University of Washington. To begin, this server asks the broadcast server at Metro to send it Metro AVL data. After the request has been honored and a connection established, the rebroadcast server receives real-time Metro AVL data. At the same time, this server accepts requests for data from other clients that are interested in obtaining AVL data. Interested clients could be a position server, a vehicle speed client, or a bus monitor client.
- The position server, called AVL_POSITION_SERV, is also located on FUSION. It is one of the clients that requests AVL data from the rebroadcast server. Upon receiving the data packets, it extracts the relevant information, which consists of the pattern file name, the distance from the starting point of that specific pattern file, and the last signpost encountered. The position server then converts Metro location data into a geographic location represented by latitude and longitude coordinates. Part of this procedure is actually done by a hash table, another component in the prototype system architecture. Finally, the position server sends the geographic information to the ITS server.
- Instead of being a dedicated server like the others, the hash table is a storage file and search algorithm that is used by the position server. However, the hash table performs a function that is as important as the functions performed by the other servers because it executes the lengthiest part of the calculation needed to determine the geographical location of Metro vehicles. From the position server, the hash table receives the reference pattern file name, the

distance from the starting point of that specific pattern file, and the last signpost encountered and searches through its pattern files to determine the world coordinates that the Metro data represents. In comparison to other sorting algorithms, the hash table requires the least amount of search time to find the correct world coordinates.

- The last server, the ITS server, is also located on FUSION. This server requests AVL geographic data from the position server. After receiving the data, the ITS server sends the vehicle location information to all ITS clients that have requested the data. One of the ITS clients is a digital map display client that can take the geographic location information and represent the locations of the transit vehicles on a digital map.

Each of the components that make up the prototype AVL architecture is described in detail in the sections that follow.

3.3.3 AVLUW Broadcast Server

Across its LAN, Metro broadcasts AVL data of a length that varies depending on the quantity of data received from Metro transit vehicles. To maintain system security and create the least amount of disturbance, the AVLUW computer, which contains the broadcast server, is connected directly to a specific port on the Metro LAN to listen for and retrieve AVL data.

The data packet received from the Metro LAN broadcast port contains several fields. The data include the vehicle identification, the route identification, the pattern file name, the distance, the last signpost, and status flags. The vehicle identification and route identification fields uniquely identify the vehicle and the route that the vehicle is traveling. The data field called pattern file holds the name of the file with the pattern of the route. The distance field contains the distance that the vehicle has traveled from the beginning of the route. The data field called last signpost is the field that stores the identity of the last signpost passed by the vehicle. Lastly, the flag field indicates specific information about the performance and condition of the vehicle, i.e., on-time or initial mode.

To accomplish the retrieval and transmission of the AVL data, the broadcast server initiates three different "child" processes. Figure 5 diagrams the detailed system architecture of the broadcast server.

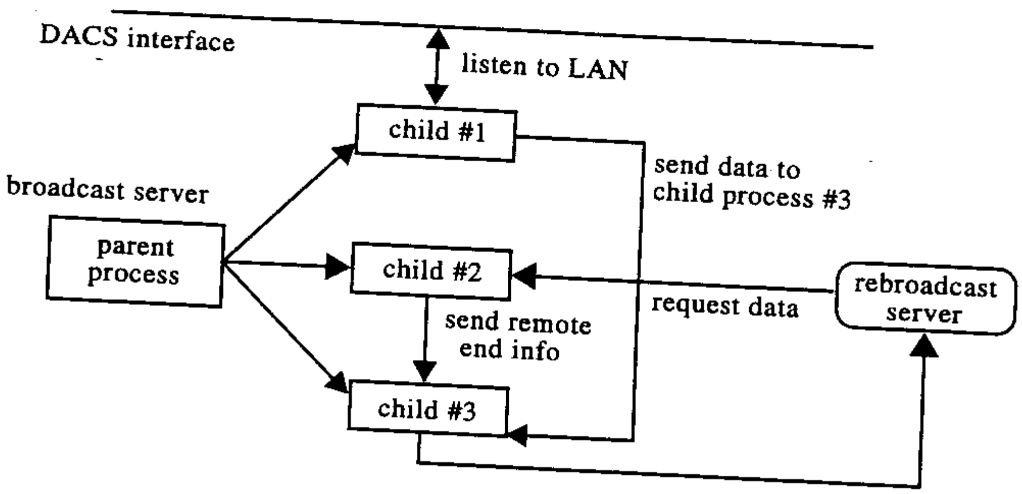

Figure 5. Broadcast Server System Architecture

The first child process monitors the Metro LAN and retrieves all AVL data; the second child process establishes the connection with the rebroadcast server whenever the rebroadcast server makes a request for AVL data; and the third child process transmits the AVL data to the rebroadcast server. Of course, before the third child process can send the AVL data, it must obtain the information that the first and second child processes have gathered, i.e., the AVL data and the connection information. Communication among the child processes occurs through a Unix internal socket pipe.

The broadcast server must initiate all three child processes to avoid any conflicts between requests for data and data transmission. For example, when a process is sending the requested data to the client, it is possible that another client will send a connection request at the same time. This second client will not get any response until the process has finished sending the first data request. If the data transmission is long, the second data request could be lost. Therefore, three child processes are required: one to capture Metro data, one to listen for requests from clients, and one to transmit the data to the clients.

3.3.4 Rebroadcast Server

The main purpose of the rebroadcast server is to reduce the load of the broadcast server; it performs the same functions - receiving and transmitting AVL data - but can handle more clients and can easily fan out to include even more clients in the future. AVLUW, which houses the broadcast server, is a an old machine that operates at a low speed, slowing down dramatically when several clients connect to it. Also, for security reasons, the Metro LAN manager only opens a single connection between AVLUW and the machine at the University of Washington. Therefore, the rebroadcast server is designed not only to take care of all clients that are interested in the raw broadcast data of the Metro LAN but also to minimize security concerns.

Like the broadcast server, the rebroadcast server produces three child processes to handle all the connections between clients and to receive AVL data. Figure 6 shows the system architecture of the rebroadcast server.

When the first child process is generated, it checks the configuration file to find out if and where the broadcast server is running, and if the broadcast server is operating, child process 1 then makes a connection request to that server. After the broadcast server grants the connection, every packet that the broadcast server receives is transmitted to the child process 1 of the rebroadcast server. Child process 1 then sends the AVL data to child process 3 through a Unix internal socket pipe.

The second child process of the rebroadcast server connects to all the clients interested in obtaining Metro AVL data in their original form. Upon starting, this process creates a well-known Internet TCP socket and listens to the Internet to determine whether anyone has made a connection request to that TCP socket. If a request is present, the

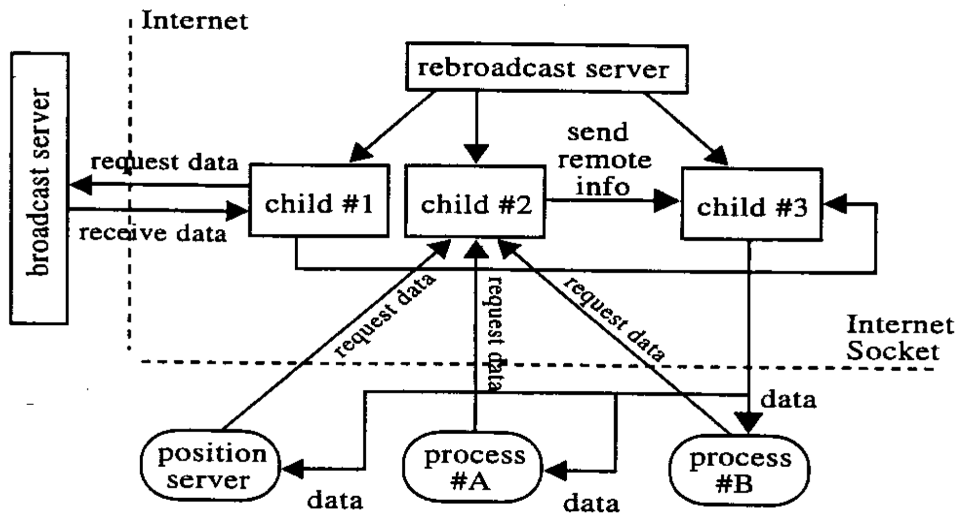

Figure 6. Rebroadcast Server System Architecture

second child process creates a file description with all the information that the client requires. Child process 2 sends the file description to child process 3 for transmission. Like processes 1 and 3, child processes 2 and 3 also use a Unix internal socket pipe to communicate with each other.

Child process 3 actually sends the AVL data to each client. If data are available from the socket pipe between process 3 and process 1, process 3 recognizes the data as AVL data from the broadcast server. It sends this data packet to all the clients currently on its client list. If data are available from the socket pipe between process 3 and process 2, process 3 recognizes the data as a file description about a new client. It adds the new client to the current client list.

3.3.5 AVL Position Server

The position server is the server in the prototype system architecture that transforms Metro's AVL data. Again, Metro's position information consists only of the pattern file name, the vehicle's relative distance from the starting point in that pattern file, and the last signpost encountered by the vehicle. The position server takes these pieces of real-time information and converts them into real-time geographic coordinates. Figure 7 shows the system architecture of this server.

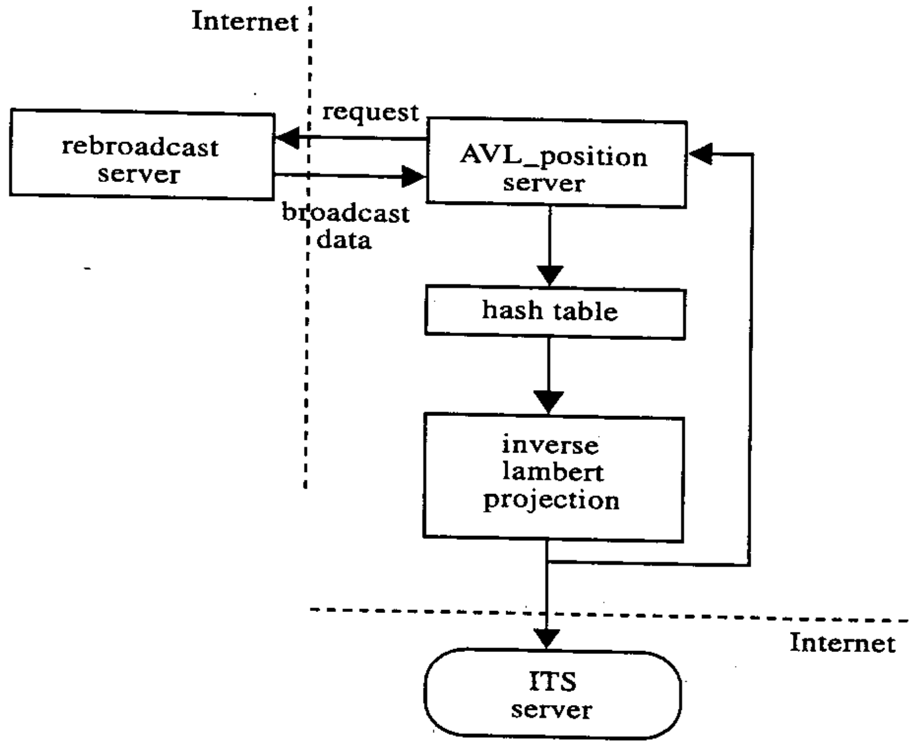

Figure 7. AVL Position Server System Architecture

First, the AVL position server requests a connection with the rebroadcast server. Once the connection has been made, the position server receives AVL data over an Internet TCP socket connection. The connection between these two servers stays in place until the AVL position server sends a disconnect request.

The position server sends the pattern file name, the vehicle's relative distance from the start of the pattern, and the last signpost encountered to a hash table. The hash table quickly finds the corresponding world coordinates represented by these data. (See section 3.3.6 for more information on the hash table.) After the hash table has provided coordinates, the position server uses an inverse Lambert Conformal Conic Projection subroutine to map the world coordinate position to a geographic location.

Lastly, if the ITS server is operating, the position server passes it the geographic coordinates of Metro's transit vehicles.

3.3.6 Hash Table

The hash table is the component that takes the Metro AVL data and converts them to their world coordinate position. To this end, the hash table must search through the Metro pattern files to find where the vehicle currently is located on the route pattern. Therefore, the hash table loads the pattern files into memory when the position server starts.

A pattern file contains a set of nodes, and each node has the following fields: sequence number, signpost, world coordinates, distance, and description. Table 1 is a sample pattern file with thirteen nodes.

Table 1. Pattern File Sample

number	signpost	world_x	world_y	distance	description
1	0	20458	34760	0	start
2	0	20427	35118	427	45st & 12ave
3	A	20455	35093	727	12ave & 42st
4	0	20467	35082	853	42st &13ave
5	B	20507	35047	1278	13ave & 45st
6	0	20480	35017	1603	45st & 14ave
7	0	20467	35002	1750	14ave & 43st
8	C	20454	34987	1923	43st & 15ave
9	0	20452	34984	1950	15ave & 40st
10	0	20427	34957	2245	40st & 16ave
11	D	20410	34938	2449	16ave & 45st
12	0	20400	34927	2567	45st & 17ave
13	0	20374	34896	2890	End

Each of the fields helps to identify where that node is located. The unique sequence number, which is in the first field, represents the actual order of this node in the pattern file. The signpost field gives the designation of the signpost, but not all nodes have a signpost at their location. If a node does not include a signpost, the signpost ID field contains a 0. The next two fields hold the world coordinates (x, y) of the node; these coordinates are not geographic coordinates. Next, the distance field describes how far this node is from the starting point of the pattern file. If this node is the first node, the distance is 0. Finally, a description field states the node's actual street location. For example, in Table 1, the description of Node 5 is "13ave & 45st." The description indicates that this node is located at the crossroad of 13th Avenue and 45th Street. Figure 8 is a graphic representation of the pattern file from Table 1.

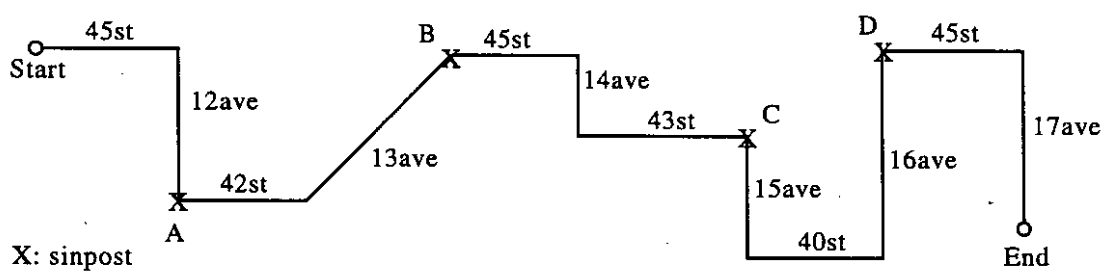

Figure 8. Pattern File Representation

In the pattern file, the node whose distance is closest to the vehicle's distance must be found, but searching for this node can be very time consuming because most of the pattern files currently used by Metro contain more than 120 nodes each. Furthermore, all nodes are not located at equal distances from each other, making the vehicle's exact location in the pattern more difficult to find. Fifty nodes may have to be checked before the correct location is found. Reading and then closing different pattern files also consumes a lot of time. Assuming that the data are updated every half second and that each data packet has information on up to 10 buses, 1,000 nodes would have to be searched and 10 files would have to be opened and closed in one second. This node searching and file acquisition activity would certainly interfere with receiving data.

To limit the number of searches, the position server uses a hash table, which has to search fewer than eight nodes in a pattern file to find where in the pattern the vehicle is located. In addition, the hash table eliminates file opening and closing activity because it reads the files into memory when the position server activates.

In the hash table, each node of a pattern file is represented as a record, which has a segment of a fixed size allocated to it. Each record also contains a pointer to the record that contains the next node in the pattern. The absolute position of the record is pointed at by a 'Key' index, and this 'Key' index is a function of the pattern file name and last signpost detected by the vehicle. (See Figure 9.)

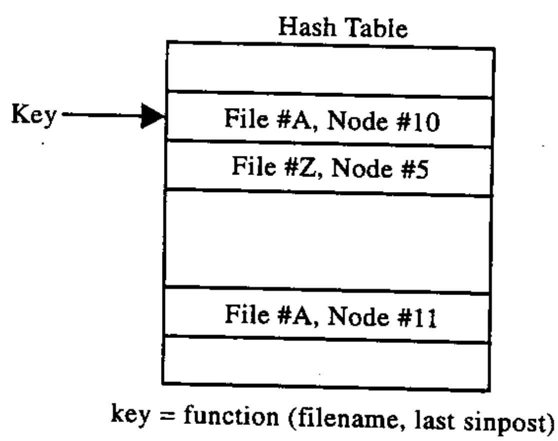

Figure 9. Pattern File Hash Table

After the 'Key' index locates the record containing the last signpost seen, that record's pointer is used to access the record that contains the next node in the pattern. The pointer in that record is followed to the next record, and this process continues until the record containing the next signpost on the route is found. With the signposts acting as endpoints, the distance filed in each record is checked to find which nodes the transit vehicle is between. Using Table 1 as an example, a transit vehicle had last seen signpost A and was at a distance of 915, and this information was passed to the hash table. The 'Key' index would point to the record containing node 3, and then records with nodes 4 and 5 would be accessed. The distance in the pattern file of nodes 3 through 5 is 727, 853, and 1278, respectively. Since a distance of 915 is between 853 and 1278, the vehicle must be located between node 4 and node 5. To complete the process, the hash table uses the world coordinate positions of the two nodes and interpolates them to find the world coordinate position (x, y) of the vehicle.

3.3.7 AVL ITS Server

The final component in the prototype system architecture is the AVL ITS server. It receives the geographical locations of Metro transit vehicles from the position server and gives this information to all ITS clients who have requested the information. ITS clients include clients who take the position information and place transit vehicles on digital graphic displays. Figure 10 shows the system architecture of the AVL ITS server.

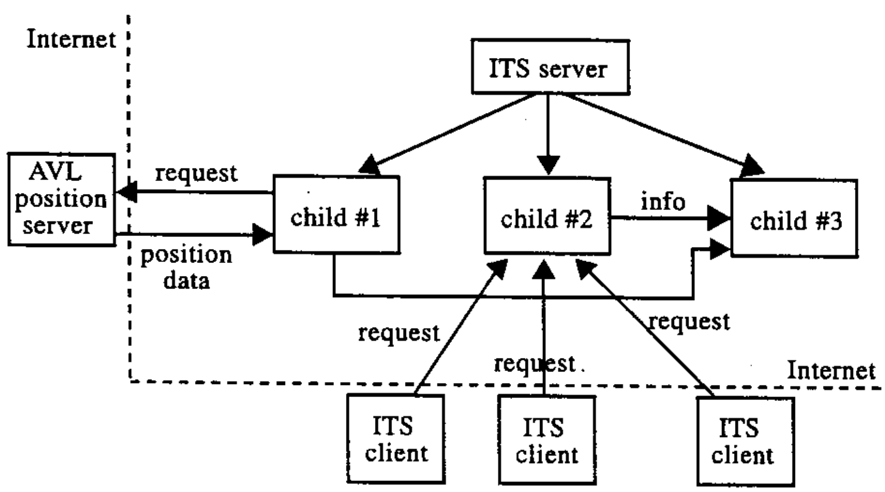

Figure 10. AVL ITS Server System Architecture

Like the broadcast and the rebroadcast server, the ITS server's architecture consists of three child processes. Again, the processes are used to request data, establish connections, and send data. However, the ITS server differs from the broadcast and the rebroadcast server in the way that clients request data. Each ITS client who has a different purpose for the position data must connect with child process 2 through a different TCP socket port number.

All of the servers described in the last sections are combined with a graphical presentation of a digital map to produce the display described in the next section.

3.3.8 AVL Display

To present the transit vehicle location information in a useful way, our implementation includes a traffic management-type display of traffic information. In our example implementation, a locally developed GIS display application accesses a set of map data derived from TIGER files, the USGS 1:100,000 scale digital maps (augmented by local measurements). These maps can be displayed on X-terminals located anywhere on the backbone. These maps are used to give context to the probe vehicle information just developed. Access to vehicle location data, vehicle information (implemented as a network data base), and congestion data (implemented by the Loop Instance Server) is handled in the same client/server way used to establish communication between the AVL fusion server and instance server. The GIS application makes a request for data from the server and then uses these data to build the display.

The demonstration display consists of the street network displayed on an X-terminal (the GIS display in Figure 2), along with the real time location of any probe vehicles and real time freeway congestion data from WSDOT. The user of this display can make selections to tailor the information. The maps can be scaled from a regional presentation to the individual street level, and various layers of the cartographic information (e.g., political boundaries, streams, lakes, streets, arterials and freeways) can be turned on or off. In future implementations, information about each probe vehicle will be obtained by pointing to the icon representing that vehicle and clicking a mouse button. Figure 11 is a snapshot of the current map display. The transit vehicle locations are represented by the route number placed on the map.

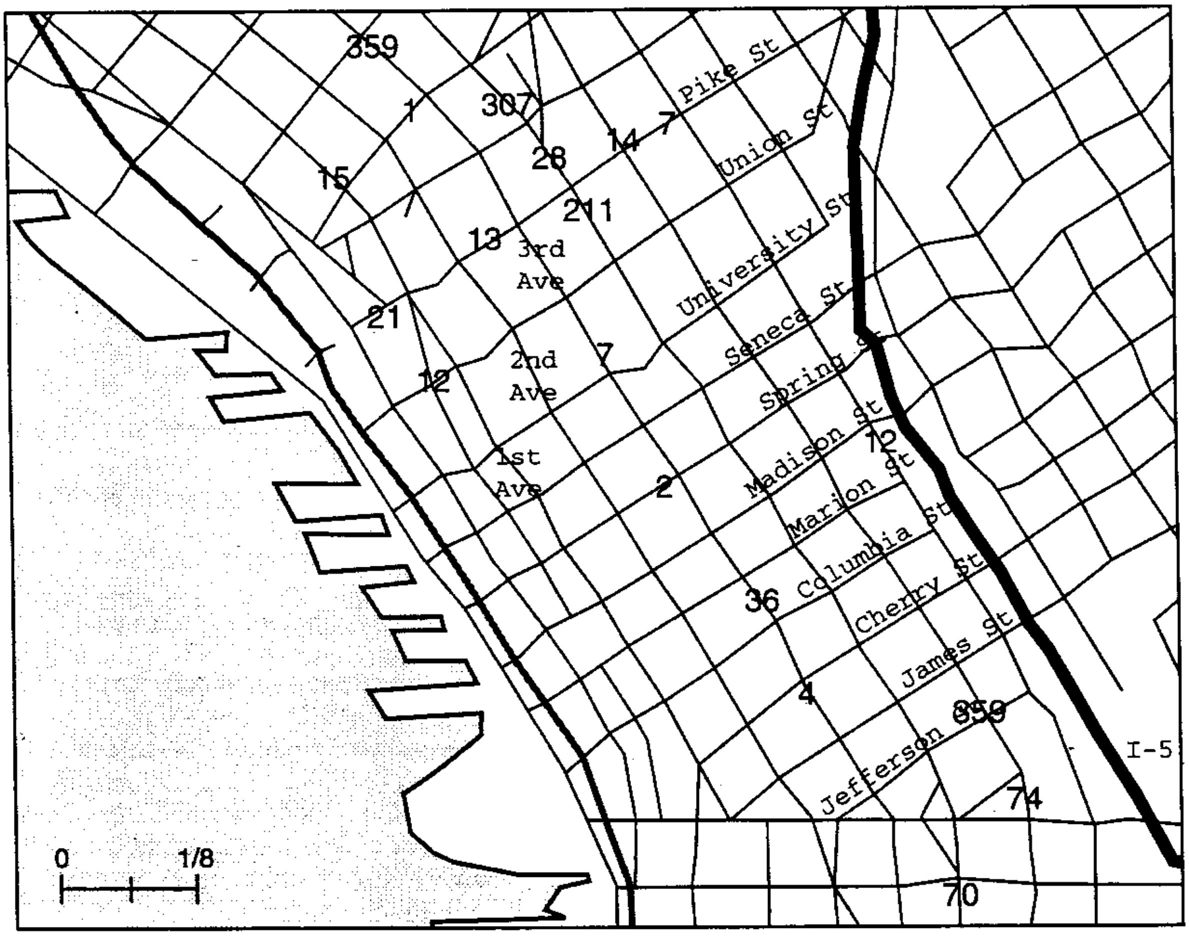

Figure 11. Display of Real-Time Bus Locations

4. CONCLUSIONS

This project accomplished two significant tasks. First, a state-of-the-art review of Automatic Vehicle Location (AVL) technologies was undertaken and is presented in the second chapter of this report. This state-of-the-art review helps to present the King County Metro AVL system in the context of possible AVL technologies. The Metro AVL system was used solely for internal fleet management prior to this project.

The second accomplishment was to demonstrate the use of real-time transit information derived from the Metro AVL system to produce a prototypical display of real-time transit coach locations suitable for wide area Advanced Traveler Information System (ATIS) use. This project further demonstrated the viability of combining multi-agency data with different technology roots in a single development environment that encourages interagency collaboration in the creation of ITS applications and services.

The rich and flexible development environment, generated at the University of Washington and used to leverage a proprietary AVL system to a prototype public ATIS, is a major advantage provided by a regional ITS infrastructure and should be incorporated into state plans under Venture Washington.

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