DIGITAL MAP REQUIREMENTS FOR AUTOMATIC VEHICLE LOCATION

Final Report

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ABSTRACT

New Jersey Transit (NJT) is currently investigating acquisition of an automated vehicle locator (AVL) system. The purpose of the AVL system is to monitor the location of buses. Knowing the location of a bus enables the agency to manage the bus fleet more efficiently and to provide their customers with up to the minute information on bus arrivals and departures. To monitor the location of the buses, their positional information (as determined by the AVL) is displayed on a digital map such as a GIS. To ensure accurate information, the location (coordinates) of the bus must be consistent (or within a small tolerance) with those of the digital map. If this is not the case, the system may yield incorrect information. This problem may become especially critical in an urban area where the system would be most valuable.

In this project, a methodology was developed for testing and evaluating the accuracies of an AVL system and supporting digital maps. The AVL system analyzed in this project was the Continuous Positioning System (CPS) by Anrew Corporation. Digital mapping products evaluated were TIGER/LINE, NAVTECH and Digital Orthophotos. The above data sets were evaluated with an accurate network of control points measured by Global Positioning System (GPS). Following the analysis of this study, some recommendations on the appropriateness of the tested AVL system and NJT's digital mapping data were made.

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1. Andrew Corporation for the use of their CPS equipment and CPS/GPS data output.
2. Navigation Technologies Inc. for the Navtech Navigable Map Database.
3. Leica GeoSystems (in particular Mr. John White) for providing the MX8600-RT GPS receiver for measuring the GPS control points.
4. NJ Department of Environmental Protection (Mr. Larry Thorton) for providing Digital Orthophotos.
5. NJ TRANSIT Bus Operations, for use of a commuter bus and related operating support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DIGITAL MAP REQUIREMENTS FOR AUTOMATIC VEHICLE LOCATION

1.0 INTRODUCTION

Automated Vehicle Locator (AVL) is a technology that enables a fleet operator to track and monitor the location of its vehicles at any given time. It is being used mainly in Transit and in commercial vehicle operation (management) systems. In Transit applications, the information on the exact location of a vehicle enables the operator to provide more accurate information to its customer. Furthermore, knowing the exact location of the buses enables speedy reaction to operation related problems.

Most AVL systems provide location information in terms of coordinates (latitude and longitude or northing and easting). These coordinates have to be matchable with coordinates on a map so that the location of the vehicle can be uniquely identified. In order for the matching process to be successful, the coordinate systems of the map and those of the AVL system must be consistent, compatible and sufficiently accurate. The accuracy requirement is such that the AVL location should correspond to a unique and unambiguous point on the map. For many AVL applications, where the various stops or destinations of the vehicle are spread out over a large area this matching process can be achieved with rather moderate accuracies of the AVL and the digital map systems. However, in a Transit application that operates in densely built urban and suburban areas with frequent bus and traffic control stops, the accuracy requirement from these systems could be much more stringent.

In an urban area the AVL system may also have location tracking problems especially if the system is based on the Global Positioning System (GPS) technology. Building canyons and overpasses can block some or all satellite signals. Interference from wireless and radio communications as well as reflections of the GPS signal from buildings and other reflective surfaces make the utilization of GPS problematic at best. Many AVL systems use additional positioning systems such as Dead Reckoning and map matching techniques to maintain the location of a vehicle where GPS fails. The actual accuracy of AVL systems under these conditions (which for example, exists in downtown Newark) is yet to be evaluated.

The digital map or the Geographic Information System (GIS) on which the location of the vehicle is to be displayed contains information about bus routes and other relevant facilities such as bus stops, intersections, landmarks etc. The position of these features must be sufficiently accurate so that if the AVL system indicates that the bus arrived at a bus stop, that bus stop could be clearly identified on the map (GIS). Incompatibility of as little as a fraction of a street block could result in matching or snapping problems. A stop for a red light at an intersection could mistakenly interpreted as a bus stop or one bus stop could be misidentified as being another nearby bus stop.

To ensure the successful implementation of an AVL system at NJT, the following research objectives have been set:

1. Develop a testing and evaluation strategy.

2. Evaluate the capabilities of AVL systems under the special operational conditions of NJT.

3. Evaluate current mapping accuracies at NJT and their appropriateness for AVL.

Testing the accuracy of positional data of a map, GIS or an AVL system involves three main tasks. The first is to select representative test areas from which the performance of the entire system could be assessed. The second task is to create a realistic operational environment of the bus during data collection. Included in this task is to operate the bus under real-world circumstances. The third task is to establish a set of "control points" with highly accurate positions to which the observed locations from the AVL system and the digital map could be compared.

2.0 DESCRIPTION OF EQUIPMENT USED IN THIS PROJECT

2.1 GPS Equipment For Position Determination Of The Control Points.

The Leica MX-8600-RT GPS receiver was used to accurately locate the selected bus stops. The MX 8600 receiver is a GPS/GIS data collection device with a wide variety of applications. These include Utility Mapping and Metering, Municipal Road and Sign Mapping, Resource Mapping, Land Management, Environmental Mapping and more. The MX 8600 offers a full day's data collection capacity and several data collection modes: points, lines, and areas. Data collection is continually monitored by the data collection computer ensuring high quality data capture even by operators with limited GPS experience. Data can be collected in real-time differential mode or corrected differentially by post processing for accuracy in the 1 - 5 m range.

The MX-8600-RT package is the real-time option for the MX-8600 series of receivers. It enables real-time differential operation mode with the extensive Coast Guard DGPS beacon. This feature eliminates the need for post processing, as well as provides the security of knowing that collected points are differentially corrected.

<u>Features of the MX-8600</u>

1. Tracking: L1 frequency C/A code (SPS) 6-channel continuous tracking
2. Sensitivity: -143 dBm Costas threshold
3. Accuracy: Without SA: 15CEP
4. With SA: 40m CEP
5. Code Differential: 2m CEP
6. Carrier Phase Differential*: 10 - 30 cm
7. Update Rate: 1/sec.
8. Data Ports: Two 9-pin RS-232 serial ports. Built-in KERMIT file transfer protocol
9. Power: Internal rechargeable (removable) battery for the computer.

10. GPS battery
11. Operating Temperature: -40° C to +54° C
12. Storage Temperature: -20° C to +45° C
13. Humidity Completely waterproof
14. Dimensions: 12.35" x 4.06" x 2.3"
15. Weight: 3 lbs.

Additional features of the MX-8600-RT

1. Beacon Receiver
2. Backpack
3. Combined GPS/DGPS Beacon Antenna
4. Cabling Battery and Charger

Figure 1 The Leica MX-8600-RT

2.2 The Continuous Positioning System (Cps)

The CPS is a land navigation system for fleet vehicle position location. It was designed to operate under diverse conditions including urban area applications where GPS positioning may fail. The CPS is built around a gyroscope to measure the vehicle azimuth change and the odometer to measure distance traveled. These two parameters constitute the required dead reckoning sensors. If the sensors were perfectly calibrated, and the initial geographic position and azimuth of the vehicle known, then the position and azimuth of the vehicle could be determined at any future time. However, even inertial grade gyroscopes accumulate angular errors with time due to bias and scale factor errors; the odometer scale factor cannot be calibrated to better than a fraction of a percent and changes slowly with time and tire pressure, and with vehicle speed. During a long drive, the dead-reckoned position would increasingly diverge from the actual position. Therefore, the system is complemented by a GPS and/or DGPS component to increase the accuracy of location determination. A block diagram of the CPS system is given in figure 2, and the unit is shown in figure 3.

The simplest approach to AVL is to use the GPS data when it is present, and switch to dead reckoning when the GPS signal is lost. However, GPS is subject to many errors from noise-like small errors to multipath that can sporadically lead to irregular, large and unexpected position errors. To avoid relying on erroneous GPS locations when large errors are present, it is necessary to aid the GPS positioning with a dead reckoned position to act as a data pre-filter. The CPS uses a Kalman filtering method to filter out jumps and inconsistent GPS positioning observations. Simply put, the algorithm estimates the present values of system descriptors (the "state variables") based on the last measurement, the previous values of the state variables, and the estimated accuracy of the state variables and sensor data. Without undertaking a mathematical exposition, one might describe the action of a Kalman filter as corresponding to our intuitive notions of how one should combine measurements:

a. If the variable estimate has large uncertainty, but the measurement is good, then the measurement is weighted heavily

b. If the variable estimate has a small uncertainty, and the measurement is bad, the measurement is lightly weighted

c. The better the measurement, the larger the reduction in variable estimate uncertainty, following incorporation of the measurement in the variable estimate

d. Between measurements, the larger the statistical uncertainty in the system parameters, the more rapidly the variable estimate uncertainty increases.

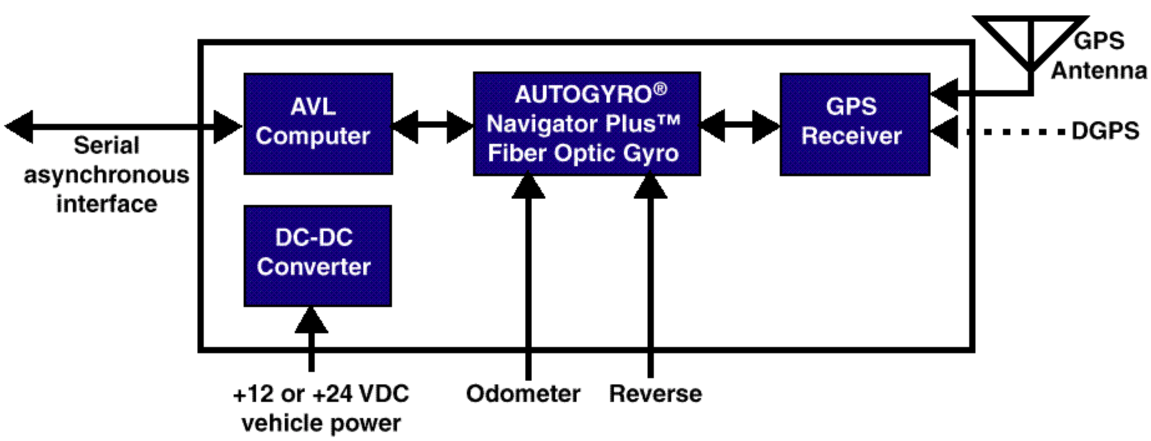

Figure 2. Continuous Positioning System (CPS) block diagram

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The choice of the state variables (such as latitude and longitude) depends on an analysis of the sensor characteristics and error models, as well as the model adopted for the equations of motion of the vehicle.

The dead reckoning sensors provide continuous data, while the GPS solution may be absent for significant periods of time. During the time that GPS data is present, the dead reckoning sensors must be calibrated well enough that vehicle location solution can be "propagated" (projected forward) with acceptable accuracy during times when the GPS signal is lost or distorted.

Except for the vehicle speed sensor (odometer) and GPS antenna, the system is housed in a single enclosure that contains the fiber optic gyroscope, GPS receiver, and navigation computer. The system specifications are given in Table 1 and the complete system is shown in Figure 3.

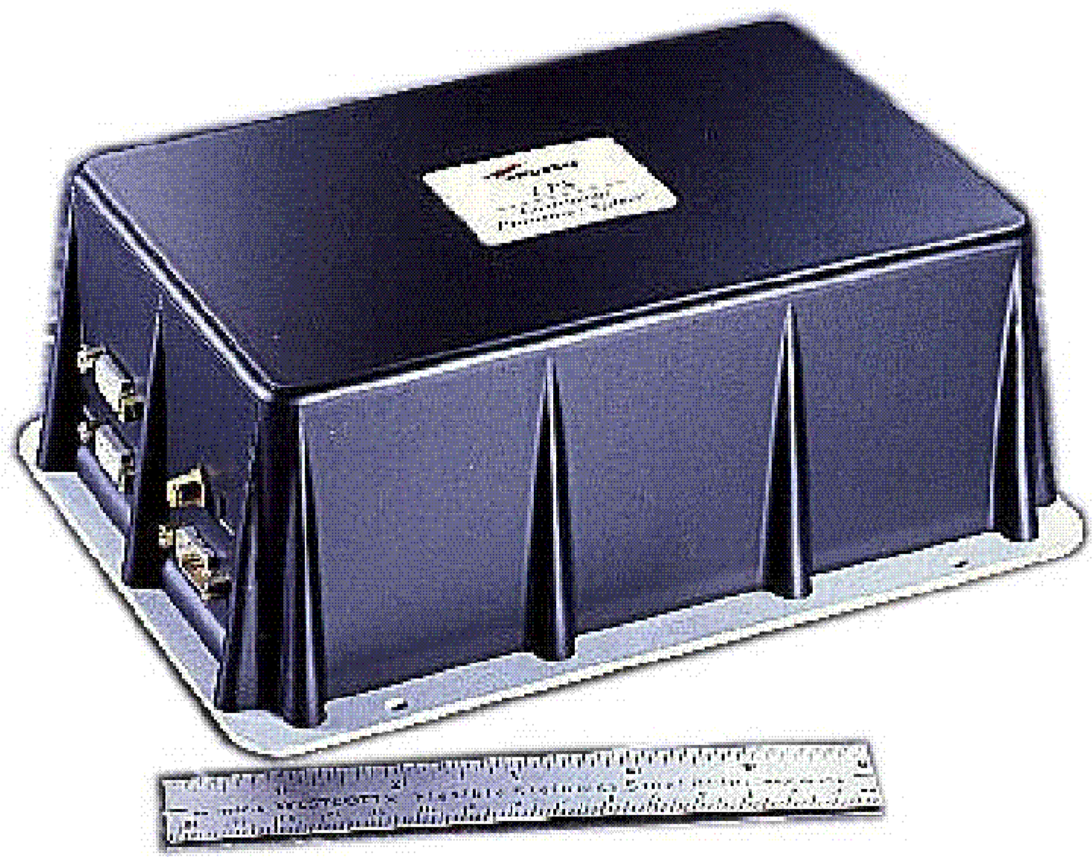

Figure 3. The CPS equipment enclosure

Characteristic	Specification
Physical Dimensions (mm)	152 x 210 x 76
Weight (kg)	0.9

Power	12 watts, +12 or +24 unconditioned vehicle power
Communications interface	RS-232 (typical), NMEA 0183data protocol
Positioning Accuracy (m, 1σ) without DGPS	20

Table 1. Continuous Positioning System Characteristics

3.0 DESIGNING AN AVL / DIGITAL MAPPING SYSTEM EVALUATION

Probably the most important aspect of designing an evaluation study is, to establish a test bed which simulate real-world conditions. The test has to be conducted under the same conditions that the system will be used on a daily basis. For this study it means that the AVL is to be tested while mounted on a bus operating under typical service conditions. Additionally, the bus route should be representative of the environmental characteristics in which the system is to be used. Hence, a special effort was made to ensure that this study is in compliance with the above principle.

The AVL system was mounted on a fully equipped bus which includes radio communication and other electronic devices emitting electromagnetic energy. The objective of this setup was to test whether the electromagnetic field generated by these devices had an adverse impact on the accuracy of the AVL system. Electromagnetic interference was a concern especially with regard to GPS that may become vulnerable to the increase in signal noise. The bus that participated in this study simulated a routine passenger pick-up and drop-off service during the testing. These circumstances provided a better idea of how the system will perform on a regular basis. Some of the routes were measured only once while others were repeated to allow consistency and repeatability analysis of the system.

Digital map data for an AVL application must be continuous and consistent throughout the entire transit system area. Assembling a digital map from different sources may result in an inconsistent map with incompatible and unmatched street segments. Such a digital map is not recommended for use for any application, not only AVL. In addition, to adhere to the real world testing philosophy of this study, the same mapping data used by NJ TRANSIT to store their bus stops information was evaluated here as well.

At the present the following spatial data sets are being used at NJ TRANSIT:

- 200 scale mapping of street centerlines developed by PSE&G. This dataset encompasses most of the PSE&G service area throughout New Jersey. It includes attribute information such as street names and TIGER/Line information.

- Navigation Technologies (Sunnyvale CA) Navigable Map Database. This dataset accurately depicts the graphical configuration of the roadway network and contains attribute information regarding the network. The dataset also includes railroad and hydrography information that appears to reference USGS 7 ½ ‘ Quadrangles.

The sources of the Navtech roadway network vary, ranging from independent photogrammetry to record municipal county, and state DOT mapping. The positional accuracy is not specifically documented, perhaps because of the multitude of contributing sources.

NJ TRANSIT staff has chosen Navtech as a land base for geocoding NJ TRANSIT bus routes.

- NJ TRANSIT staff is currently mapping bus stops using mapping grade GPS equipment (Trimble PRO XR) to 1-5 meter accuracy.

Bus stops are associated with bus routes through a non-graphic relational database. NJ TRANSIT staff is currently implementing a method of associating stops with bus routes to enable cartographic display of the stops as a milestone station along the route. Unlike bus stops where the spatial attributes are referenced from Navtech, the GPS coordinates captured from each stop serve as the spatial attribute stored in the NJ TRANSIT database.

Based on the above, the Navtech data set was used in this study. While the TIGER/Line data was examined in this study, the result of this evaluation had no bearing on AVL or other spatial data applications at NJ TRANSIT. NJ TRANSIT has established long before this study was undertaken that TIGER/Line data are not appropriate for supporting AVL due to both positional and connectivity accuracy issues.

Another aspect of evaluating digital maps is the completeness and accuracy of the attribute information. The combined AVL/GIS systems could have problems working together not only because of spatial inaccuracy but also because of incompleteness of information. This means that the GIS has to be reviewed to determine whether it contains all the necessary information and whether this information is recorded correctly. It has to be checked for data omission and data commission. Data omission occurs when important features that exist in the real world are not represented in the database. Data commission occurs when erroneous features are in the database but do not exist in the real world. Thus, it is necessary to examine the database for its content accuracy.

It is the intent of this study to compare the consistency of the spatial attributes compiled for bus stops (GPS coordinates) and the Navtech roadway network. In addition, the Navtech network will be examined for its accurate representations (data omissions and data commissions) with existing street configurations that are encountered in an AVL application. This comparison will be used as a benchmark for emerging efforts within NJ TRANSIT to develop AVL application based on these sources.

The following table summarizes the different tasks that were performed under this study:

TASK	**Description**
A	Select Routes for AVL (and GIS) testing.

B Select features (bus stops, intersections and landmarks) along these routes as test points.

C Measure the selected test points with independent GPS receivers (not associated with AVL).

D Data processing of the GPS control survey.

E Prepare a map (indicating features to be positioned and their locations) to be used during AVL testing.

F Coordinate bus availability and installing the AVL system on it

G Perform AVL positioning along the selected routes.

H Analyze and compare data from AVL and GIS with the GPS based "control data".

I Report on findings

3.1 Selecting Routes For AVL (And GIS) Testing

Selecting test areas for evaluating the AVL system implies that the operating conditions of NJT should be divided into several categories. Each category represents a different degree of difficulty for the AVL system. A densely built urban area with high-rise buildings, tunnels, overpasses and other obstructions (e.g. downtown Newark near Penn Station) may present serious operational problems for any AVL system. Since many of the bus routes operated by NJT converge at or originate from locations with such surroundings the system must be tested under these conditions. At the other extreme of operating conditions are routes in rural areas with no obstructions or surroundings that could pose difficulties to the AVL positioning sensors. Between these two extreme operating conditions, there are additional categories with varying degrees of difficulties that must be tested as well. A proposed ranking of operating conditions to be tested is:

Rank	Operating environment
a.	Underground and completely enclosed areas.
b.	Urban areas with adjacent building heights exceeding 4 stories.
c.	Suburban and open areas with adjacent building heights less than 4 stories.

There are two approaches for selecting testing routes. The first is to select a few routes that operate entirely under one or two of the above conditions. An example of such a route is the Air-Link line between Penn Station and Newark International Airport. This route operates mostly under the condition of category ‘b’. The second approach for selecting test routes is to select routes that operate under varying conditions which include all of these categories (for example, a route that originates at category ‘a’ and terminates at category ‘c’). The latter approach is preferable since the same AVL setup on the same vehicle could provide a better indication of the accuracy of the AVL system where the only element that changes is the environmental characteristic of the area. In this study both approaches were adopted. First a route that encompassed all the above listed environments was selected, followed by a small test in the city of Newark that was made up of mainly category ‘b’. Therefore, this study constituted a complete AVL/GIS test.

3.2 Selecting Control Along The Tested Routes

A total of 32 points were selected as control points. All of these points are at actual bus stops along the tested routes. Points 1-20 are in the suburbs and represent category "c". Points 31-42 are located in the city of Newark and represent categories "a" and "b". Some of these points were selected during a reconnaissance trip that took place prior to the actual bus run while others were selected during the testing. Each point was photographed during the actual data collection (bus run) to ensure that the same point is surveyed later with GPS. The pictures of the bus and the control points are shown in Appendix A. Table 2 lists the location and the ranking of the control points.

Point	Rank	Location
1*	c	N. Broad St. and ridgeway, Hillside
2*	c	Westfield Ave. and Elmora Ave., Elizabeth
3*	c	Chestnut St. and Westfield Ave., Roselle Park
4	c	Aiden St. and Route 28, Cranford
5*	c	Elm St. and North Ave., Westfield (west bound)
6*	c	N. Martine Ave. and Midway Ave., Fanwood
7*	c	Wiley Ave., and E. Front St., Scotch Plains
8*	c	West End Ave. and W. Front St., Plainfield (west bound)
9*	c	Jackson Ave, and North Ave., Dunellen (west bound)
10*	c	S. Washington Ave. and North Ave., Dunellen
11	c	Jackson Ave, and North Ave., Dunellen (east bound)
12	c	West End Ave. and W. Front St., Plainfield (east bound)
13*	c	Central Ave. and W. 2nd St., Plainfield
14*	c	Watchung Ave. and E. 5th St., Plainfield

15*	c	Elm St. and North Ave., Westfield (east bound)
16*	c	Cranford Train Station
17*	c	Cestnut St. and W. Grant Ave., Roselle Park
18*	c	Cestnut St. and W. Lincoln Ave., Roselle Park
19	c	Marshall Ave. and Salem Road, Roselle Park
20*	c	Bloy St. and Princeton Ave., Hillside
31*	a	Raymond Plaza W. and Raymond Blvd., Newark (Penn station)
32*	b	Washington St. and Raymond Blvd., Newark
33*	c	Lock St. and New St., Newark (NJIT)
34*	b	Dr. Martin Luther King Blvd. and New St., Newark (NJIT)
36*	c	Washington St. and Hill St., Newark
37	b	Broad St. and Market St., Newark
40*	b	Commerce Ct. and Commerce St., Newark
42*	c	Broad St. and Court St., Newark

Table 2. The location and the ranking of the control points. (*) Indicate "Marked Points"

All bus stops and additional features such as intersections and landmarks along the selected routes were recorded by the AVL system as farther checkpoints. Unfortunately, these points were not saved properly as a result of a setup error of the AVL software. Andrew staff re-created this data, in part, from the CPS observation files in a post processing effort. The checkpoints file was re-constructed by selecting all the observation in the CPS files that had zero velocity (i.e. the bus was in stop state). These selected points are named, henceforth, as "Marked Points".

3.21 Digital Orthophoto Quarter Quad (DOQQ).

GPS control points provided means for evaluating the CPS, GPS, Marked Points, Navtech and TIGER/Line data at specific points. But it was necessary to find an additional accurate data source that could provide a continuous reference check for these tested data sets. It was found that digital quarter quad orthophotos (DOQQ) compiled by the USGS are suitable for this purpose. The field measured location of all GPS control points matched exactly the corresponding points on the orthophotos. Therefore, it was decided to use DOQQs as a basis for evaluating the tested data sets.

Understanding the sources of errors in an orthophoto can support the validity of this decision. Positional errors in an orthophoto stem from either the photo orientation process or from an inaccurate digital elevation model (DEM). Photo orientation errors cause every point (pixel) on the orthophoto to be displaced. If the used orthophotos had an orientation problem then the GPS control points would have been displaced. Thus, the location of the GPS control would have not matched the image of these points on the orthophoto. The same argument is true with regard to DEM errors. Since the test area was rather flat with very moderate changes in elevations, it is very unlikely that the orthophoto had local inaccuracy anomalies. If the digital elevation model was inaccurate then large segments of street images should have been displaced. This was not found to be the case in the used DOQQs.

Seven DOQQs from Essex, Middlesex and Union Counties of New Jersey were used in this project. They were made available to the study and geocoded by the New Jersey Department of Environmental Protection. The orthophoto codes and corresponding names that were used in this study were:

Code	Name		Code	Name
0504	Chatham SE		0523	Elizabeth SW
0512	Roselle NE		0521	Elizabeth NW
0513	Roselle SW		0522	Elizabeth NE
0514	Roselle SE			

The locations of these othophotos are shown in figure 4. Two additional DOQQs - 0611 (Plainfield NW) and 0612 (Plainfield NE)- were provided by NJT but not used due to image formatting incompatibility.

3.3 Control Point Measurements With GPS

The selected control points were measured with the Leica MX-8600-RT GPS receiver. The GPS campaign was carried out in the winter of 1998 to avert GPS signal weakening or blockage stemming from the presence of dense foliage. Each point was visited at least three times on different dates. The reason for the multiple visits was to increase the statistical reliability of the positions for these points. All measurements were made with real-time differential correction. The real-time DGPS status was verified in the field (the presence of an indicator on the receiver that a correction is being applied) as well as in the office when the data was processed. Each point was observed for at least 15 minutes per visit. The receiver was set to an averaging mode with a 5 second sampling rate. Thus, the computed coordinate for each visit was based on the average of at least 180 (12x15) position observations. The minimum PDOP (an indicator of the satellite constellation geometry) was set to a maximum of 6. If, at any point, the above minimum standard was not met, additional visits were made to these points.

Points 32 and 37 that are located in the city of Newark were problematic in this GPS survey. At point 32 a maximum of 4 satellites could be observed at any given time because of obstruction in the vicinity of that point. As a result of the above circumstance, poor (high number) PDOP was observed. For similar reasons differential correction at point 37 was successfully achieved only once. Nevertheless, the positional accuracy of these points was at least twice better than the 30 feet (10 m) error tolerance used in this study.

The results of the GPS control survey are presented in table 3. σ_N and σ_E are the standard deviations in Northing and Easting respectively. The PDOP is a GPS related indicator of satellite geometry that is used for evaluating the expected positioning accuracy. The lower PDOP value the better with a PDOP of less than 6 being considered as good quality. The complete set of measurements of the GPS survey is included in appendix B.

Station Number	Average Northing (m)	Average Easting (m)	σ_N	σ_E	Number of Satellite	PDOP
1	206719.3979	174007.4117	2.0965	0.8999	4.7500	3.3250
2	203462.2960	172441.6537	2.4803	2.0004	6.0000	2.3000
3	203019.3883	169979.5638	1.8368	3.4931	5.3333	2.9167
4	202416.8885	166705.1852	1.5403	1.1359	6.0000	3.1286
5	201728.6632	162886.3499	1.2692	1.0849	4.4286	1.6571
6	201131.3838	159256.0122	2.0852	2.0004	4.6667	3.8667
7	200850.9259	157926.5870	2.9090	0.7590	5.0000	5.2000
8	197149.9675	155383.5425	1.2748	0.4781	5.8333	2.8833
9	195408.6299	153329.7271	0.8947	0.7009	6.0000	2.6000
10	195262.9619	153268.4494	0.5669	1.3637	6.0000	2.6000
11	195382.7777	153316.8073	0.5585	0.8196	6.0000	2.6000
12	197213.9204	155446.6095	1.1723	2.8320	4.3333	3.1833
13	197917.4046	156351.1404	1.4521	1.9105	6.0000	2.7000
14	198141.4970	156996.0486	3.4209	5.7022	5.4000	3.1000
15	201719.4992	162898.5849	1.0403	1.5820	4.8333	1.9000

16	202346.9638	166663.6848	0.5627	1.6612	6.0000	3.7800
17	203308.8095	169907.8721	4.1567	4.4112	6.0000	2.6000
18	203699.7830	169834.9896	3.1019	1.6216	6.0000	3.1167
19	204700.6924	169765.4327	1.6330	3.7376	6.0000	3.2222
20	206893.8332	172166.1519	2.3297	0.9276	5.3750	3.6625
31	211223.8445	178400.5090	0.4880	0.4319	5.0000	2.4333
32	211546.4914	177570.9084	2.8790	4.2193	4.0000	10.8333
33	212034.4449	176949.1054	0.5947	0.3728	6.0000	2.4000
34	211978.4159	177315.6559	0.2845	0.9981	6.0000	3.3667
36	210866.3905	177274.9378	0.1077	0.4062	6.0000	2.9000
37	211229.1525	177699.9568	0.0000	0.0000	6.0000	2.9000
40	211375.2171	177836.2395	0.1428	3.1847	5.0000	6.6000
42	210723.4471	177447.5227	0.1326	0.4972	5.0000	4.4000

Table 3. The results of the GPS control survey. The units are in meters.

From the above table one can see that in most cases the accuracy of the GPS control points was around 2m (~6 ft) or better. Since the error tolerance used in this study was 10m (~30 ft) these points could be considered as error free in comparison to the tested data sets.

A detailed journal of the experiences encountered during the two days operational testing of the CPS on August 18 and 19, 1997 are given in appendix C. The journal could be used to explain some of the AVL positioning accuracy problems that were found in this study. The journal also demonstrates the implementation difficulties of a real-world AVL system.

4.0 DATA ANALYSIS

As mentioned earlier, the study area was mainly based on the bus route between Dunellen, New Jersey, and the Port Authority bus terminal (PABT) in New York City (Manhattan). This route encompasses many of the operational environment categories that were defined earlier. The PABT is a roofed parking deck adjacent to the Lincoln Tunnel and therefore falls into category ‘a’. The first clear sky is not visible until after the exit from the Lincoln tunnel in New Jersey.

The rest of the route passes through suburban communities with varying degrees of built up, dense tree covered and open areas. Routes 1-5 follow portions of NJT #113 while route 6 follows closely NJT #40. An additional short bus route in the city of Newark was tested as well. Since many of the NJT bus routes originate or terminate in Newark's Penn Station the conditions around this facility were important for this study.

The selected routes and the dates in which data recording was conducted are shown in table 4 and figures 4, 5 and 6. In figure 5, a single route (PABT to Denellen) represents Routes 3 and 4 of table 4. The reason for presenting two separate routes (PABT to Cranford and Cranford to Dunellen) in table 4 is because the data for these segments was originally stored in two separate files. An equipment malfunctioning caused the system to stop collecting data in Cranford. The CPS was then reinitialized and the route was completed in Dunellen as planned.

Route	Origin	Destination	Date	Bound
1	Iron Bound, Newark, NJ	Dunellen, NJ	8/18	West
2	Dunellen, NJ	Iron Bound, Newark, NJ	8/18	East
3	PABT, NYC	Cranford, NJ	8/19	West
4	Cranford, NJ	Dunellen, NJ	8/19	West
5	Dunellen, NJ	PABT, NYC	8/19	East
6	PABT, NYC	Iron Bound, Newark, NJ	8/19	city

Table 4. Bus routes on which the AVL system was tested.

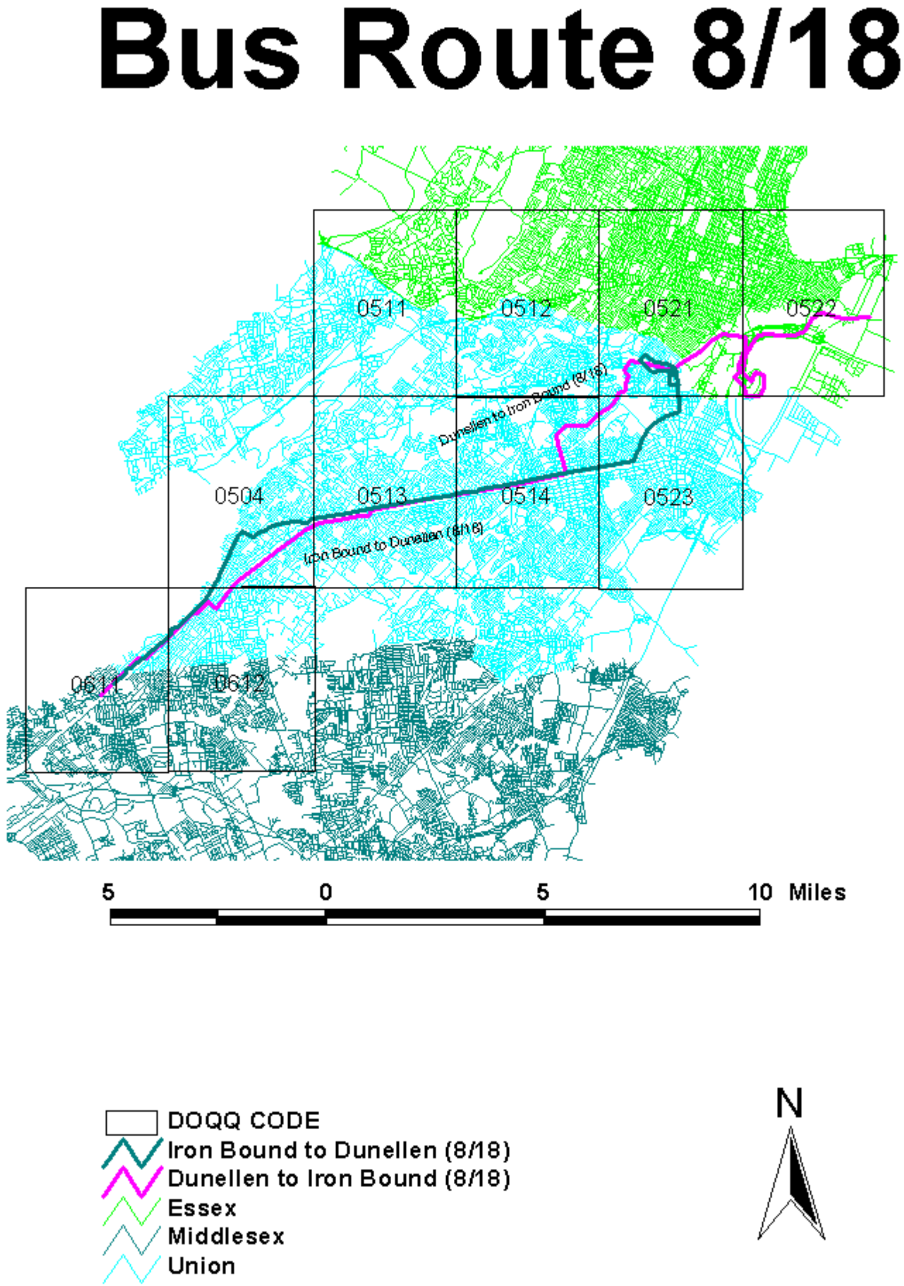

Figure 4. Bus Route of August 18

Bus Route 8/19

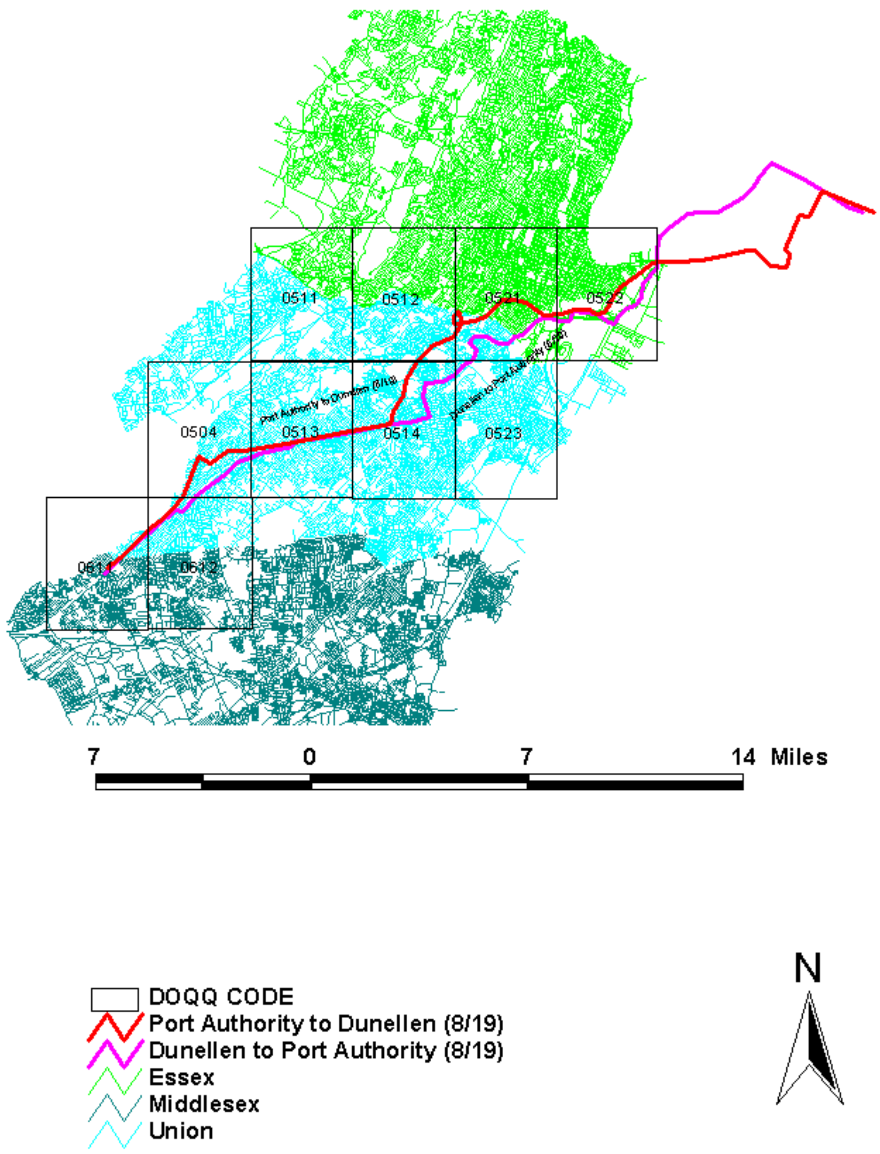

Figure 5. Bus Route of August 19

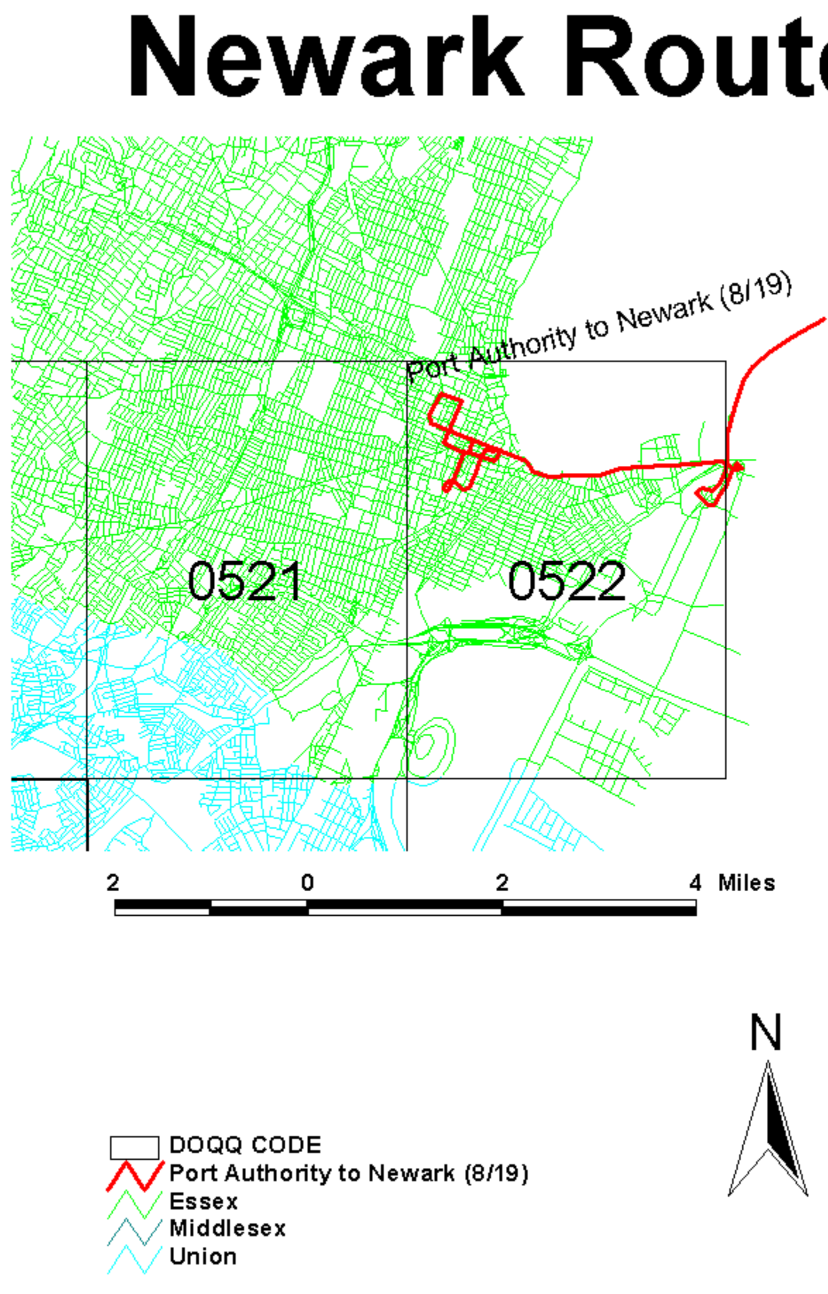

Figure 6. Newark Bus Route of August 19

4.01 Route Name Convention

Each route produced at least two data files. One file contained the CPS positions of the bus while the other consisted of GPS positions only. Additional data files on all the bus stops along these routes were recorded during the bus runs. Unfortunately, as mentioned earlier they were recorded in an unusable fashion. To make it easier to identify the files and associate them with a traveled route, the following six character file-name convention was established.

Character	Meaning
1	Positioning device
2	Origin
3	2 (indication to…)
4	Destination
5, 6	Date

To illustrate this naming convention let's look at an example. The file containing the CPS data for the route from Iron Bound to Dunellen, that was run on August 19, was named "ci2d19".

In general:

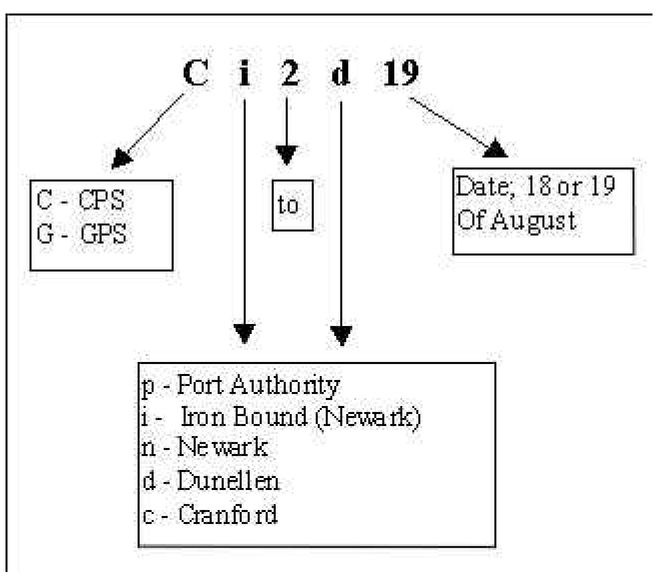

Figure 7. File name convention for CPS and GPS data

In addition, the files named Essex, Middlesex and Union refer to the TIGER/Line data and files that start with "t" are the Navtech digital map data.

4.02 Defining An Acceptable Error Tolerance.

Once the reference or the baseline data was established it was necessary to define an accepted minimum discrepancy between the reference data and the tested data. The acceptable discrepancy was subjectively set to 30 feet or about 10 meters for this study. The establishment of an error threshold can be determined only through an evaluation of an AVL device and its ability to snap to the nearest logical event location. The determination of an appropriate error tolerance would require an additional study.

The 30 feet conservative tolerance used for this study was adopted because it represents an average width of a street in the tested area. This tolerance allows a distinction between a stop at a traffic control (e.g. light) and a bus stop that are located on opposite sides of a street intersection. Location differences smaller than 30 feet were treated as correct and location differences larger than 30 feet were marked as error. When the locations differed by more than 30 feet (i.e. error), the actual distance error was recorded.

4.03 The Data Analysis Process

To facilitate the data analysis process a detailed street map of the entire routes was assembled. The street map was made of several sheets of street maps printed out from DeLorme's Map and Go software. Locations where errors were found were marked manually on these maps. In addition to the location of the error, the magnitude of the error was recorded as well.

The following AVL and GIS spatial data analysis were performed:

A. Visual inspection of disparities between the recorded CPS data and the reference data

B. Visual inspection of disparities between the recorded GPS data and the reference data.

C. Comparison between the locations of the GPS control data and the AVL data.

D. Comparison between the DOQQ and the TIGER/Line and NavTech street coverage data.

E. Comparison between two different runs of the same route, made on two different days. This was a consistency study or evaluation of the repeatability characteristics of the AVL system.

F. Examination of sites where the AVL system displayed irregular and significantly erroneous patterns of behavior.

4.04 Terms and Parameters Used in the Following Tables and Figures.

Many of the tables and figures in this chapter contain terms that require further clarification.

Understanding these terms will facilitate a better insight into the analysis presented in this report. The terms used in this report are:

Route Code – A code for identifying the analyzed bus route. An explanation of the code was presented in section 4.01.

Total Route Length – As the name indicated, this is the total distance traveled on the particular route. The unit of distance used for this parameter is feet rather than Miles, to make it consistent with the error measurements which was in feet.

Erroneous GPS [or CPS, Navtech, …] Length – The total length of all the segments along the route in which the evaluated data was more than 30-ft. off the reference data. For example, let's assume that the CPS location was off by more than 30-ft. along 2 street blocks. The linear distance along these 2 street blocks was measured to be 500 ft. long. Accordingly, an erroneous CPS length of 500 ft. was recorded. If additional errors were observed along other segments of the route, then the total sum of all of the error lengths were recorded under "Erroneous CPS Length" of that route.

Percentage of error – This value is computed from:

The *percentage of error* points out the relative amount of the entire route in which an error of more than 30-ft. (compared to the reference data) was observed. This parameter is used to assess the expected performance of the tested systems. That is, if the CPS performed correctly along 95% of the tested route one may rank its performance as 95% correct.

4.1 Comparison Between Recorded GPS Data And The Reference Data.

The first analysis presented here is a comparison between the recorded AVL's GPS data and the reference data.

Observations

It was observed that two tested routes showed higher error rates than others. The first route was the one of the city of Newark in which the GPS seemed to fail on about 45% of the time.

Another route that produced relatively inaccurate results was the one between Dunellen and the PABT, traveled on August 19. The percent of erroneous GPS positioning of route d2p19 was 8.51%. Most of the errors occur on the sections near Dunellen (Rt. 28) and North West to Newark airport (Rt. 22). A possible reason for this failure is poor GPS signal and lack of differential correction. The accuracy of GPS positioning without differential correction is relatively poor due to an intentional degradation of the GPS signal by the US department of defense (DOD). Table 5 and figure 8 summarize these findings.

Route Code	Total Route Length (ft)	Erroneous GPS length (ft)	Percent of GPS error

d2i18	135836	4280	3.15
i2d18	102127	2828	2.77
d2p19	130732	11130	8.51
p2d19	124892	2930	2.35
p2n19	33677	15301	45.43
Sum	527264	36469	6.92

Table 5. Positional error of GPS only.

From the above it can be seen that except for the two problematic routes mentioned above, GPS was more than 95% of the time within the reference location. If we exclude the Newark route from these statistics then the overall percent of erroneous GPS positioning drops to 4.29%.

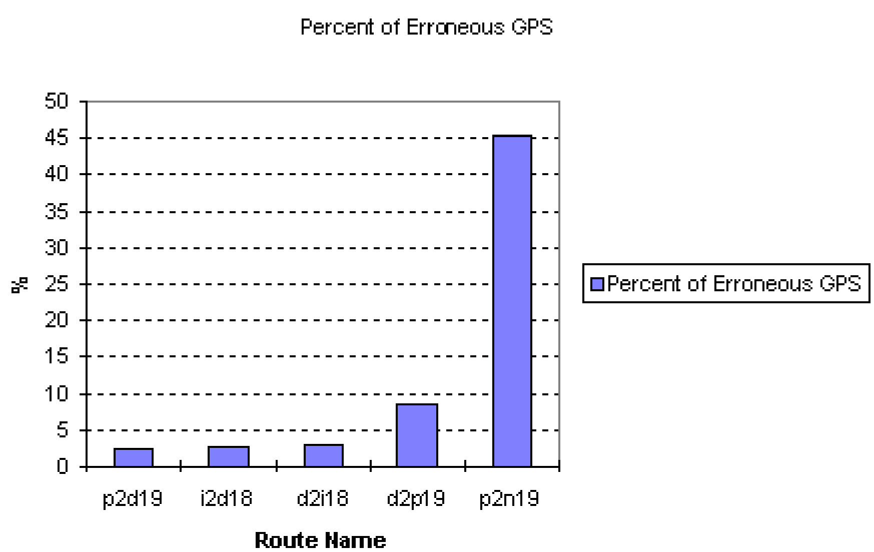

Figure 8. Positional errors of GPS only.

The distribution of the GPS errors excluding the data from the Newark route is shown in figure 9. The figure indicates that almost one half of the errors are less than 100 ft. long. The distribution of GPS data errors follow, in general, familiar statistics pattern in which large errors are less likely to occur than small ones. The seemingly increase in the percentage of errors of 150 feet or more is because it refers to a much wider class interval. If the 30-ft. interval was maintained (i.e. 150-180, 180-210, etc.) one could have seen a decrease in the percent of erroneous length as the distance increases.

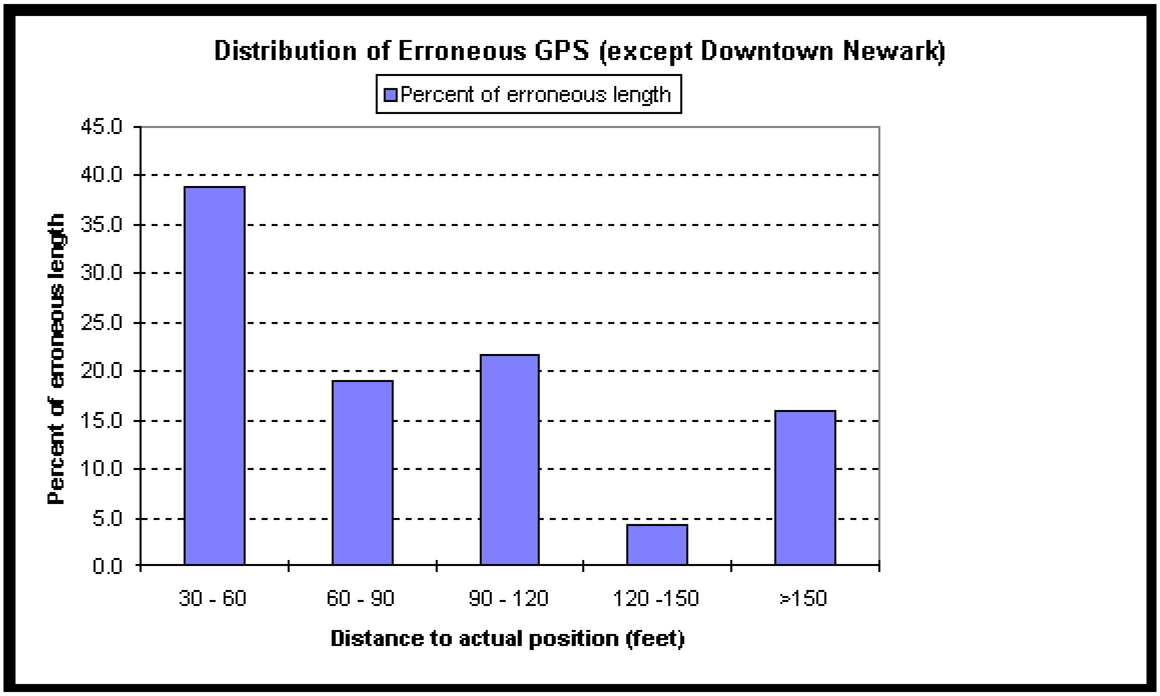

Figure 9. The distribution of GPS errors.

<u>Conclusions</u>

Overall, GPS was more than 95% of the time within the 30-ft. set tolerance. Poor performance was experienced in the city of Newark. This can be attributed to the dense urban environment of this route (categories 'a' and 'b'). As mentioned earlier, such an environment is hardly suitable for GPS positioning due to signal blockage and excessive signal reflections (multipath).

4.2 Comparison Between Recorded CPS Data And The Reference Data.

The next analysis is of the CPS data. It is important to mention here that positions computed by the CPS are based on data from both sensors, dead reckoning and GPS. While in most cases GPS assists the CPS in refining its position, it may also have in some occasions a negative effect. In locations where the GPS is erroneous, CPS positions may exhibit biases towards the erroneous GPS as a result of trying to adjust its positioning with the GPS input.

<u>Observations</u>

One of the most interesting results from the analysis of the CPS data was the performance of the system in the city of Newark. In the city of Newark the CPS system performed within the 30 feet error tolerance more than 96% of the time. A possible explanation for this outstanding performance by the CPS is that the length of the Newark route was relatively very short (less than a couple of miles). The CPS system, as other dead reckoning devices, performs relatively well at a short distance immediately after its initialization. It is only after some distance that it becomes more dependent on GPS data to correct accumulated odometer and gyro errors. That could be the reason why the inaccurate GPS data in Newark had practically no impact on the CPS results.

Overall the CPS performance was slightly better than 95%. As expected, most of the CPS errors were experienced at the origin of the routes. Only on one route, Iron Bound to Dunellen, the results were less than 90% accurate. No particular reason for this poor performance could be inferred from the data. The results of the CPS analysis are presented in table 6 and figure 10.

Route Code	Total Route Length (ft)	Erroneous GPS length (ft)	Percent of CPS error
d2i18	135836	5000	3.68
i2d18	102127	11130	10.90
d2p19	130732	6000	4.59
p2d19	124892	400	0.32
p2n19	33677	1200	3.56
Sum	527264	23730	4.50

Table 6. Positional error of CPS only.

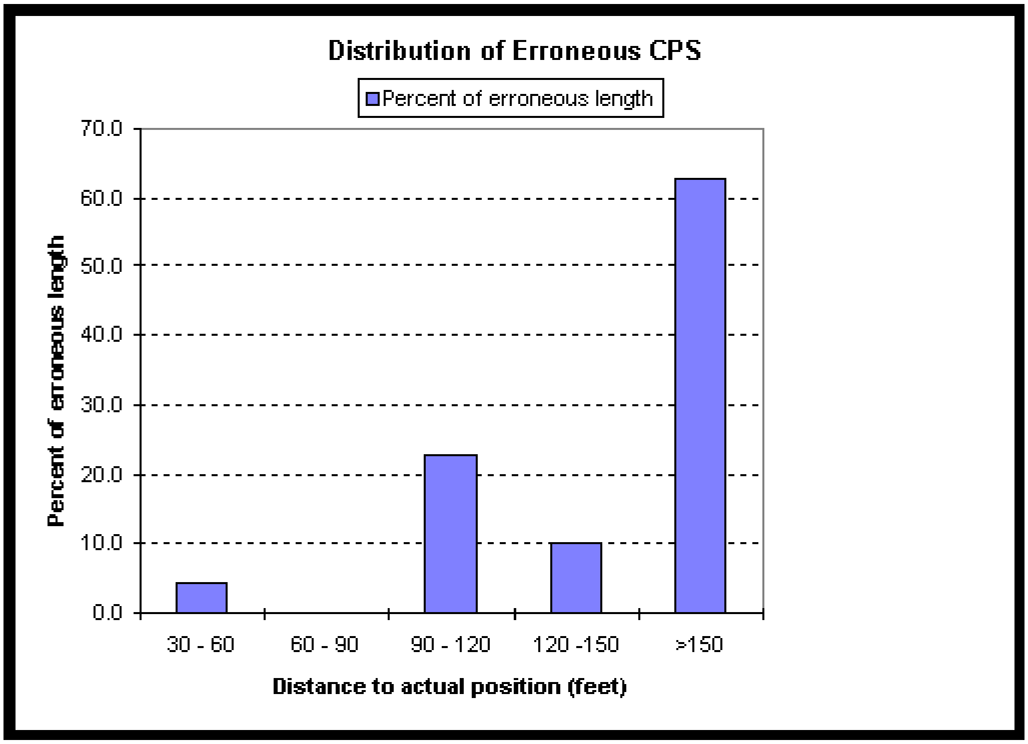

Figure 10. Positional error of CPS only.

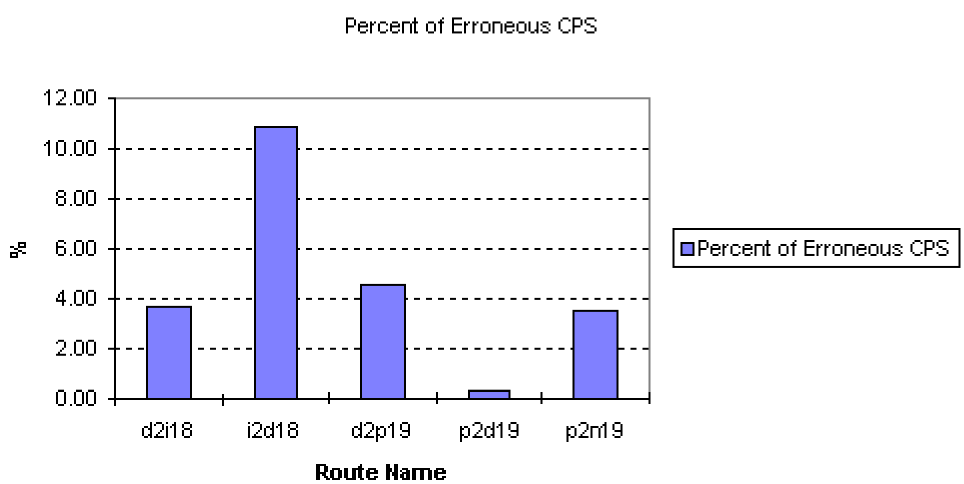

Figure 11. The distribution of CPS errors.

A combined comparison of CPS and GPS accuracies is shown in table 7 and in figure 12. It is interesting to note that if we are to exclude the Newark route, on the average the performance of GPS and CPS is practically the same. Both systems performed at around 95% correctly. However, while the average is the same, there appears to be no correlation between the magnitude of the error of each positioning system in specific routes. In other words, routes that had larger GPS errors (e.g. d2p19) did not necessarily have more CPS errors and visa versa (e.g.

i2d18).

	With	Newark	Without	Newark
Route Code	GPS Error (%)	CPS Error (%)	GPS Error (%)	CPS Error (%)
p2d19	2.35	0.32	2.35	0.32
i2d18	2.77	10.9	2.77	10.9
d2i18	3.15	3.68	3.15	3.68
d2p19	8.51	4.59	8.51	4.59
p2n19	45.43	3.56		
Average	12.44	4.61	4.20	4.87

Table 7. Combined CPS and GPS errors.

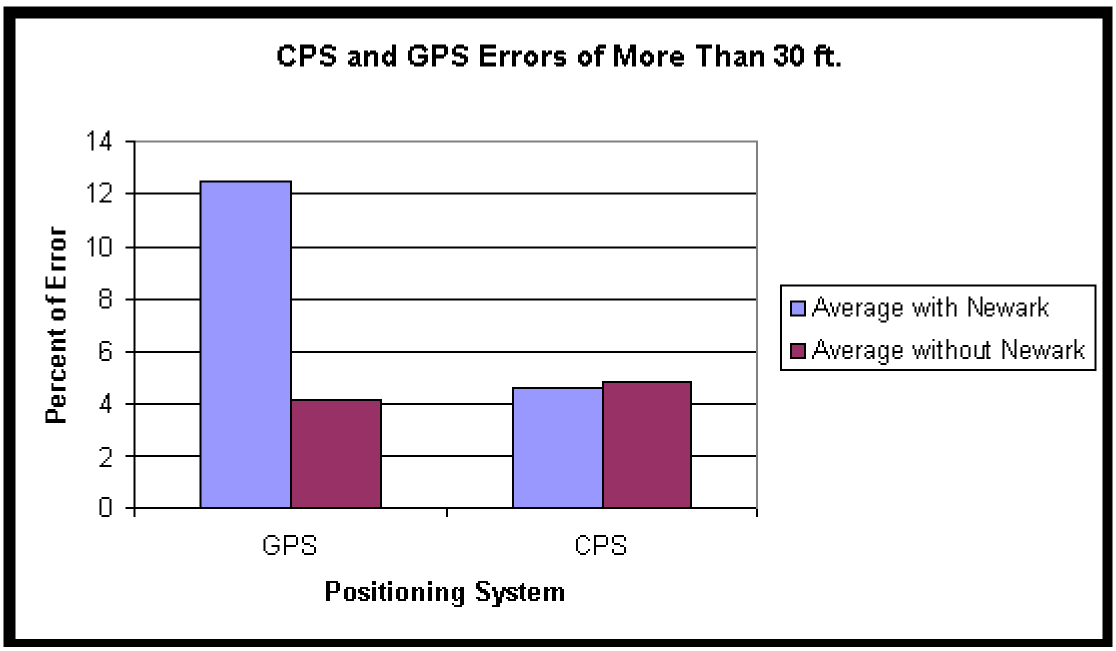

Figure 12. Combined CPS and GPS error

<u>Conclusions</u>

CPS performed at 95% on the average independent of the three operational environments defined in section 3.1 The performance of the CPS in Newark was impressive. Most of the 5% CPS errors observed in this study are relatively large (more than 150ft.). This may present a problem for Transit type AVL if not filtered or otherwise treated properly.

4.3 Comparison Between TIGER/Line And Navtech Data Sets, And The Reference Data

As mentioned earlier, the GPS control points exactly matched the digital orthophoto quarter quads of the tested area. This led us to a reasonable assumption that the DOQQs are correct for the entire tested area. Hence, the Navtech and TIGER/Line data sets were overlaid on the DOQQs and discrepancies between them was measured.

<u>Observations</u>

This analysis revealed that in about 96% of the time Navtech data is within the adopted 30-ft error tolerance. The average Navtech distance error (not in the entire routes but in the 4 % of erroneous segments) was about 56 feet. Almost all the errors fell inside the range of 30-60 feet. The predominant characteristic of the Navtech data errors was a parallel shift of streets or street segments with respect to the orthophoto. This looks like a coordinate shift error with no scale change, since the relative position of the streets seemed to be okay.

On the other hand, TIGER/Line data is erroneous in 66% of the tested area. The average distance error of TIGER/Line is 105 feet. The characteristics of TIGER/Line errors are more arbitrary than those of Navtech. TIGER/Line errors displayed coordinate shifts as well as variations in scale and orientation. The finding of this TIGER/Line data evaluation is presented in table 8.

Data Set	Erroneous length (ft)	Average distance Error (ft)	Percent of total length
Navtech	13168	56	4.02 %
TIGER/Line	215440	105	65.79 %

Table 8. The accuracy of the TIGER/Line and Navtech data sets

<u>Conclusions</u>

The decision made by NJ TRANSIT not to rely on TIGER/Line data for AVL and bus stop mapping applications was fond to be correct. TIGER/Line is not suitable for these applications. Conversely, aside from some isolated location, Navtech data was observed to be amply accurate for AVL application. However, a visual check of the Navtech dataset against DOQQs is advised to locate the few possible errors.

4.4 Accuracy Analysis With Respect To GPS Control Points.

The previous analyses were based on a visual inspection of bus route measurement with CPS and

GPS and their correspondence to the Digital Orthophoto Quarter Quads (DOQQ). During the visual inspection process, areas with apparent errors were marked and measured. Therefore, this was somewhat a subjective detect and measure error analysis.

In this section the AVL and digital mapping data sets were evaluated directly against the pre-selected GPS control points. This constitutes a more accurate evaluation model of the actual positional accuracy of the data. The only weakness of this evaluation model is that only a limited number of measured control points are being tested. Nevertheless, the 30 control points utilized in this study should provide a sound statistical foundation for our findings.

4.41 Comparison Between GPS Control Points And Digital Map Data (TIGER/Line And Navtech).

The first analysis to be presented is GPS control vs. TIGER/Line and Navtech data sets. All of the GPS control points except for points 10 and 16 were included in this analysis. Point 10 is a non-service bus stop in the back of a small shopping complex in Dunellen. It is the last point of the westbound Dunellen route that is used as a rest area and waiting point for the next scheduled eastbound departure for this route. Since this point is off the main street it was difficult to assess the location this control point with respect to the TIGER/Line and Navtech street network data. Point 16 is at an inner access road to Cranford train station and, similarly, it was difficult to directly relate its location to the main road. The measured distance from the main road to points 10 and 16 were 200 and 130 feet respectively for the more accurate Navtech data. These access roads are missing from both TIGER/Line (expected) and Navtech (unexpected) data sets. The results of this analysis are shown in table 9 and figure 13.

An apparent (and expected) conclusion from this analysis is that the TIGER/Line data is inadequate for applications where 30-ft. distance error tolerance is required. For more general application where larger error tolerances (such as 200 ft) are acceptable, TIGER/Line data may be considered.

GPS Point	Navtech	TIGER/Line		GPS Point	Navtech	TIGER/Line
1	46	187		15	9	9
2	60	10		17	25	200
3	37	60		18	20	171
4	36	36		19	3	42
5	18	38		20	36	260
6	26	67		31	65	186
7	11	103		32	65	182

8	14	57		33	20	199
9	30	141		34	11	224
11	4	104		36	29	95
12	21	70		37	39	219
13	51	136		40	13	75
14	22	140		42	45	134

Table 9. Distances between Navtech and TIGER/Line data sets, and GPS control points

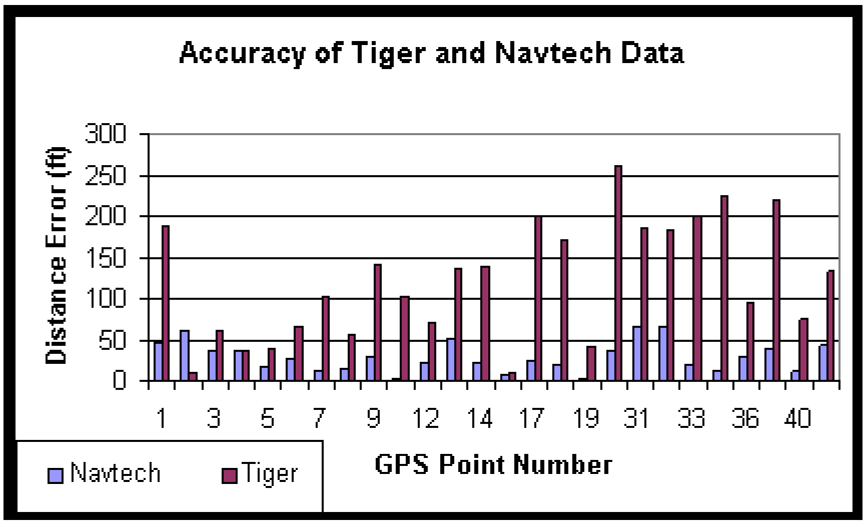

Figure 13. Distances between Navtech and TIGER/Line data sets, and GPS control points.

4.42 Comparison Between GPS Control Points And AVL Data (CPS And GPS).

Next the location of the GPS control points is compared to those obtained by the AVL system. As mentioned earlier, the accuracy of the CPS system on the August 18th run was rather poor. On the average the error on that date was 37 feet compared to 18 feet for the August 19th run. At points 7, 11, and 14 rather large errors of 189, 165 and 166 feet respectively were observed. The reasons for such large errors at these particular points are unclear. There is no apparent special environmental circumstance at these points that would bring about such an extraordinary increase in the error.

For GPS (AVL) data analysis, two different average errors were computed. The first computed average included all the control points even those that were located in the city of Newark. Since in the city of Newark the GPS (AVL) data had unusually large errors, this average was deemed as not representative of the performance of this system in a non-downtown environment. Consequently, another, Newark-less, average was computed. The Newark-less average GPS (AVL) error was found to be very small. In fact, our analysis indicates that if Newark data is excluded, GPS (AVL) positioning is as good as CPS or even slightly better. On the average the accuracy of both systems was about 18 feet.

The accuracy analysis of the AVL with respect to the GPS control points seems to exhibit better results than those observed during the comparison with the DOQQ. The accuracy improvement can be explained by the fact that the bus actually made a complete stop at these points for a couple of minutes. Thus, the system had more time and additional data to refine its position. The results of this analysis are shown in table 10 and figures 14, 15.

GPS Point	CPS 18 Error (ft)	GPS18 Error (ft)		GPS Point	CPS19 Error (ft)	GPS19 Error (ft)
1	0	36		4	0	0
2	23	0		6	26	36
3	0	0		7	22	22
4	0	0		8	10	85
5	18	0		9	23	18
6	68	26		11	27	27
7	189	0		12	0	0
8	0	23		13	9	20
9	0	19		14	12	30
10	35	0		15	18	19
11	165	67		16	0	0
12	29	29		17	13	0
13	21	77		18	0	0
14	166	20		19	20	6
15	0	0		20	54	0

16	0	0		31	10	102
17	8	36		32	36	95
18	20	20		36	28	20
19	0	0		34	10	65
20	0	0		36	0	0
				37	17	40
Average	37	18		40	14	14
				42	65	46
				Average	18	28
				Aver 4-20		18

Table 10. The accuracy of CPS and GPS with respect to GPS control.

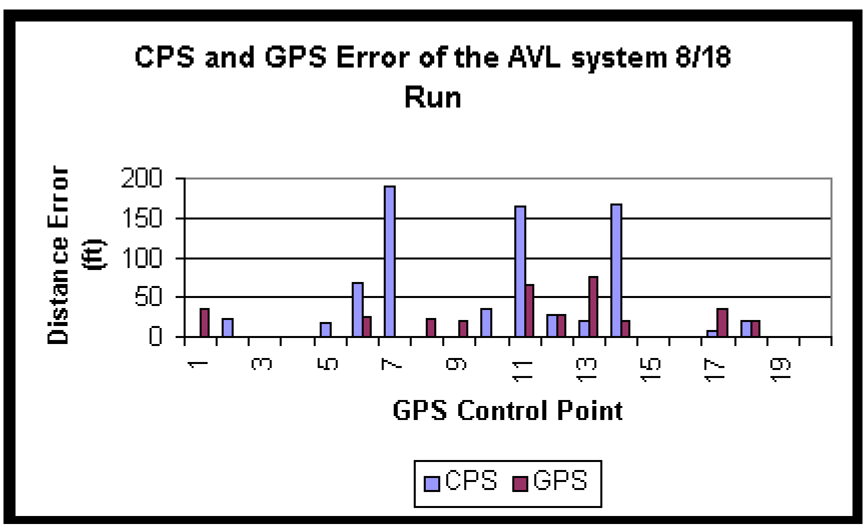

Figure 14. The accuracy of CPS and GPS with respect to GPS control (8/18 run).

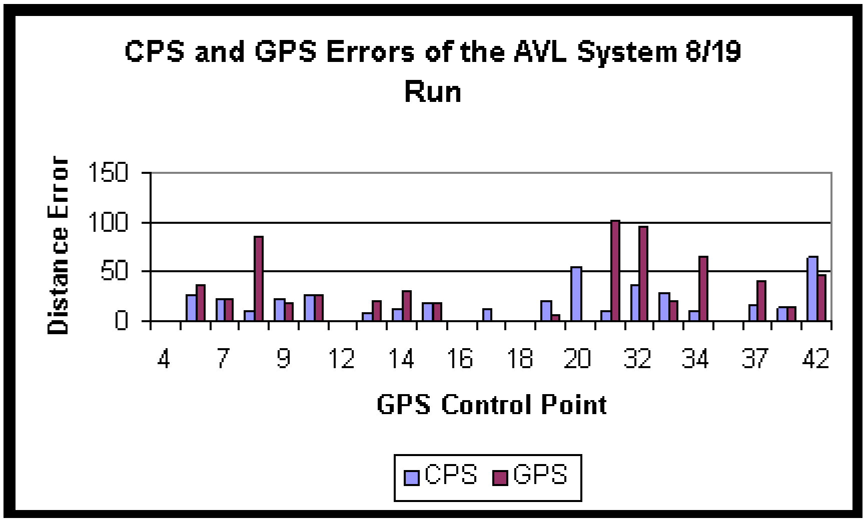

Figure 15. The accuracy of CPS and GPS with respect to GPS control (8/19 run).

4.5 Consistency (Repeatability) Analysis Of Two Runs Of The Same Route

The objective of this analysis was to measure the consistency with which the AVL system is able to reproduce the same position to the same point on different runs. This is an important characteristic of an AVL system since under similar conditions a reliable system is expected to produce the same positional values. This analysis could also provide an indication whether the incorrect locations observed by the system are environment or system related. In other words, if the same error occurred at the same location during different runs, it may mean that the cause for the error is not necessarily hardware/software related but perhaps due to external circumstances. In other words, the system is be expected to fail or succeed under similar environments. On the other hand, if the location of the errors is arbitrary (not location specific), then these errors could be indicative of the limitations of the AVL system. If the latter case were observed from the data, then one would expect to have similar types of errors under routine operations. Since in our test the same bus was used for both runs, it is unlikely that the specific bus setup contributed to the observed inconsistency.

The routes between Dunellen and Iron Bound were run twice on two different days. A comparison between the data from two runs showed that over 11% of the routes were inconsistent or differed from each other by more than 30 ft. The average distance error on the Iron Bound to Dunellen (the westbound route) was 113 feet and the average distance error on eastbound route (Dunellen to Iron Bound) was 173 feet. This is quite a significant deviation. It should be noted that there was no correlation between the location of the errors in these runs. Thus, these errors can be considered as a quality or performance characteristic of the systems. Table 11 summarizes the finding of this analysis.

Route	Total length of Inconsistency (ft)	Percent of total length	Average distance between 2 runs (ft)
Iron Bound – Dunellen	6670	11.31%	112.6
Dunellen - Iron Bound	11300	11.32%	172.8

Table 11. Consistency analysis of the AVL system.

4.6 Location Error CPS Marked Points With Respect to GPS Control

As mentioned earlier, additional bus stops and selected features such as intersections and landmarks along the selected routes were recorded with the AVL system as farther checkpoints. These points were not saved properly but were re-created in part by Andrew from the CPS observation files. The checkpoint file was re-constructed by selecting all the observation in the CPS files that had zero velocity. These selected points were named earlier in this report as Marked points. In this section the locations of the Marked points are compared to the location of the GPS control points.

Before presenting the results of this analysis it is necessary to make following disclaimer. Since the Marked point file was not created in the field, the office selected Marked points may not correspond precisely to the actual bus stops at the GPS control points. However, if the correspondence is correct, it could add information on the along-route location error. The along-route error is illustrated in figure 16. Figure 16 shows a section of a traveled bus route and the locations of individual observation points as sampled by the CPS. Also shown in figure 16 are the location of a GPS control point and the location of the (believed) corresponding Marked point. The previous CPS error analysis presumed that the CPS error corresponds to the distance between the nearest observation point and the GPS control point. In the present analysis the CPS error is presumed to be the distance between the GPS control point and the Marked point. The distance to the Marked point reflects not only an (almost perpendicular) offset from the route but also an offset along the route. This is termed here as an along-route error.

Figure 16. Error determination with respect to GPS control.

Figure 17 presents the distance or the error between the GPS control point and the Marked point and the nearest CPS point. All of the Marked points have larger distances to the GPS control points compared to the nearest point. What this means is that none of the Marked points was the nearest point to the GPS control. This observation is also evident from figure 16 since the best case scenario is that the nearest point is also the Marked point. In that case both distances to the GPS control are equal. The average error of the Marked points was 59 feet with a standard deviation of ± 50 feet while the average error of the nearest points was 23 feet with a standard deviation of ± 27 feet.

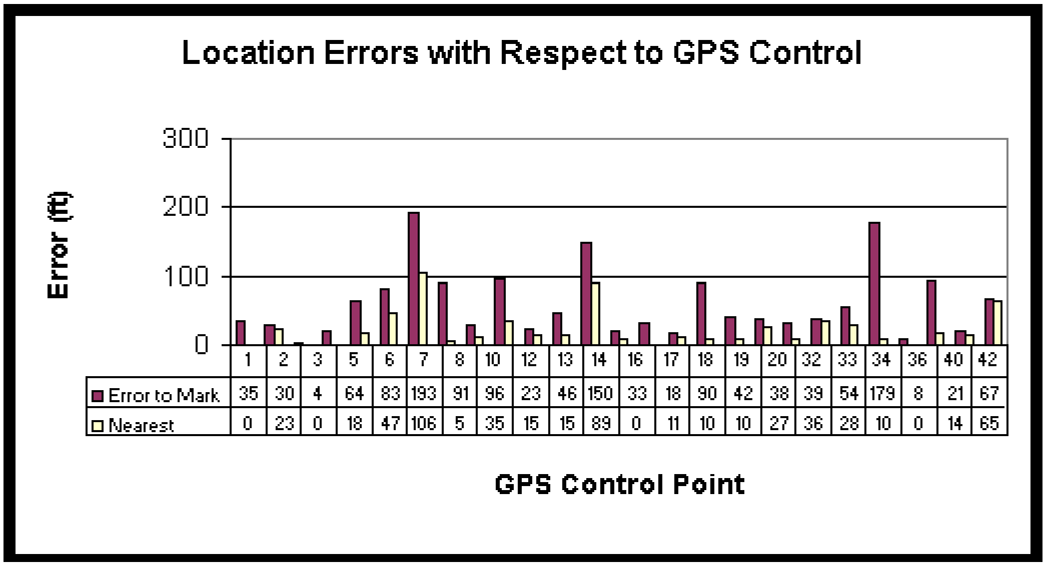

Figure 17. Location error the CPS with respect to the GPS control.

The most important consequence from the above analysis is that the evaluation of the AVL system as presented in this report is a best case scenario. The findings of this report evaluate the error between the AVL and the nearest observation point. That nearest point is not necessarily the actual point where the bus stopped.

4.7 Location Error as a Function of Environment Ranking

The GPS control points were selected in such a way that they are representative of the operational environment of NJ Transit. A ranking system from ‘a’ (most challenging) to ‘c’ (least challenging) was established to indicate the degree of difficulty presented especially to the GPS component of the AVL system. From table 12 it can be seen that the rank of the environment had no clear impact on the CPS component of the AVL system. A parameter that may affect the precision of the CPS is the accumulated error as a function of distance traveled from the initialization point. However, this parameter was not tested nor verified in this study. As before, Marked points had larger errors than nearest points.

The GPS component of the AVL system showed a definite dependency on the rank of the environment. The point with rank ‘a’ had the largest error while points with rank ‘c’ were found to be within the acceptable error tolerance adopted in this study.

The redundancy data in table 12 indicates the statistical strength of the average error in the different operating environment. Rank ‘a’ had only 1 GPS control point, therefore, the measured error was determined based on a single observation. The average error of the other ranks were based on a more numerous sample points and therefore are more statistically sound.

Environment	Error to	Error to	Error to	Redundancy

Rank	Mark	Nearest Obs. Point	Nearest GPS (AVL)	
a	33	10	102	1
b	83	19	54	4
c	56	24	16	23

Table 12. Location error in various operation environments of the AVL system with respect to the GPS control.

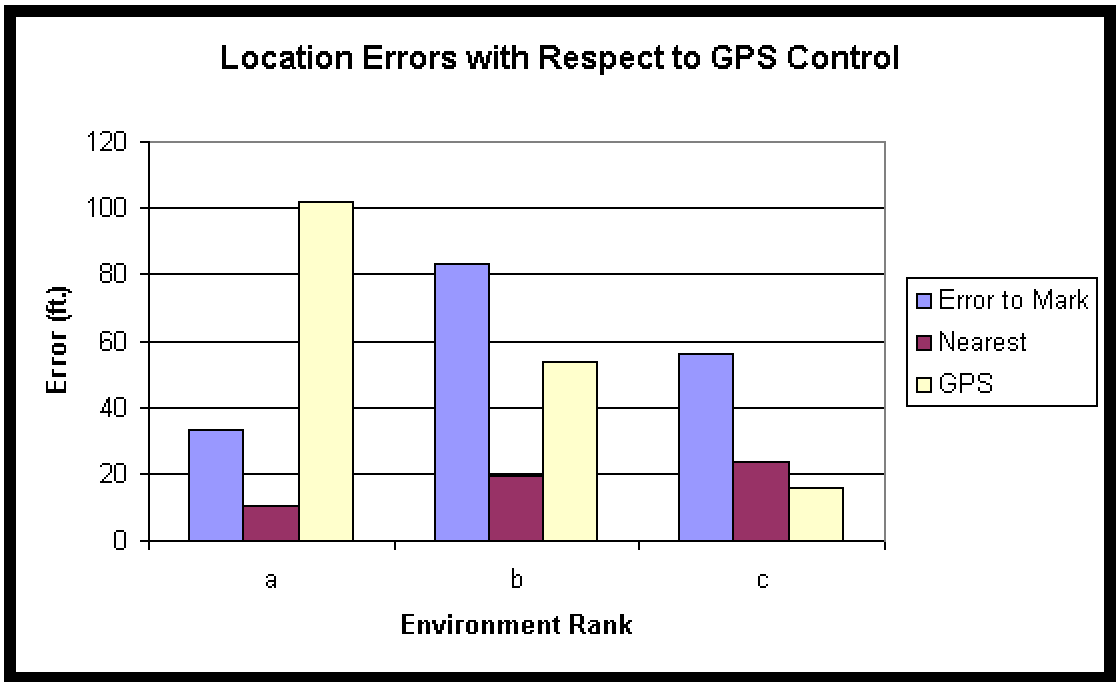

Figure 18. Location error in various operation environments of the AVL system with respect to the GPS control.

5.0 SUMMARY OF INACCURATE DATA.

In this section the locations where inaccuracies were observed are presented. A location error is defined as a location difference in excess of 30 ft. As mentioned earlier, about 87% of the tested routes were within this established error tolerance. Table 13 lists the locations where CPS, GPS and Navtech data errors were found. The table lists the locations of the found errors in terms of street segments and the linear length along which the error persisted.

DOQQ Code	Location	Length of Erroneous segment
504	4th - Hetfield (along South Ave.)	4182
514	Eastman - Garden State PKWY (along Route 28)	5292
523	28 - Chester Lang (along Route 439)	2094
504	Front - Midway (along Terrill Rd.)	1600
504	Richmond to Central (along South Ave.)	50
504	Woodland to Beividere (along South Ave.)	850
504	Coolidge to Terrill Rd. (along South Ave.)	50
504	Terrill yo Fariey (along Route 28 Ave.)	500
504	N Martine to Forest (along Route 28 Ave.)	300
504	Timberline to Rainier (along Route 28 Ave.)	300
513	W Dudley to Cowderthwaite (along Route 28)	300
513	Drake to Hort (along South Ave.)	300
513	Ferris to E Broad (along Route 28)	300
514	28 to Charles (along Chestnut St.)	700
521	Bus Termial in Hillside	5860
522	Express Rd. in Newark Airport	500
522	Route 78	1400
522	Route 78	300
522	Delancey	750

522	Newark Downtown	15300
	Total erroneous route length =	40928
	% of total route length =	**12.5**
	% of total acceptable route length	**87.50%**

Table 13. The locations where CPS, GPS and Navtech data errors were found.

To better understand the types of errors that were found in this study, it is prudent to illustrate some of these errors by visual examples. The following is a collection of figures presenting interesting views of route sections where location errors and peculiar erratic behavior of the AVL system were observed. Indices showing the locations of these errors are presented in figures 19 and 20.

1. **Error location 1 - Downtown Newark**

   Figure 21 - CPS positioning (Cp2n19) in Downtown Newark is consistent with the reference data except for a section between Wickliffe St. and Dr. M L King Blvd. along Central Ave., which is 1225 feet in length and 120 feet off correct positions.

   Figure 22 - GPS positioning (Gp2n19) in Downtown Newark is erratic compared with the reference data. This route passes by many high rising buildings and under overpasses so GPS signal is mostly blocked or reflected.

2. **Error location 2 - Dunellen**

   Figure 23 - A long section of CPS positioning (Cd2i18) is deflected from the reference positions. The CPS output displays a sizeable displacement or shift from Dekalb Ave. to Brokaw Blvd. along W Front St.

   Figure 24 - In contrast to CPS, GPS positioning (Gd2i18) seems to be consistent with respect to the reference data in this area.

3. **Error location 3 - Plainfeild.**

   Figure 25 - CPS positioning (Ci2d18 and Cd2i18) seems to be consistent with the

   reference data in this area.

   Figure 26 - GPS positioning (Gi2d18 and Cd2i18) is problematic in this area and does not seems to be consistent with the reference data

4) Error location 4 - Plainfeild

Figure 27, 28 - This is another example where CPS seems to be consistent with the reference data while GPS positioning was erratic and erroneous.

5. Error location 5 - Fanwood

Figure 29 - A long section of CPS positioning (Ci2d18) is shift by 60-190 ft. from the reference data.

Figure 30 - On the other hand GPS positioning along the same location (except for a the intersection of Terril Road and E. Front St.) seems to be consistent with the reference data.

6. Error location 6 - Westfield

Figure 31 - In this figure we see inconsistent repeatability of the same route by CPS.

Figure 32 - GPS route is not as smooth as the CPS one but (Gi2d18) in general the repeatability is consistent.

7. Error location 7 - Hillside

Figure 33 - The CPS route is completely off the traveled route.

Figure 34 - The GPS positioning in the same area (Gi2d18) is consistent with the reference data.

8. Error location 8 - Newark Airport

Figure 35 - The CPS route (Cd2i18) seems to be consistent with the reference data along the circular ramp of the expressway around Newark Airport.

Figure 36 - The GPS output (Cd2i18) is not as consistent with the reference data in some sections of the road.

9) Error location 9 - Cranford

Figures 37, 38 - The Navtech data is off from the GPS control points (4 and 16), CPS, GPS and DOQQ data. The shift of Navtech data is apparent in all local streets. On South Ave., even the TIGER/Line data seems to be more consistent with the reference data.

10) **Error location 10 - North Plainfield**

Figure 39 - The Navtech data at street intersections and especially in the lower left quadrant of the figure seems to be inconsistent with the reference data.

11. Error location 11 - Cranford

Figure 40 - Another example of inconsistent Navtech data with respect to the

reference data.

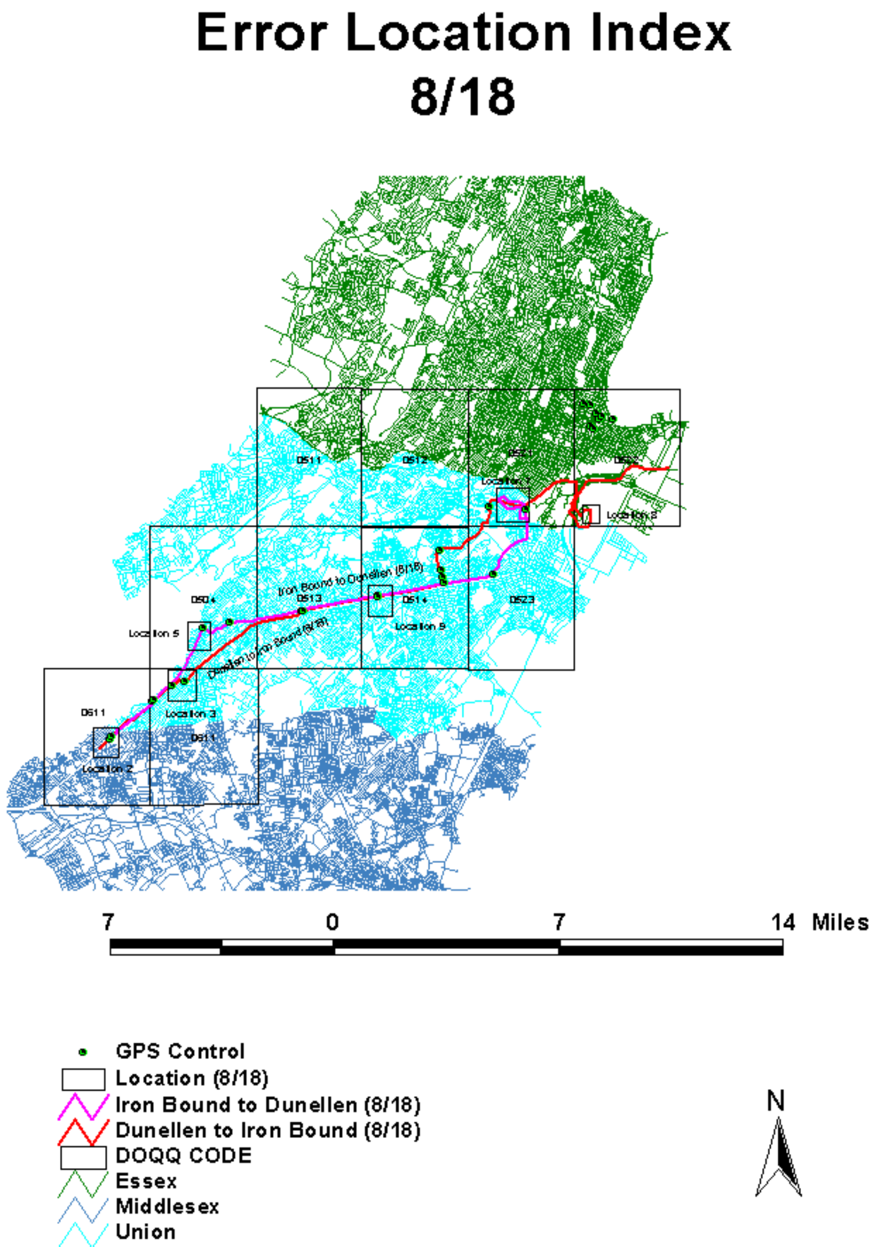

Figure 19. Index of error locations 8/18

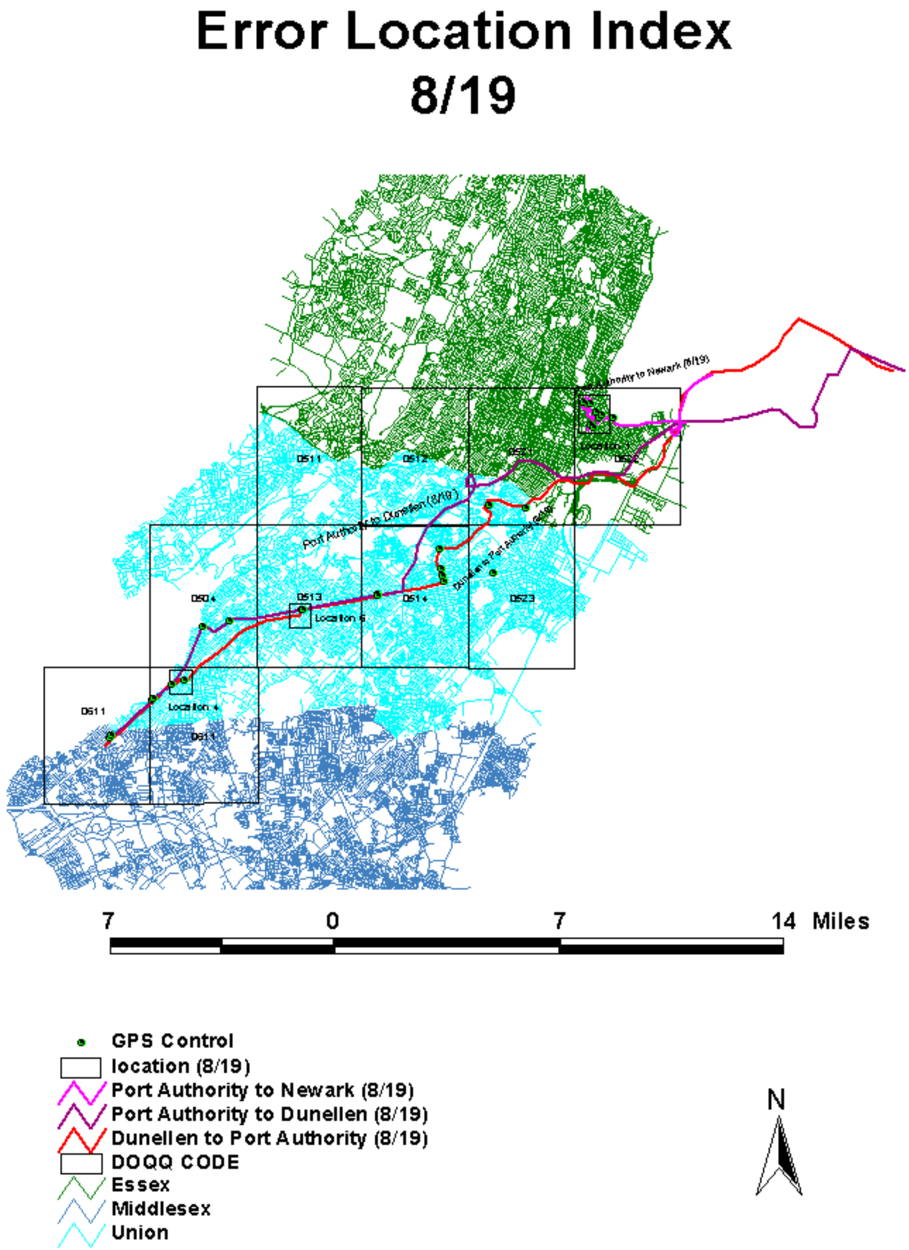

Figure 20. Index of error locations 8/19

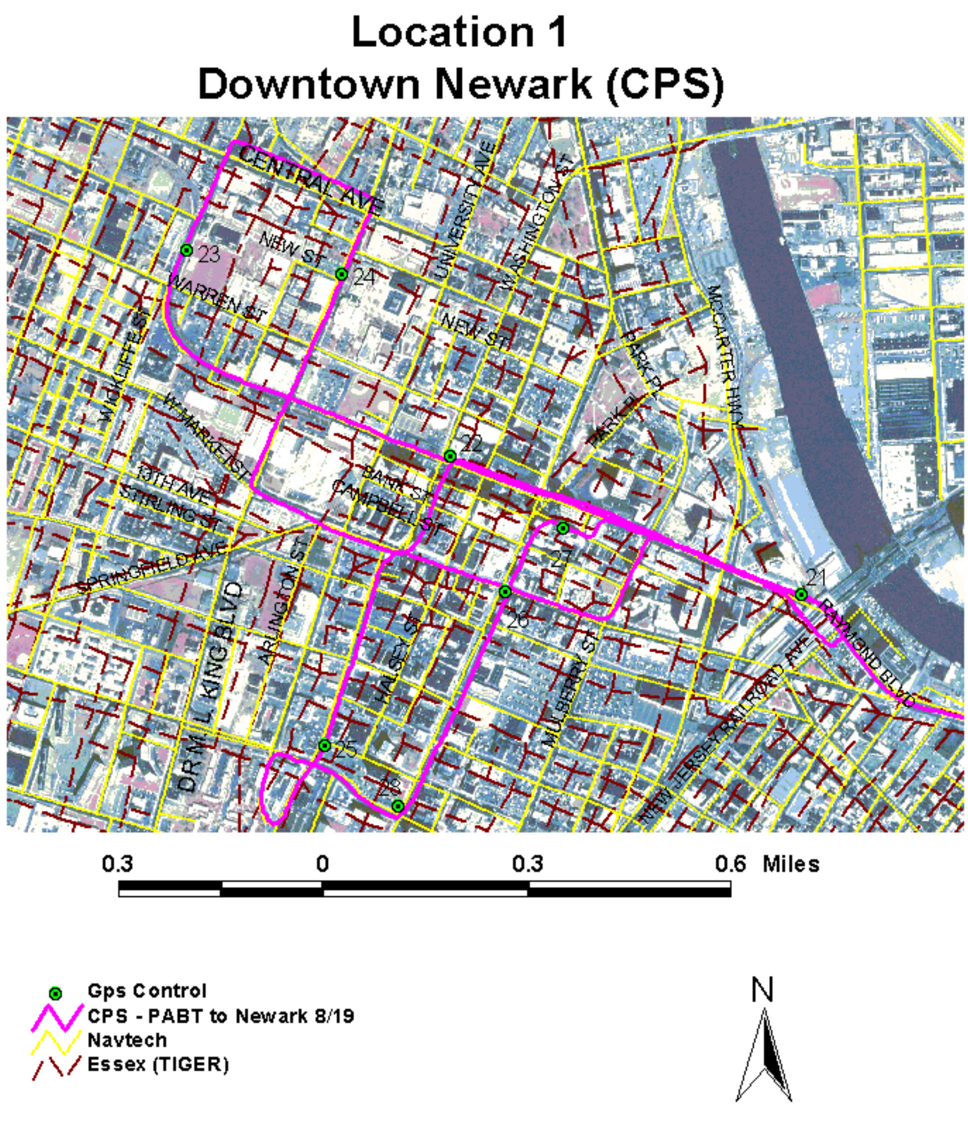

Figure 21. Location 1, CPS

Location 1
Downtown Newark (GPS)

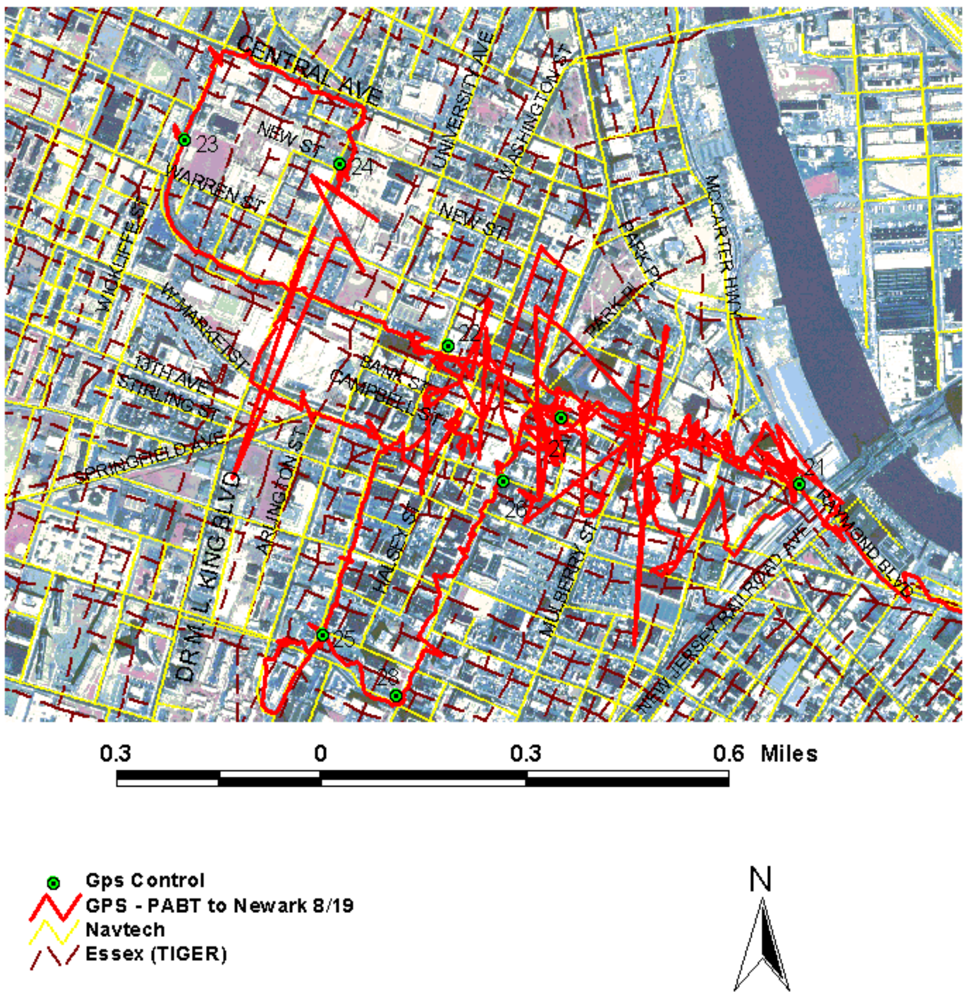

Figure 22. Location 1, GPS

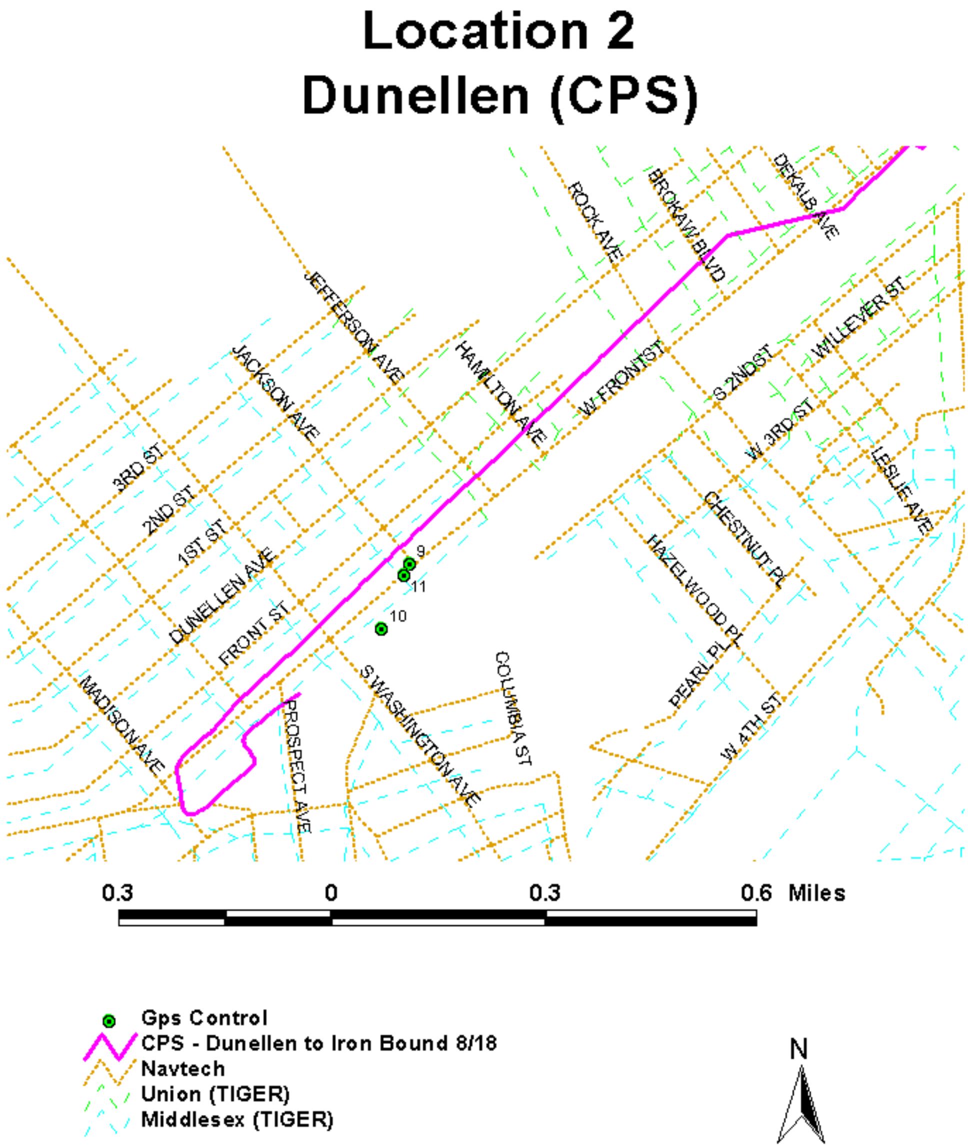

Figure 23. Location 2, CPS

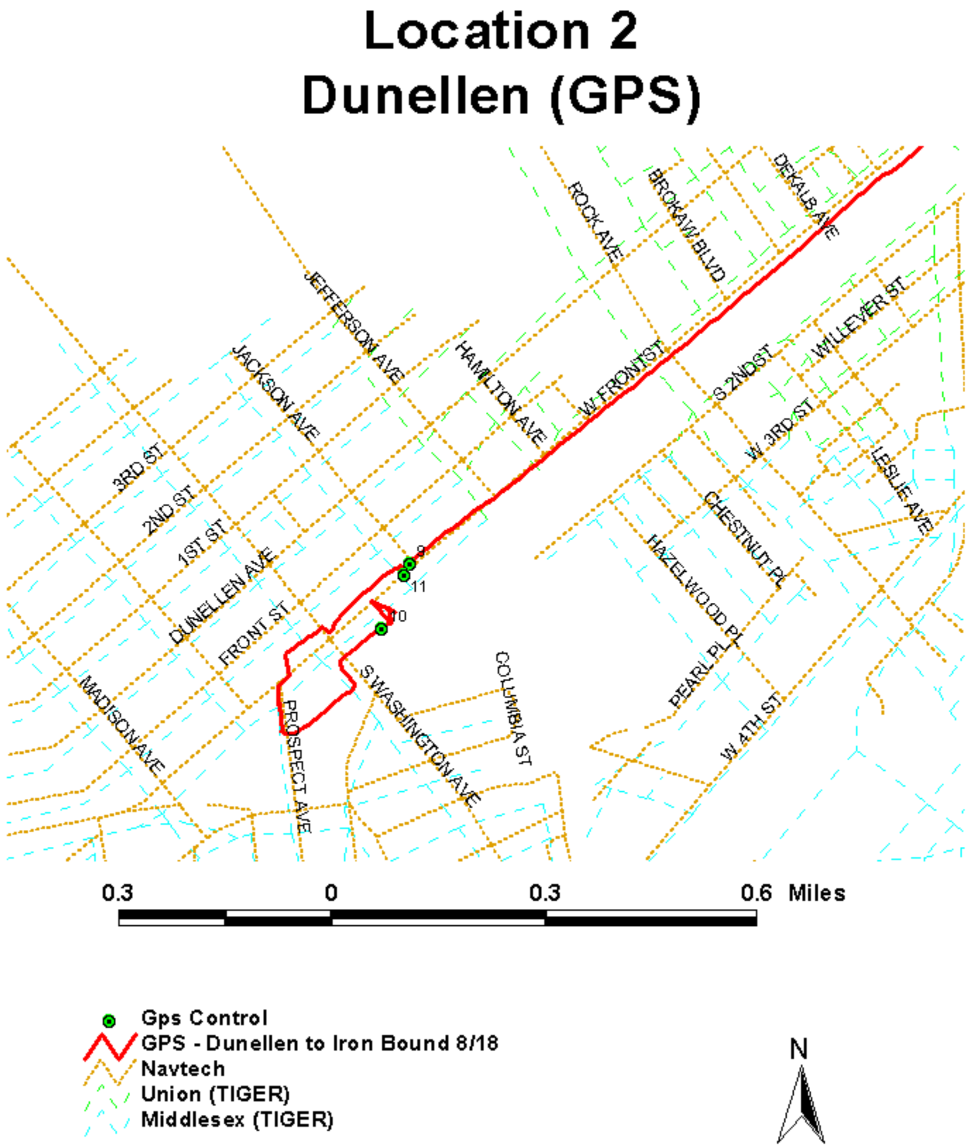

Figure 24. Locations 2, GPS

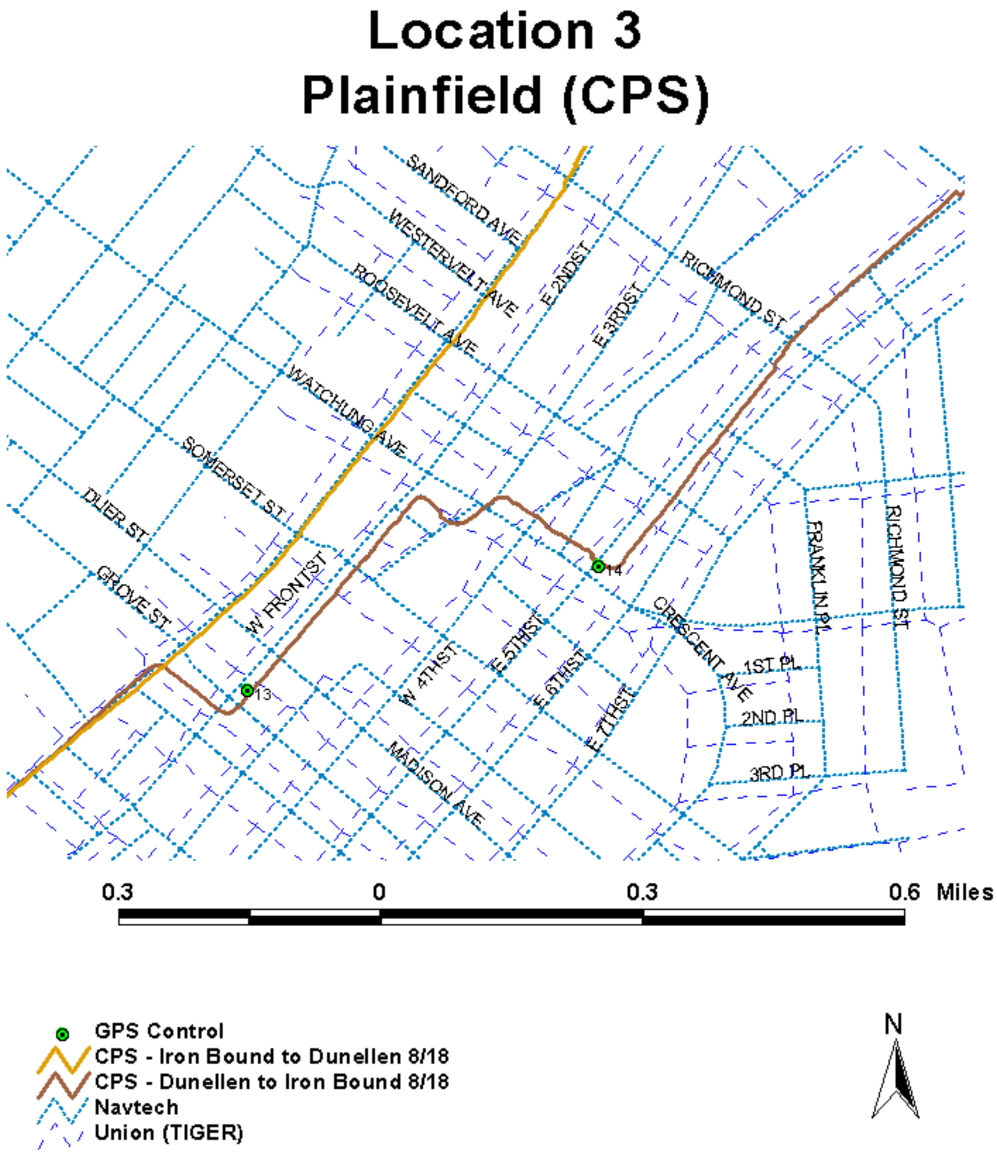

Figure 25. Location 3, CPS

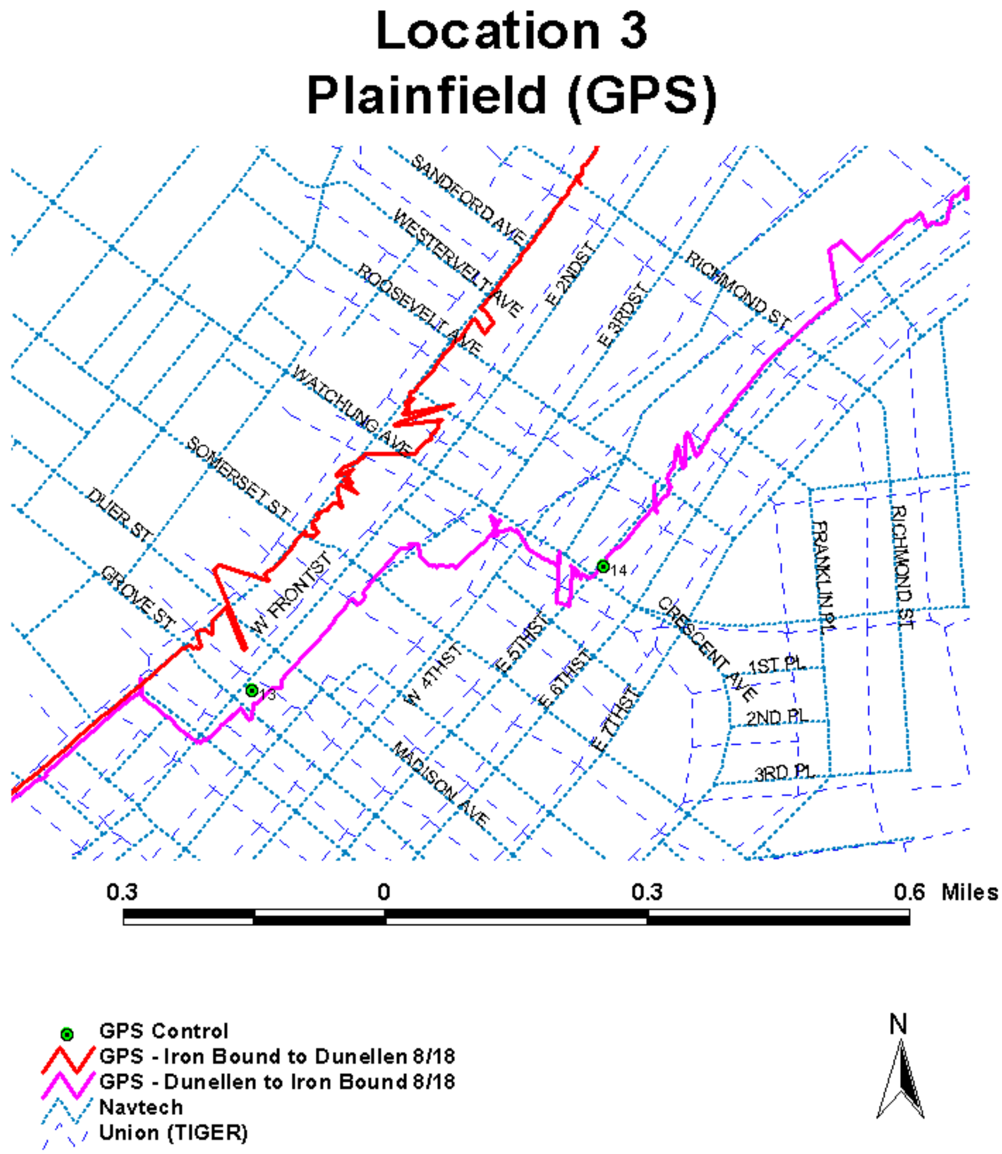

Figure 26. Location 3, GPS

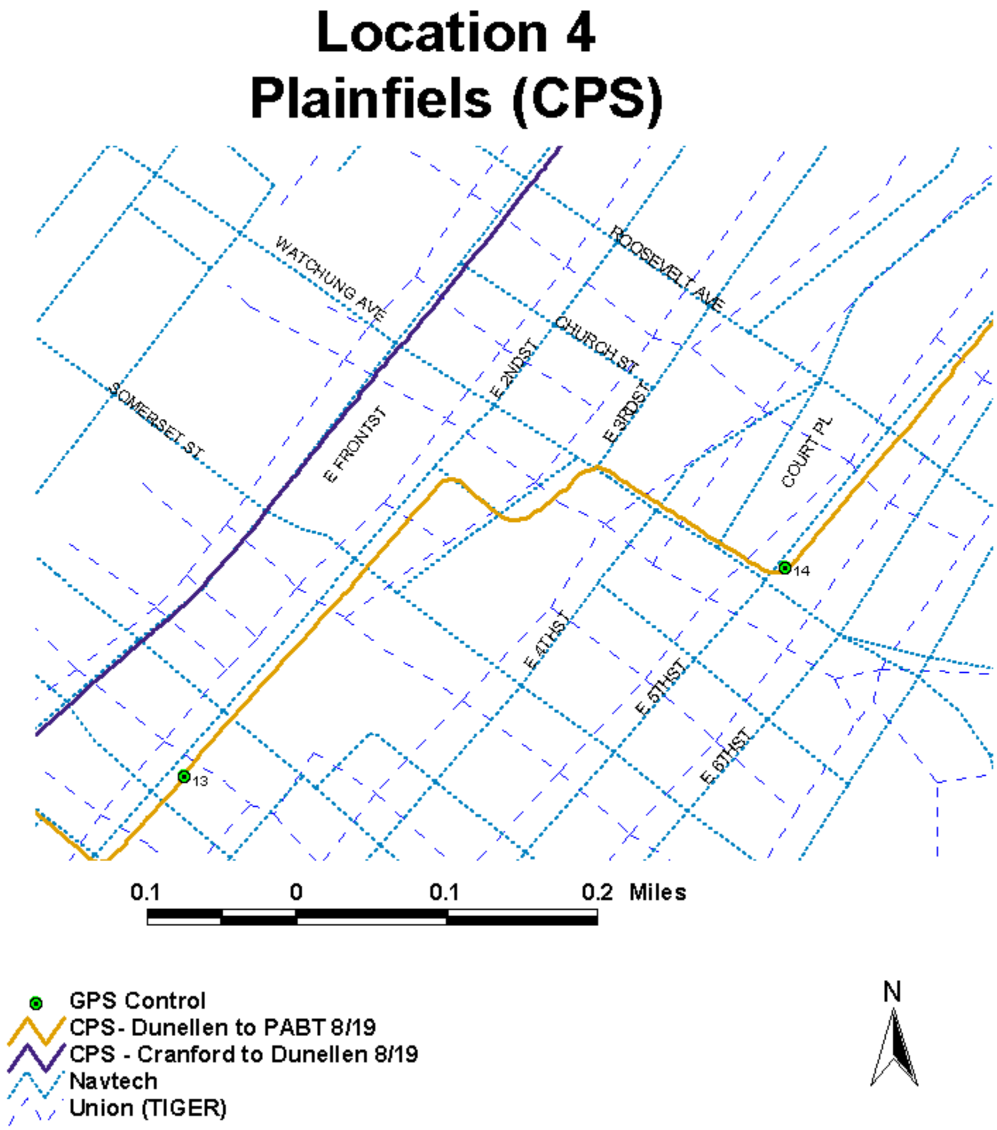

Figure 27. Location 4, CPS

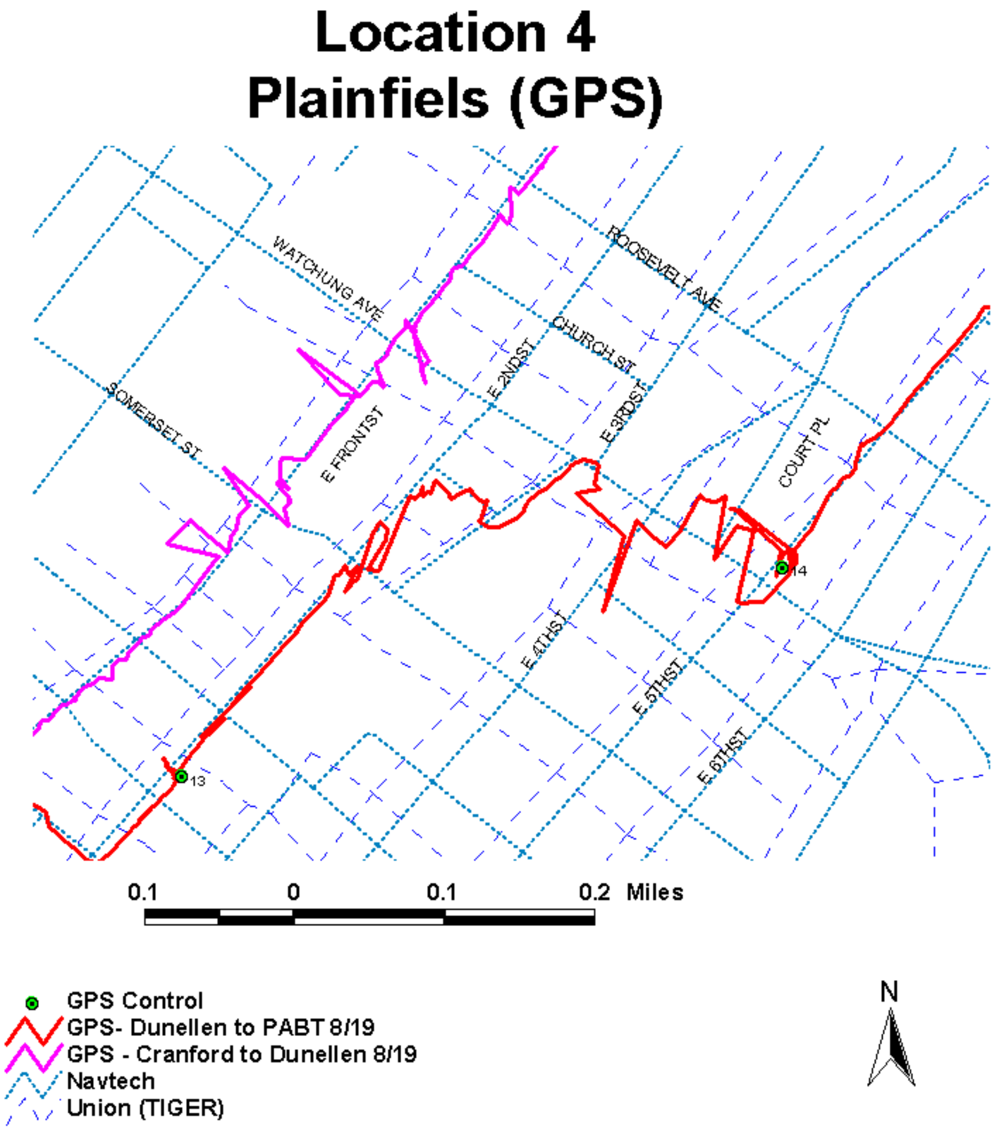

Figure 28. Location 4, GPS

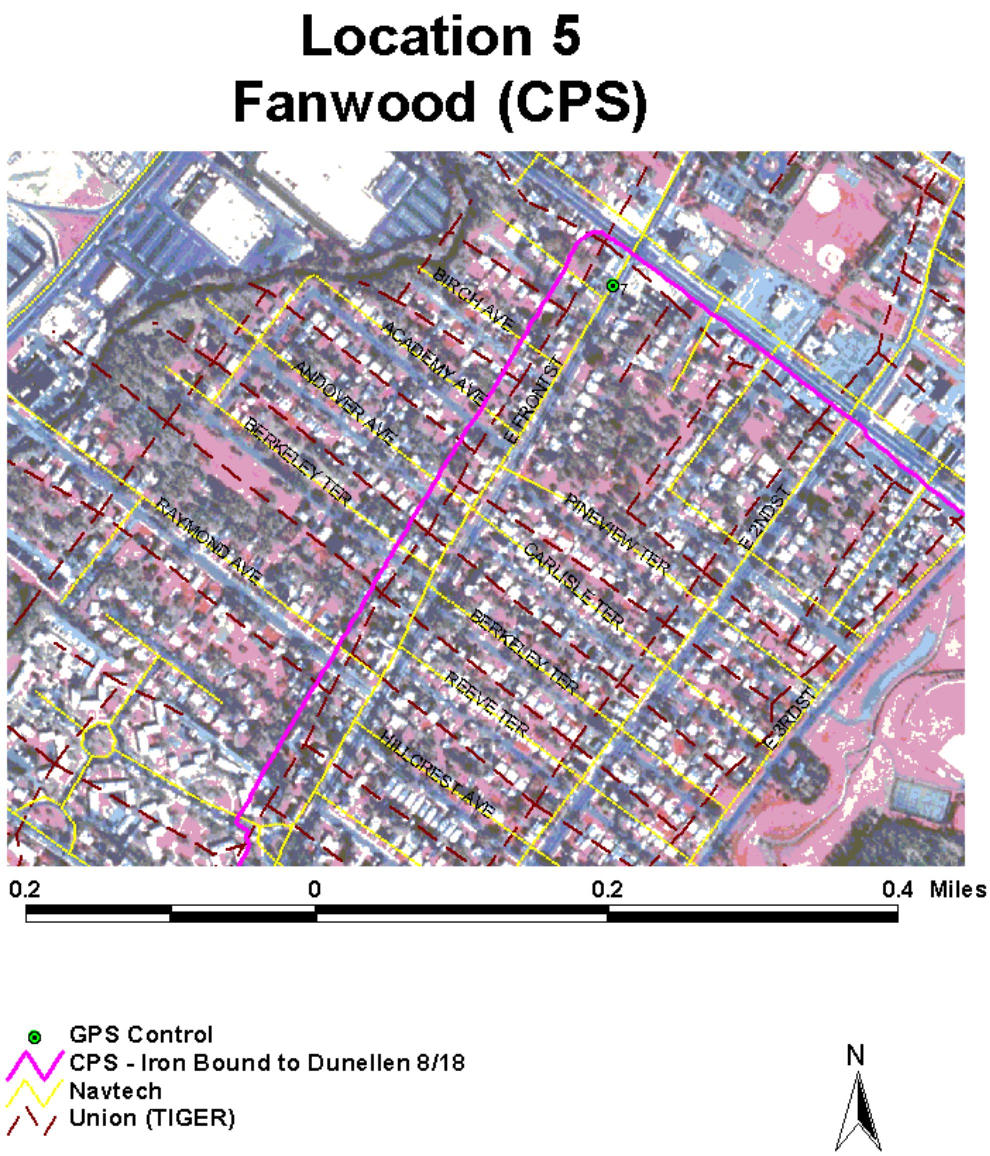

Figure 29. Location 5, CPS

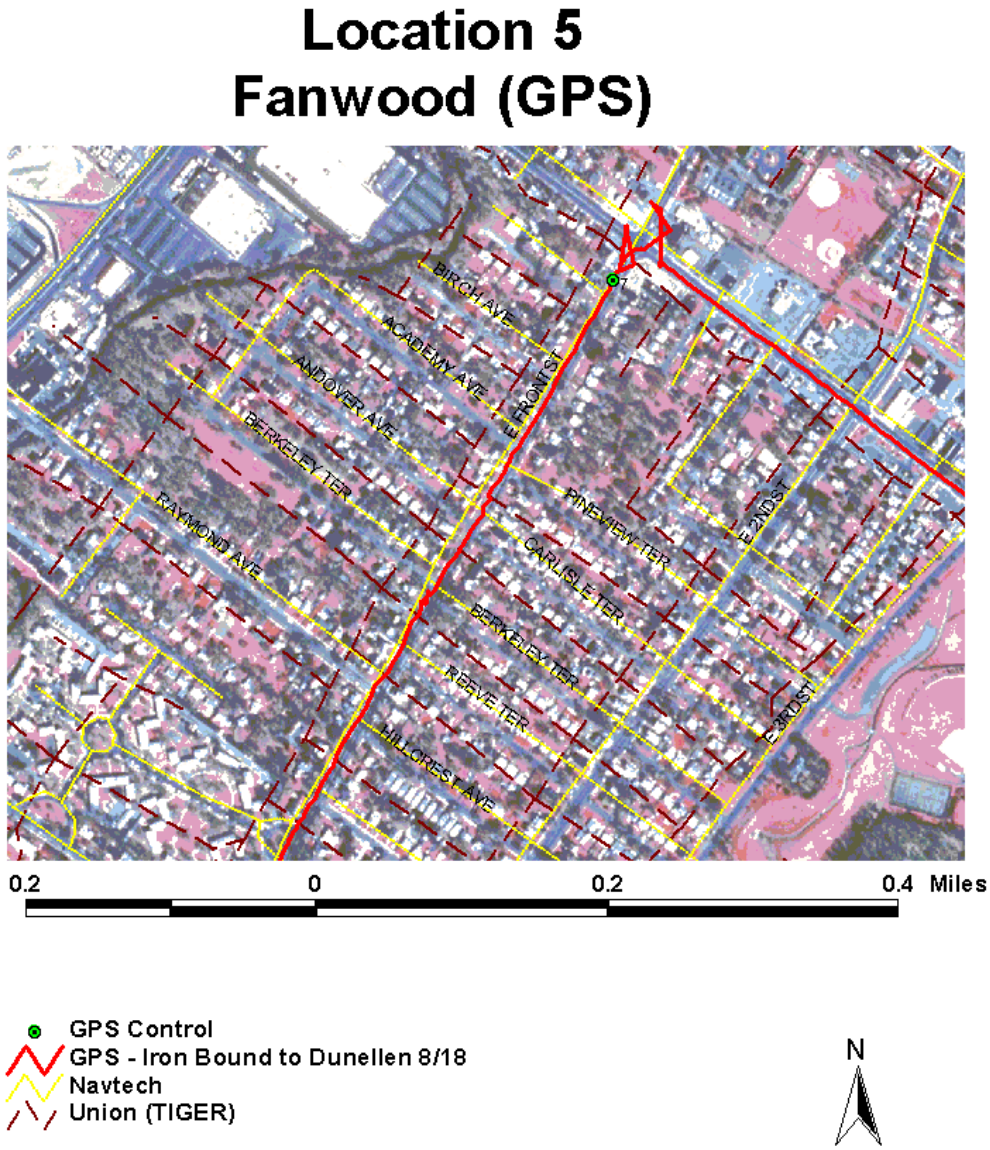

Figure 30. Location 5, GPS

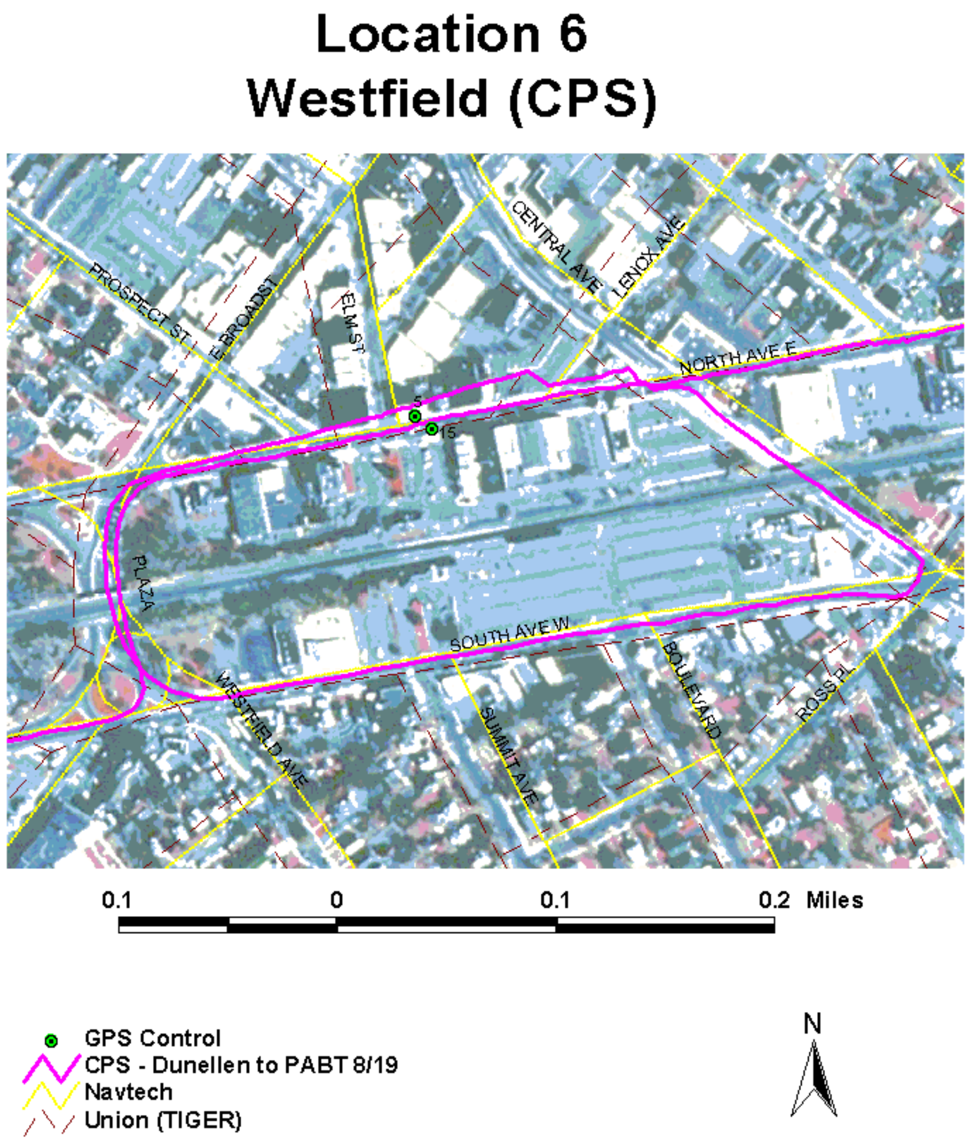

Figure 31. Location 6, CPS

Location 6
Westfield (GPS)

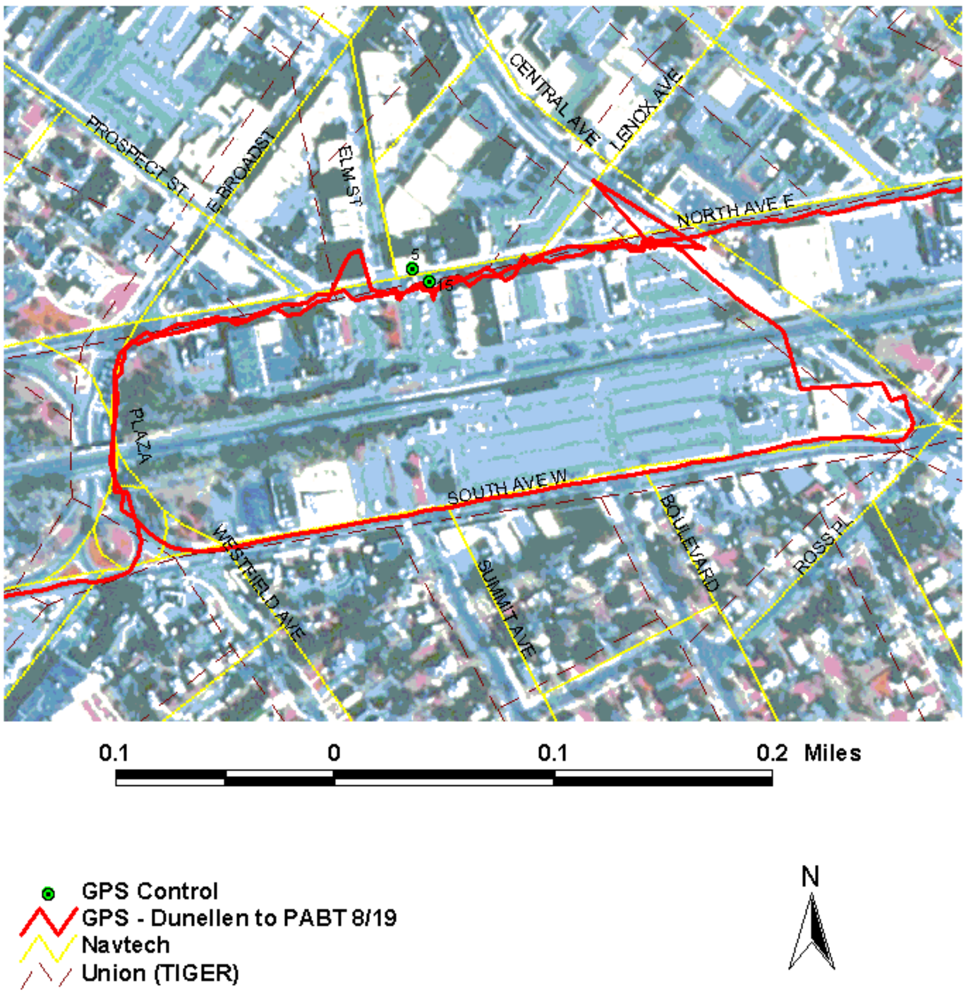

Figure 32. Location 6, GPS

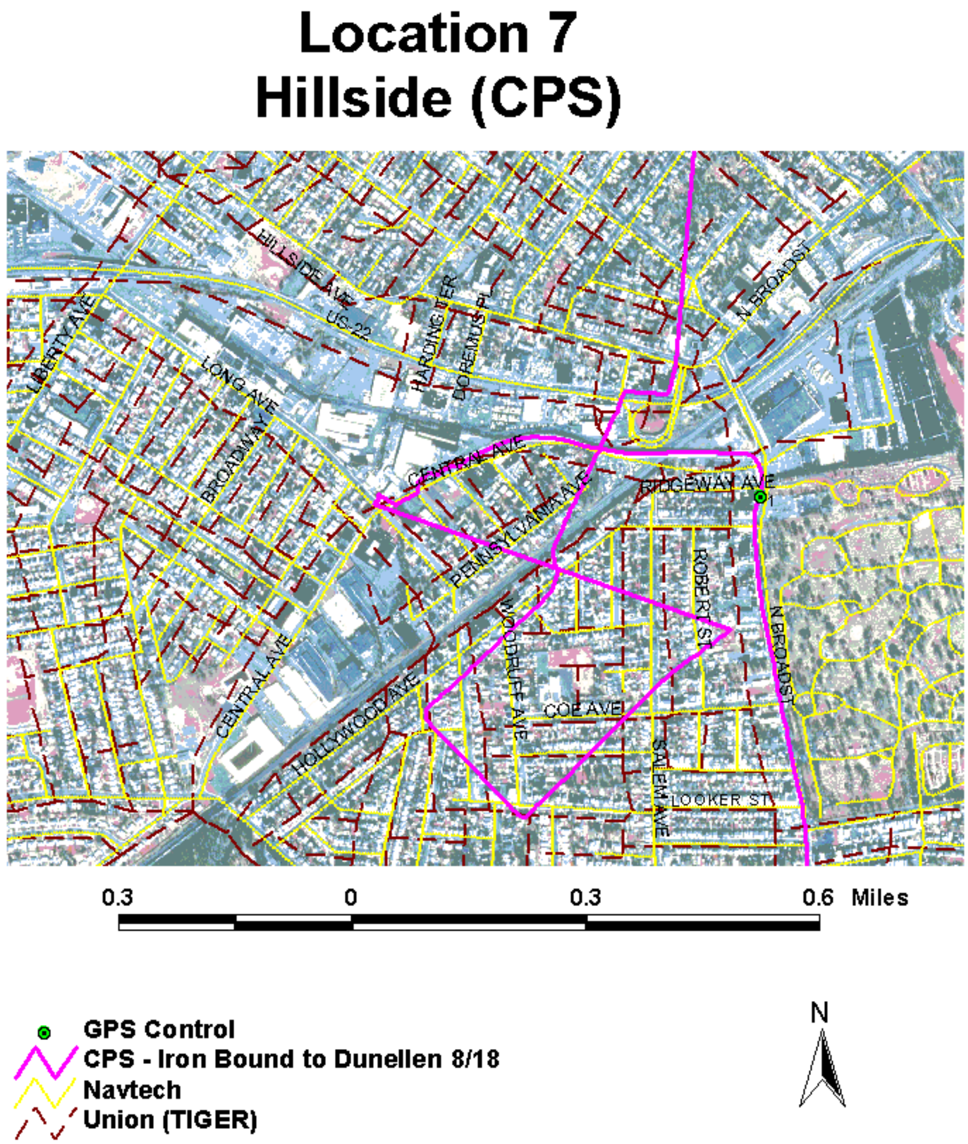

Figure 33. Location 7, CPS

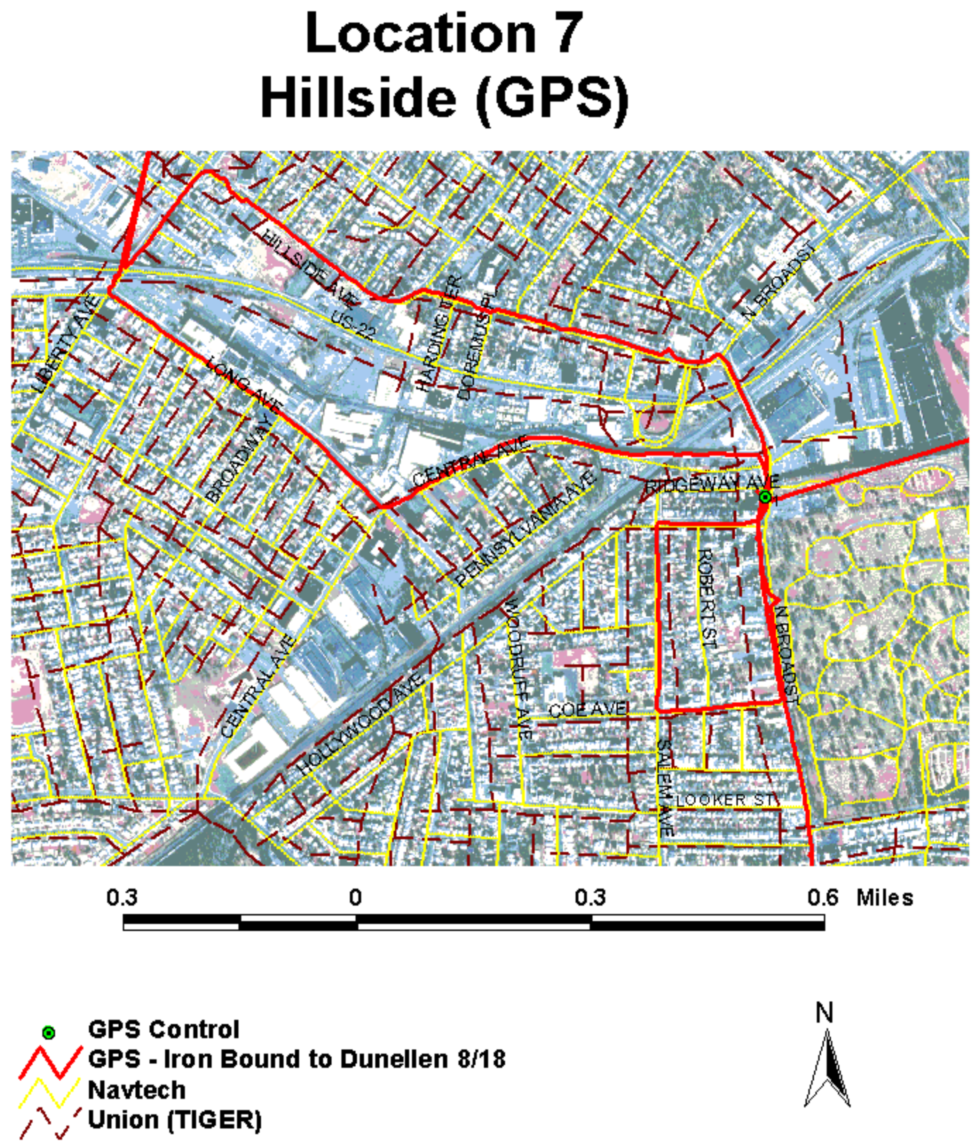

Figure 34. Location 7, GPS

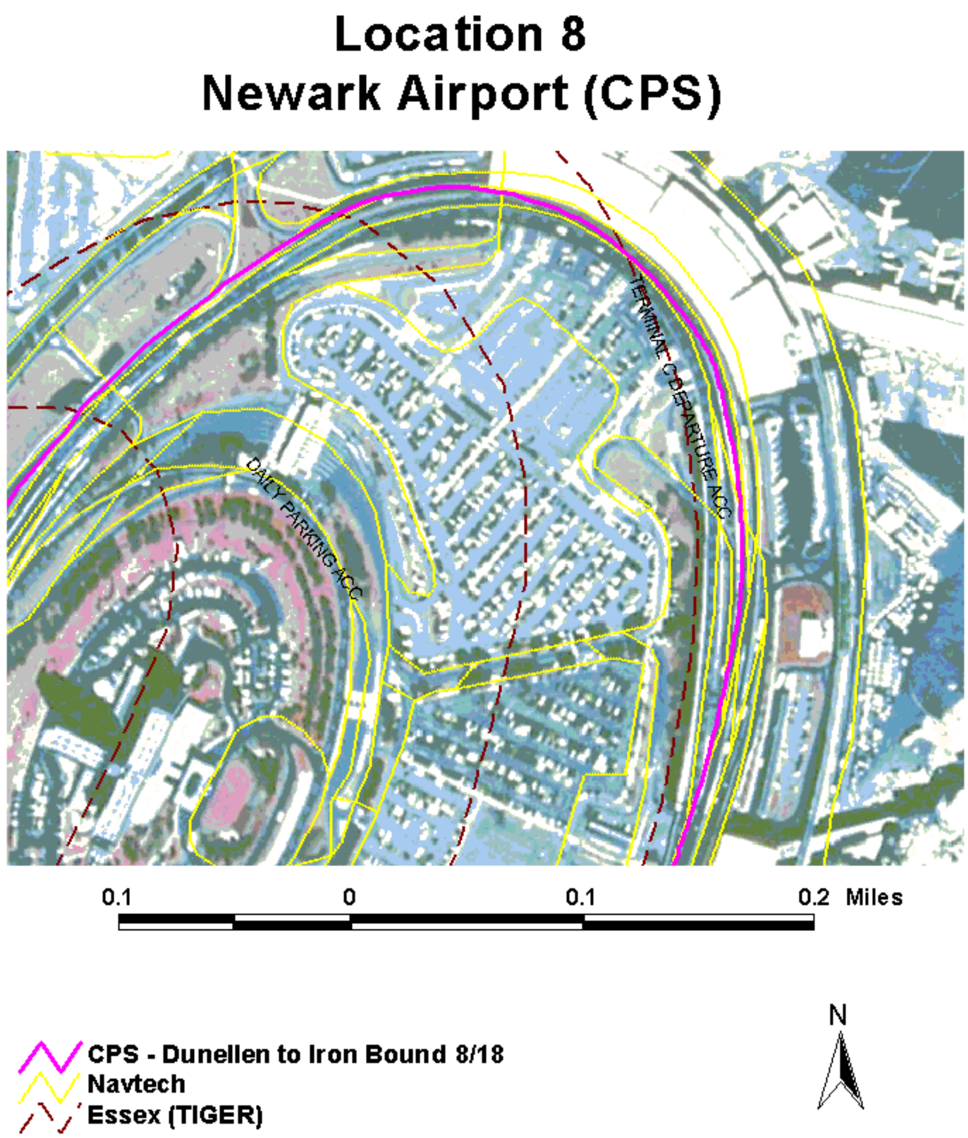

Figure 35. Location 8, CPS

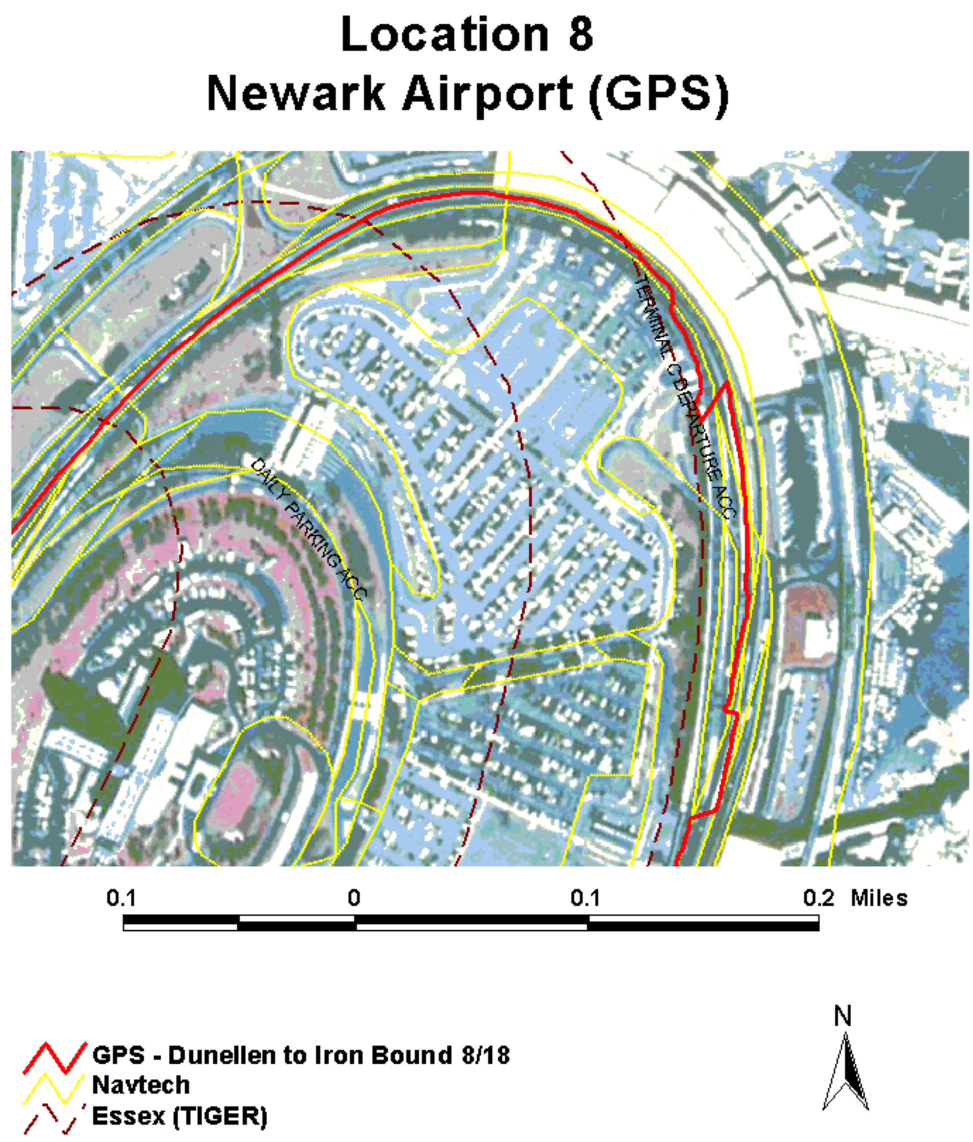

Figure 36. Location 8, GPS

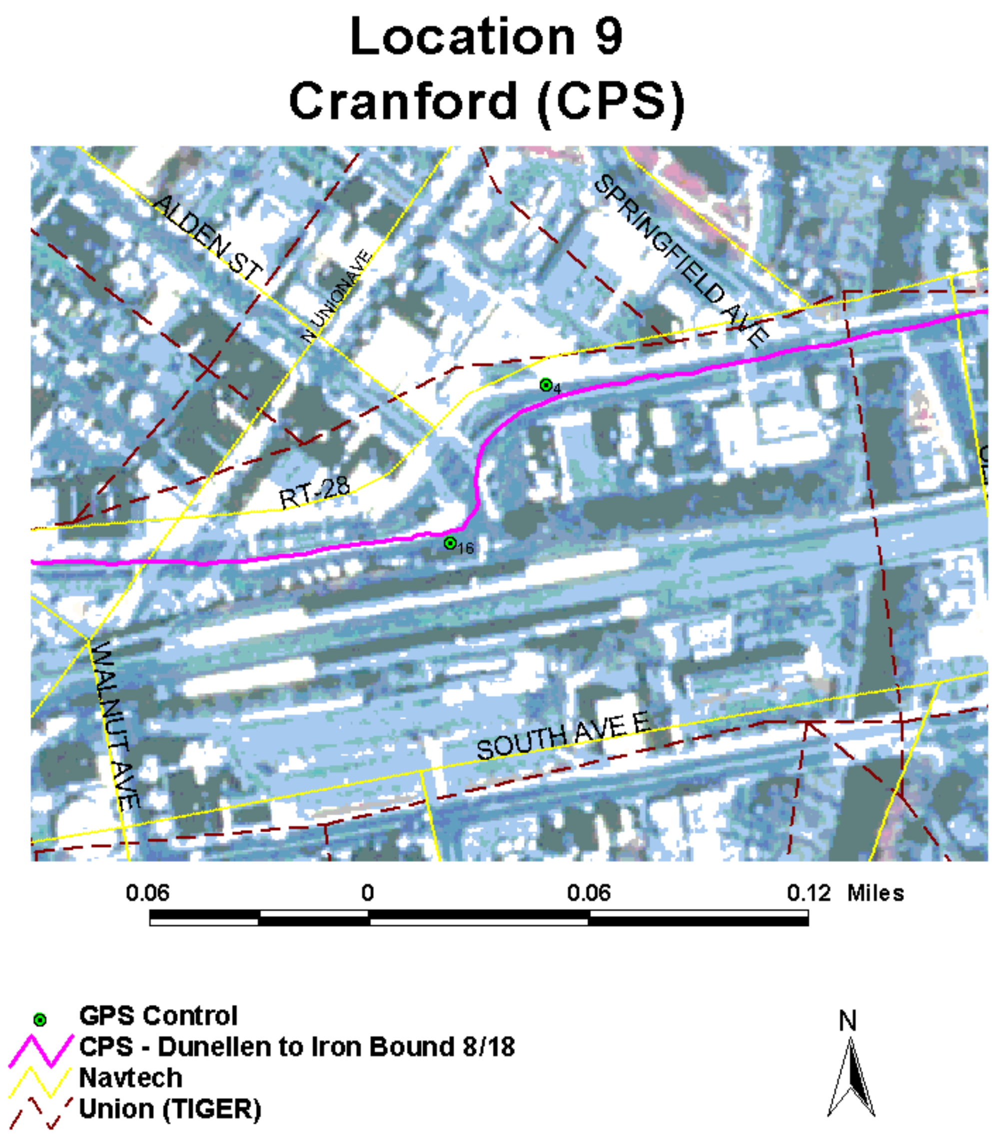

Figure 37. Location 9, CPS

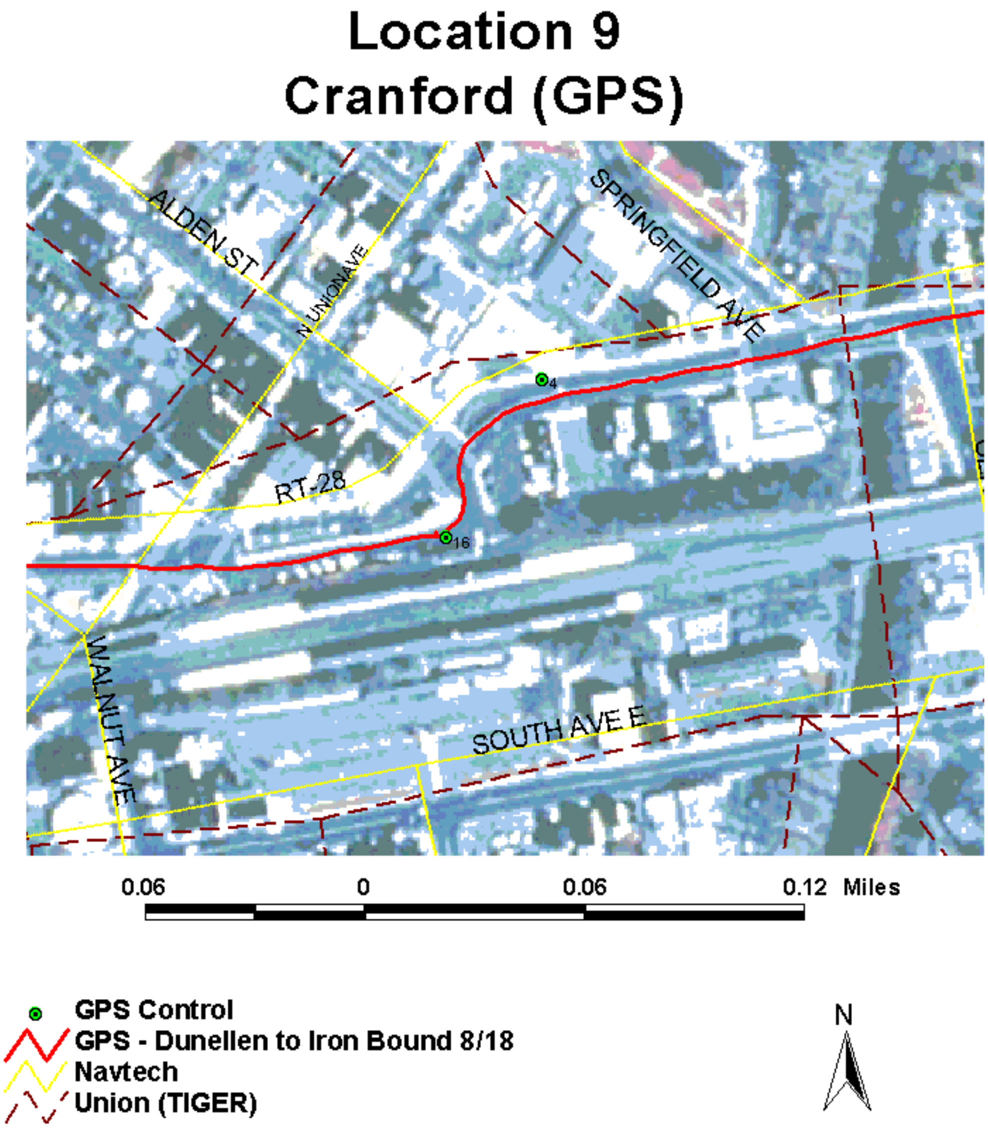

Figure 38. Location 9, GPS

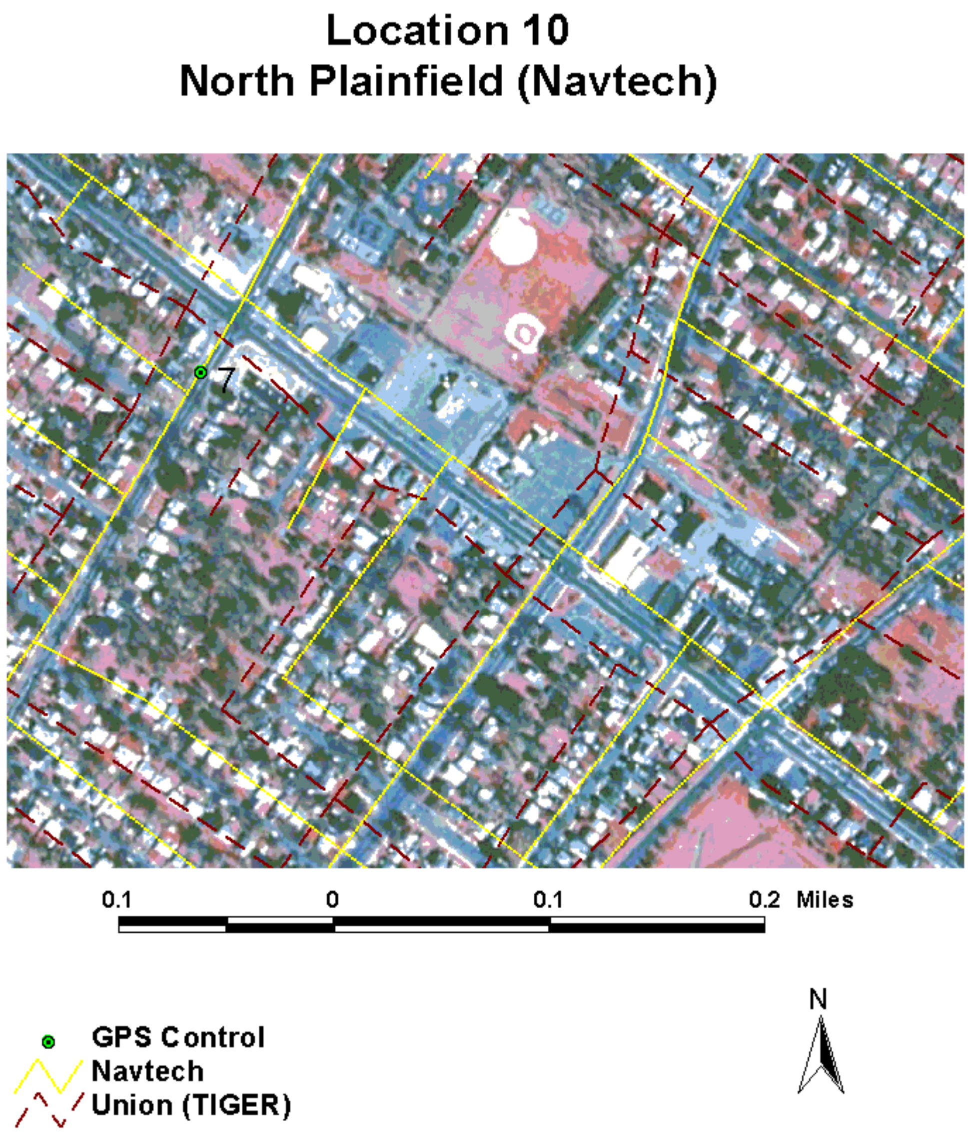

Figure 39. Location 10, Navtech

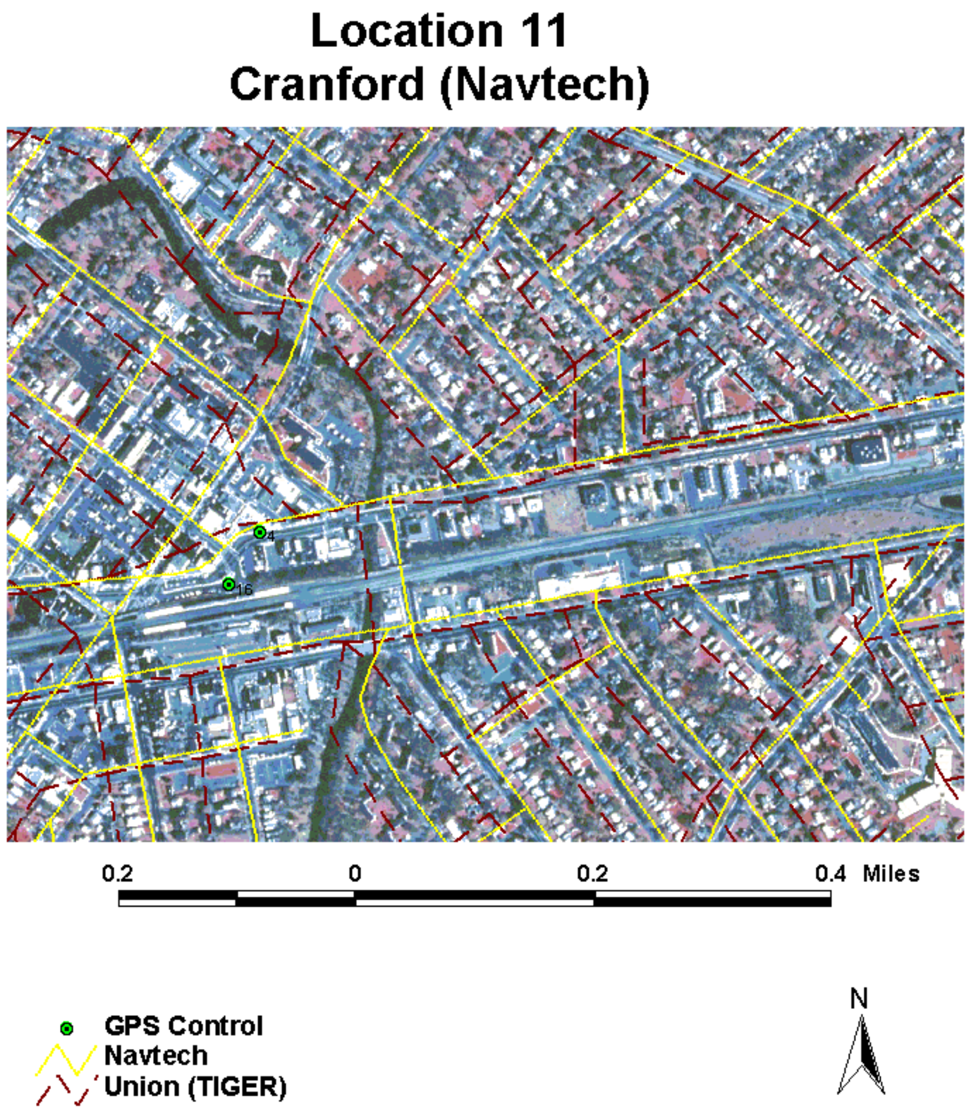

Figure 40. Location 11, Navtech

6.0 SUMMARY OF FINDINGS AND CONCLUSIONS

The objective of this study was to develop a methodology for evaluating AVL systems and the necessary supporting digital map data. GPS control points and Digital Orthophoto Quarter Quads were used as accurate reference data in this study. The locations of the GPS control points were selected in such a way that they represented various environmental categories under which NJT buses are expected to operate. The AVL system was installed on a typical NJT bus and tested under real-world conditions. All of the above were necessary to obtain meaningful results.

The main findings of this study were:

- The accuracy of about 87% of the tested routes was within the established error tolerance of 30 ft (~10m). Actual determination of the required error tolerance for AVL application at NJT was beyond the scope of this study. Therefor, a conservative 30 ft. tolerance was selected to reflect a rather stringent accuracy requirements.

- In most cases, AVL with a CPS sensor does not offer a measurable advantage over an AVL system with differential GPS sensor only. GPS based AVL was found to be as accurate and as reliable as the CPS based AVL except for downtown-like areas with tall buildings and numerous over/under passes. The advantage of a GPS/AVL system is that it is less expensive and that it requires a lesser-complicated setup. A simpler setup usually means fewer problems and less malfunctioning.

- The repeatability of the system is 89%. In other words, if the same route is run with the same bus one can expect that 11% of the route will differ by more than 30 ft. This could potentially cause problem in sophisticated AVL applications.

- Buses operating in predominantly downtown routes of large cities such as Newark, are to be equipped with CPS sensors. In this environment GPS is practically ineffective.

- Navtech data is 96% of the time within 30 feet of the correct location of the street network. Thus, using Navtech as a GIS base map is appropriate. It is recommended to identify and correct the predicted 4% errors in this data set.

- As expected and previously determined by NJT staff, TIGER/Line data is inappropriate for AVL application at New Jersey Transit.

- The errors observed in this study (except for Newark) seem to be independent of the operating environment. In other words, one can not predict the performance accuracy of the AVL as a function of the characteristic of the operating environment. The accuracy performance of the tested AVL seems to be related to the systems limitations/capabilities.

Appendix A

Bus stops that were used as GPS control points

Figure 41. GPS point 1, North Broad St. and Ridgeway, Hillside

Figure 42. GPS point 2, Westfield Av. And Elmora Av., Elizabeth

Figure 43. GPS point 3, Chestnut St. and West Westfield Ave., Roselle Park

Figure 44. GPS point 4, Aiden St. and Route 28, Cranford

Figure 45. GPS point 5, Elm St. and North Ave., Westfield

Figure 46. GPS point 6, North Martine Ave. and Midway Ave., Fanwood

Figure 47. GPS point 6 (view II), North Martine Ave. and Midway Ave., Fanwood

Figure 48. GPS point 7, Wiley Ave and East Front St., Scotch Plains

Figure 49. GPS point 8, West End Ave. and West Front St., Plainfield

Figure 50. GPS point 9, Jackson Ave. and North Ave., Dunellen

Figure 51. GPS point 10, South Washington Ave. and North Ave., Dunellen

Figure 52. GPS point 10 (view II), South Washington Ave. and North Ave., Dunellen

Figure 53. GPS point 11, Jackson Ave. and North Ave., Dunellen

Figure 54. GPS point 12, West End Ave. and West Front St., Plainfield

Figure 55. GPS point 13, Central Ave. and West 2nd St., Plainfield

Figure 56. GPS point 14, Watchung Ave. and East 5th St., Plainfield

Figure 57. GPS point 15, Elm St. and North Ave., Westfield

Figure 58. GPS point 16, Aiden St. and West Westfield Ave., Roselle Park

Figure 59. GPS point 17, Chestnut St. and West Grant Ave. Roselle Park

Figure 60. GPS point 18, Chestnut St. and west Lincoln Ave., Roselle Park

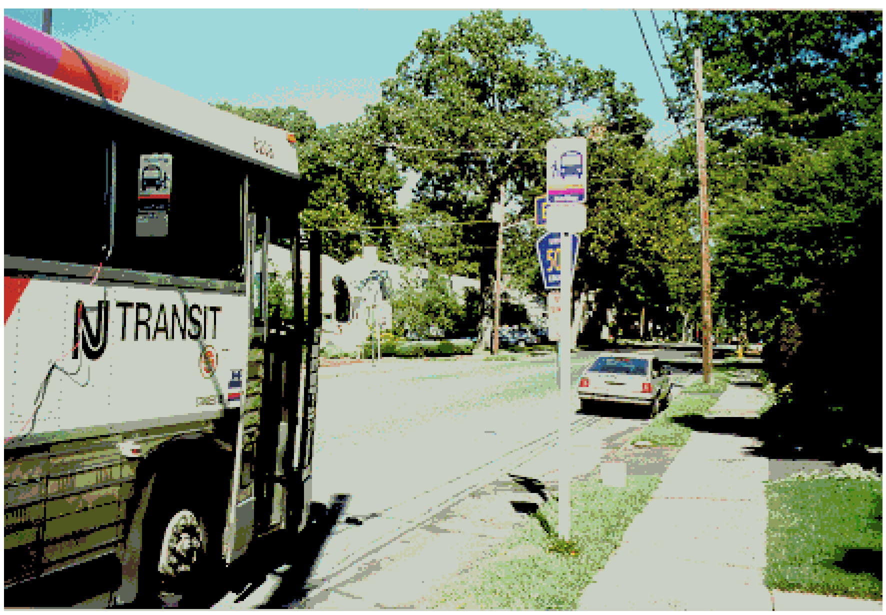

Figure 61. GPS point 19, Marshall Ave and Salem Rd., Roselle Park

Figure 62. GPS point 20, Bloy St. and Princeton Ave., Hillside

Figure 63. GPS point 31, Raymond Plz W and Raymond Blvd., Newark

Figure 64. GPS point 32, Washington St. and Raymond Blvd., Newark

Figure 65. GPS point 33, Lock St. and New St., Newark

Figure 66. GPS point 34, Dr. Martin Luther King Blvd. And New St., Newark

Figure 67. GPS point 36, Washington St. and Hill St., Newark

Figure 68. GPS point 37, Broad St. and Market St., Newark

Figure 69. GPS point 40, Commerce Ct. and Commerce St., Newark

Figure 70. GPS point 42, Broad St. and Count St., Newark

Appendix B

GPS Control Point Measurements

RAW GPS MEASUREMENTS

** Indicates rejected observations **GPS Control point No. 1**

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	206721.0627	174007.1599		678218.7096	570889.6322	5	3.2
	206718.2886	174007.7322		678209.6083	570891.5098	5	3.1
	206716.9954	174008.4407		678205.3655	570893.8343	5	3
	206721.2450	174006.3141		678219.3077	570886.8573	4	4
Average	***206719.3979***	***174007.4117***		***678213.2478***	***570890.4584***	***4.7500***	***3.3250***
SD	***2.0965***	***0.8999***		***6.8783***	***2.9525***		

GPS Control point No. 2

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	203472.3622	172435.1411	**	667560.2434	565732.0902	5	2.5
	203460.5421	172443.0682		667521.4636	565758.0978	6	2.3
	203464.0498	172440.2392		667532.9718	565748.8163	6	2.3

Average	***203462.2960***	***172441.6537***		***667527.2177***	***565753.4570***	***6.0000***	***2.3000***
SD	***2.4803***	***2.0004***		***8.1375***	***6.5630***		

GPS Control point No. 3

	Northing	Easting		Northing	Easting	Number of	PDOP
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	203020.8558	169986.2069		666078.9232	557697.5292	4	5.8
	203020.6518	169979.1611		666078.2539	557674.4131	5	2.2
	203020.8365	169979.0197		666078.8599	557673.9491	5	2.2
	203053.7875	169982.7362	**	666186.9669	557686.1424	5	5.1
	203016.2115	169979.5958		666063.6860	557675.8392	6	1.9
	203019.3495	169976.6279		666073.9813	557666.1020	6	2.7
	203018.4246	169976.7713		666070.9468	557666.5725	6	2.7
Average	***203019.3883***	***169979.5638***		***666074.1085***	***557675.7342***	***5.3333***	***2.9167***
SD	***1.8368***	***3.4931***		***6.0263***	***11.4602***		

GPS Control point No. 4

	Northing	Easting		Northing	Easting	Number of	PDOP
	Meters	Meters		Feet	Feet	Satellites	
	202418.5252	166704.1144		664102.7730	546929.5092	6	5.2
	202418.3414	166704.6786		664102.1699	546931.3602	6	3
	202418.7097	166703.8322		664103.3783	546928.5833	6	2.9
	202415.3862	166707.2221		664092.4744	546939.7051	6	2.6
	202415.7519	166705.2482		664093.6742	546933.2290	6	2.7
	202415.7528	166705.6710		664093.6772	546934.6161	6	2.8
	202415.7525	166705.5301		664093.6762	546934.1539	6	2.7
Average	***202416.8885***	***166705.1852***		***664097.4033***	***546933.0224***	***6.0000***	***3.1286***
SD	***1.5403***	***1.1359***		***5.0536***	***3.7267***		

GPS Control point No. 5

	Northing	Easting		Northing	Easting	Number of	PDOP
	Meters	Meters		Feet	Feet	Satellites	
	201727.8681	162885.2036		661836.8376	534400.2743	5	1.4
	201726.9428	162885.2052		661833.8018	534400.2795	5	1.4

	201727.4980	162885.2042		661835.6234	534400.2762	5	1.4
	201730.4626	162887.3133		661845.3497	534407.1959	4	1.8
	201729.7226	162887.4555		661842.9219	534407.6624	4	1.8
	201729.1669	162887.1746		661841.0988	534406.7408	4	1.9
	201728.9814	162886.8930		661840.4902	534405.8169	4	1.9
Average	***201728.6632***	***162886.3499***		***661839.4462***	***534404.0352***	***4.4286***	***1.6571***
SD	***1.2692***	***1.0849***		***4.1639***	***3.5595***		

GPS Control point No. 6

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	201133.7891	159255.6333		659887.7595	522492.2352	4	1.8
	201130.2761	159258.1750		659876.2339	522500.5741	5	4.9
	201130.0862	159254.2283		659875.6109	522487.6257	5	4.9
	201120.2845	159259.4561	**	659843.4531	522504.7772	4	5.3
	201124.5396	159258.4641	**	659857.4134	522501.5226	4	5.2

	201125.4655	159258.8858	**	659860.4511	522502.9062	4	5.1
Average	***201131.3838***	***159256.0122***		***659879.8681***	***522493.4783***	***4.6667***	***3.8667***
SD	***2.0852***	***2.0004***		***6.8412***	***6.5631***		

GPS Control point No. 7

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	200906.4971	157941.6957	**	659142.0509	518181.4163	5	5.2
	200854.8484	157925.8216		658972.5997	518129.3360	5	5.2
	200853.1830	157925.9644		658967.1358	518129.8045	5	5.2
	200848.3728	157927.2382		658951.3543	518133.9836	5	4.4
	200849.4835	157927.5190		658954.9984	518134.9049	5	4.4
	200848.7420	157926.3920		658952.5656	518131.2073	5	4.2
Average	***200850.9259***	***157926.5870***		***658959.7308***	***518146.8523***	***5.0000***	***5.2000***
SD	***2.9090***	***0.7590***		***9.5439***	***2.4901***		

GPS Control point No. 8

	Northing	Easting		Northing	Easting	Number of	PDOP
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	197151.9409	155382.7889		646823.9531	509786.0528	5	4
	197148.4257	155384.0607		646812.4203	509790.2254	6	2.6
	197149.9060	155383.7776		646817.2769	509789.2966	6	2.6
	197150.0912	155383.9185		646817.8845	509789.7589	6	2.7
	197150.6460	155383.4950		646819.7047	509788.3694	6	2.7
	197148.7953	155383.2143		646813.6329	509787.4485	6	2.7
Average	***197149.9675***	***155383.5425***		***646817.4787***	***509788.5253***	***5.8333***	***2.8833***
SD	***1.2748***	***0.4781***		***4.1823***	***1.5687***		

GPS Control point No. 9

	Northing	Easting		Northing	Easting	Number of	PDOP
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	195409.1547	153330.7849		641106.1506	503053.7562	6	2.7
	195409.1545	153330.3617		641106.1499	503052.3678	6	2.7

	195409.8944	153329.5149		641108.5774	503049.5896	6	2.7
	195408.0438	153329.5158		641102.5059	503049.5925	6	2.5
	195407.8586	153329.2337		641101.8983	503048.6670	6	2.5
	195407.6734	153328.9516		641101.2907	503047.7415	6	2.5
Average	***195408.6299***	***153329.7271***		***641104.4288***	***503050.2858***	***6.0000***	***2.6000***
SD	***0.8947***	***0.7009***		***2.9355***	***2.2995***		

GPS Control point No. 10

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	195262.0048	153266.2397		640623.3753	502841.9938	6	2.7
	195263.4861	153268.0729		640628.2352	502848.0082	6	2.7
	195262.5607	153267.7912		640625.1991	502847.0840	6	2.7
	195263.3015	153269.0605		640627.6296	502851.2484	6	2.5
	195263.1167	153269.7660		640627.0233	502853.5630	6	2.5
	195263.3018	153269.7659		640627.6306	502853.5627	6	2.5

Average	***195262.9619***	***153268.4494***		***640626.5155***	***502849.2433***	***6.0000***	***2.6000***
SD	***0.5669***	***1.3637***		***1.8598***	***4.4739***		

GPS Control point No. 11

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	195383.4254	153316.8305		641021.7369	503007.9741	6	2.7
	195383.0556	153317.6771		641020.5236	503010.7516	6	2.7
	195383.2408	153317.8180		641021.1312	503011.2139	6	2.7
	195382.1295	153315.7025		641017.4852	503004.2733	6	2.5
	195382.6849	153316.2665		641019.3074	503006.1237	6	2.5
	195382.1299	153316.5489		641017.4865	503007.0502	6	2.5
Average	***195382.7777***	***153316.8073***		***641019.6118***	***503007.8978***	***6.0000***	***2.6000***
SD	***0.5585***	***0.8196***		***1.8324***	***2.6889***		

GPS Control point No. 12

	Northing	Easting		Northing	Easting	Number of	PDOP
	Meters	Meters		Feet	Feet	Satellites	
	197214.7218	155445.9272		647029.9272	509993.1995	5	2.7
	197213.0590	155449.5954		647024.4718	510005.2343	4	3.4
	197213.0580	155448.3261		647024.4685	510001.0699	4	3.4
	197212.8728	155448.0441		647023.8609	510000.1447	4	3.4
	197215.8290	155441.5543		647033.5597	509978.8527	5	2.8
	197213.9818	155446.2099		647027.4993	509994.1270	4	3.4
Average	***197213.9204***	***155446.6095***		***647027.2979***	***509995.4380***	***4.3333***	***3.1833***
SD	***1.1723***	***2.8320***		***3.8463***	***9.2913***		

GPS Control point No. 13

	Northing	Easting		Northing	Easting	Number of	PDOP
	Meters	Meters		Feet	Feet	Satellites	
	197906.0900	156364.0394	**	649298.1955	513005.3786	5	2.8
	197914.9646	156354.4424		649327.3117	512973.8924	6	2.7
	197917.3674	156350.9148		649335.1949	512962.3189	6	2.7

	197917.7368	156350.0683		649336.4068	512959.5417	6	2.7
	197918.2924	156350.6319		649338.2297	512961.3907	6	2.7
	197918.6617	156349.6445		649339.4413	512958.1512	6	2.7
Average	***197917.4046***	***156351.1404***		***649335.3169***	***512963.0590***	***6.0000***	***2.7000***
SD	***1.4521***	***1.9105***		***4.7640***	***6.2680***		

GPS Control point No. 14

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	198134.8338	156994.8985	**	650048.6673	515075.1263	4	4.3
	198135.3972	157003.6411		650050.5157	515103.8094	6	3.4
	198143.1669	157000.6724		650076.0069	515094.0696	6	3.4
	198143.3429	156991.0830		650076.5843	515062.6083	5	2.9
	198142.6042	156992.6349		650074.1608	515067.6998	5	2.9
	198142.9739	156992.2115		650075.3737	515066.3107	5	2.9
Average	***198141.497***	***156996.048***		***650070.528***	***515078.899***	***5.4000***	***3.1000***

	0	***6***		***3***	***5***		
SD	***3.4209***	***5.7022***		***11.2235***	***18.7079***		

GPS Control point No. 15

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	201718.4542	162899.1740		661805.9521	534446.1089	5	1.4
	201719.0108	162900.0187		661807.7782	534448.8802	6	2.9
	201718.2706	162900.0200		661805.3497	534448.8845	6	1.4
	201720.2829	162895.7879		661811.9518	534434.9997	4	1.9
	201720.4881	162898.1838		661812.6250	534442.8602	4	1.9
	201720.4884	162898.3247		661812.6260	534443.3225	4	1.9
Average	***201719.4992***	***162898.5849***		***661809.3805***	***534444.1760***	***4.8333***	***1.9000***
SD	***1.0403***	***1.5820***		***3.4129***	***5.1904***		

GPS Control point No. 16

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	

	202347.1875	166664.3890		663868.7254	546799.1765	6	5.3
	202346.2628	166664.6729		663865.6916	546800.1079	6	5.3
	202347.7452	166665.5152		663870.5551	546802.8714	6	2.9
	202363.0512	166641.3804	**	663920.7717	546723.6890	6	2.7
	202346.6269	166661.9943		663866.8862	546791.3199	6	2.7
	202346.9967	166661.8525		663868.0994	546790.8547	6	2.7
Average	***202346.9638***	***166663.6848***		***663867.9915***	***546796.8661***	***6.0000***	***3.7800***
SD	***0.5627***	***1.6612***		***1.8463***	***5.4500***		

GPS Control point No. 17

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	203303.5834	169899.6258		667006.5072	557413.4705	5	5
	203303.9505	169898.4974		667007.7116	557409.7684	5	4.9
	203311.0036	169906.2292		667030.8517	557435.1352	6	4.6
	203313.6005	169908.4770		667039.3717	557442.5098	6	2.6

	203311.5626	169907.6369		667032.6857	557439.7536	6	2.6
	203309.1564	169907.5025		667024.7913	557439.3127	6	2.6
Average	***203308.8095***	***169907.8721***		***667023.6532***	***557440.5254***	***6.0000***	***2.6000***
SD	***4.1567***	***4.4112***		***13.6374***	***14.4725***		

GPS Control point No. 18

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	203696.2940	169833.6133		668294.9278	557196.8940	6	4.1
	203695.5507	169832.4879		668292.4892	557193.2018	6	4.2
	203700.1840	169835.0120		668307.6903	557201.4829	6	3.1
	203702.2234	169836.4157		668314.3812	557206.0883	6	2.5
	203702.2231	169836.2748		668314.3802	557205.6260	6	2.4
	203702.2227	169836.1339		668314.3789	557205.1637	6	2.4
Average	***203699.7830***	***169834.9896***		***668306.3746***	***557201.4094***	***6.0000***	***3.1167***
SD	***3.1019***	***1.6216***		***10.1767***	***5.3203***		

GPS Control point No. 19

	Northing	Easting		Northing	Easting	Number of	PDOP
	Meters	Meters		Feet	Feet	Satellites	
	204700.0605	169759.7829		671588.1250	556954.6683	6	3.8
	204700.2493	169761.1914		671588.7444	556959.2894	6	3.8
	204698.0301	169761.7608		671581.4636	556961.1575	6	3.8
	204701.2016	169771.3333		671591.8688	556992.5633	6	3
	204698.7872	169768.0991		671583.9475	556981.9524	6	3
	204700.4498	169766.9675		671589.4022	556978.2398	6	2.9
	204702.4843	169766.5394		671596.0771	556976.8353	6	2.9
	204702.6701	169766.8207		671596.6867	556977.7582	6	2.9
	204702.2989	169766.3990		671595.4688	556976.3747	6	2.9
Average	***204700.6924***	***169765.4327***		***671590.1982***	***556973.2043***	***6.0000***	***3.2222***
SD	***1.6330***	***3.7376***		***5.3577***	***12.2626***		

GPS Control point No. 20

	Northing	Easting		Northing	Easting	Number of	PDOP
	Meters	Meters		Feet	Feet	Satellites	
	206898.5562	172167.4583		678801.0374	564853.8658	6	4.3
	206893.3678	172165.2202		678784.0151	564846.5230	6	4.3
	206894.2985	172167.0485		678787.0686	564852.5213	6	4.2
	206895.5914	172166.1995		678791.3104	564849.7359	4	6.2
	206892.9972	172165.0804		678782.7992	564846.0643	5	2.8
	206892.6284	172165.5041		678781.5892	564847.4544	5	2.8
	206891.8885	172165.6471		678779.1617	564847.9236	5	2.8
	206891.3375	172167.0573		678777.3540	564852.5502	6	1.9
Average	***206893.8332***	***172166.1519***		***678785.5420***	***564849.5798***	***5.3750***	***3.6625***
SD	***2.3297***	***0.9276***		***7.6433***	***3.0433***		

GPS Control point No. 31

	Northing	Easting		Northing	Easting	Number of	PDOP
	Meters	Meters		Feet	Feet	Satellites	
	211224.3979	178400.0376		692993.4314	585301.9606	5	2.5

	211223.6598	178400.6035		692991.0098	585303.8173	5	2.4
	211223.4758	178400.8858		692990.4062	585304.7434	5	2.4
Average	***211223.8445***	***178400.5090***		***692991.6158***	***585303.5071***	***5.0000***	***2.4333***
SD	***0.4880***	***0.4319***		***1.6010***	***1.4172***		

GPS Control point No. 32

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	211544.3758	177566.0364		694043.2277	582565.7362	4	11.1
	211549.7699	177573.3362		694060.9249	582589.6857	4	10.8
	211545.3284	177573.3527		694046.3530	582589.7398	4	10.6
Average	***211546.4914***	***177570.9084***		***694050.1685***	***582581.7206***	***4.0000***	***10.8333***
SD	***2.8790***	***4.2193***		***9.4454***	***13.8429***		

GPS Control point No. 33

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	

	212034.1997	176949.5286		695650.2615	580543.0728	6	2.4
	212034.0120	176948.8255		695649.6457	580540.7661	6	2.4
	212035.1229	176948.9622		695653.2904	580541.2146	6	2.4
Average	***212034.4449***	***176949.1054***		***695651.0658***	***580541.6845***	***6.0000***	***2.4000***
SD	***0.5947***	***0.3728***		***1.9509***	***1.2231***		

GPS Control point No. 34

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	211978.1651	177314.5777		695466.4209	581740.7405	6	3.5
	211978.7250	177315.8424		695468.2579	581744.8898	6	3.3
	211978.3575	177316.5476		695467.0522	581747.2034	6	3.3
Average	***211978.4159***	***177315.6559***		***695467.2437***	***581744.2779***	***6.0000***	***3.3667***
SD	***0.2845***	***0.9981***		***0.9333***	***3.2746***		

GPS Control point No. 36

	Northing	Easting		Northing	Easting	Number of	PDOP
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	210866.5147	177275.1720		691819.2739	581611.4567	6	2.9
	210866.3297	177275.1726		691818.6670	581611.4587	6	2.9
	210866.3271	177274.4688		691818.6585	581609.1496	6	2.9
Average	***210866.3905***	***177274.9378***		***691818.8665***	***581610.6883***	***6.0000***	***2.9000***
SD	***0.1077***	***0.4062***		***0.3529***	***1.3326***		

GPS Control point No. 37

	Northing	Easting		Northing	Easting	Number of	PDOP
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	211287.3460	177672.5705	**	693199.9541	582915.2575	3	4.6
	210866.5147	177275.1720	**	691819.2739	581611.4567		2.9
	211389.0546	177651.7794	**	693533.6437	582847.0453	5	3.8
	211256.3095	177687.1859	**	693098.1283	582963.2083	5	3.1
	211229.1525	177699.9568		693009.0305	583005.1076	6	2.9
Average	***211229.152***	***177699.956***		***693009.030***	***583005.107***	***6.0000***	***2.9000***

	5	***8***		***5***	***6***		
SD	***0.0000***	***0.0000***		***0.0000***	***0.0000***		

GPS Control point No. 40

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	211333.2422	177820.9123	**	693350.5322	583401.9432	4	9.8
	211375.3181	177838.4914		693488.5764	583459.6175	5	6.6
	211375.1161	177833.9876		693487.9137	583444.8412	5	6.6
Average	***211375.2171***	***177836.2395***		***693488.2451***	***583452.2293***	***5.0000***	***6.6000***
SD	***0.1428***	***3.1847***		***0.4685***	***10.4484***		

GPS Control point No. 42

	Northing	**Easting**		**Northing**	**Easting**	**Number of**	**PDOP**
	Meters	**Meters**		**Feet**	**Feet**	**Satellites**	
	210756.6644	177396.9296	**	691458.8727	582010.9239	5	4.4
	210723.3532	177447.1711		691349.5840	582175.7582	5	4.4
	210723.5409	177447.8743		691350.1998	582178.0653	5	4.4

Average	***210723.4471***	***177447.5227***		***691349.8919***	***582176.9117***	***5.0000***	***4.4000***
SD	***0.1326***	***0.4972***		***0.4353***	***1.6314***		

Appendix C

Data and notes provided by Andrew Corporation.

The objective of this section is to report on the experiences encountered during the two days operational testing of the CPS on August 18 and 19, 1997. Most of the text in this section is based on notes compiled by Bob Kidwell of Andrew Corporation immediately following the completion of the field test.

The CPS was installed in a coach style bus and operation verified on Sunday 17th. On Monday and Tuesday we followed a set of pre-selected but typical NJT bus routes . The tests were done with a CPS outfitted with external DCI FM broadcast differential corrections. The unit was run with corrections almost all of the time. In addition, there was an attempt to demonstrate a differential correction receiver which works with the AM Coast Guard beacons. We were unable to receive corrections from the Coast Guard beacons.

There were a few hardware problems during the course of the data collection. The reason why these problems are given here is to provide an insight into why some discrepancies or erroneous data may have been experienced. The problems and their resolution are listed below.

There was a problem with the design of the odometer used in this particular bus. It is a Hall effect sensor, which produces a pulse each time one of four bolts on the wheel hub passes the sensor. In this case, there are so few bolts that the distance traveled is .8 meters per pulse. Typically it is recommended to work with .04 to .4 meters per pulse. The coarse output causes little difference at high speed but makes the position solution less accurate at low speeds. In the tests the unit nevertheless performed well in general.

A second problem was also related to the odometer design. When the vehicle was stopped we saw a few instances in which odometer pulses occurred. It is believed that this is due to the following occurrence. If the hall sensor is sitting adjacent to a bolt when the vehicle is stopped, the vehicle jitter will generate odometer pulses. As a result the CPS position will creep forward when the vehicle is not moving and require the CPS to slowly correct the position in subsequent travel. We observed this a few times in the two days data. The CPS software is already designed to recognize and eliminate this type of noise based on physical limits of motion of a vehicle. The odometer scale factor is so coarse that one stray pulse is an apparent motion of .8 meters which is large enough to be indistinguishable from real bus motion. Our analysis indicates that above .3 meters per pulse, the algorithm cannot filter this noise properly. The solution to both problems should be to find a transmission speed sensor in the bus, modify the existing sensor to be more precise, or install a different wheel sensor.

We also had introduced a ground loop through the communications interface between the monitor computer and the CPS because of differences in the power routing in the bus for the CPS and the computer. This was eliminated by using a floating supply for the computer but *raised a question about proper isolation of the communication circuits. Since we cannot rely on proper isolation in other equipment we had already redesigned CPS communications to be fully isolated. We were told that the board change had already been implemented but was not available at the time this testing took place.*

There was one instance of the CPS failing due to a quick repeat of starting the bus engine, causing multiple dips in supply voltage. Since the power supply monitor element was removed during the tests, this CPS was susceptible to this and indeed failed. After a short initialization the system was performing again.

The above description could be used to explain some of the AVL positioning accuracy problems that were found in this study. The above description is also an indication of what can go wrong during a real-world implementation of an AVL system.

August 20, 1997

Andrew Sensor Products visit to New Jersey Transit Ironbound Garage, Newark NJ.

<u>Notes pertaining to each data run.</u>

The data sets are all named uniformly. For each run there are three Mapinfo tables (consisting of 4 files each) and one file of the direct NMEA 0183 ASCII output of the CPS. Mapinfo requires all four files of a particular name to be in the same directory. Do not modify any of the four files independently. Only make changes from within Mapinfo, where all four files are handled as one table.

Tables beginning with MARK contain points specifically marked during the run. GPSlink copies the latest point from the CPS table at the time of mark with added comments entered by the operator. Unfortunately the last time I worked with Honkus Assoc., the vendor who sells GPSlink, they had me set up my machine a little differently than we normally do. It has since worked fine on a number of occasions except that I do not mark events. I now find that the marker files reference a non-existent vehicle, that is the operator comments are in the files but all position data is zero. I have therefore created a new mapinfo table beginning with 'newmark' for each of the tables. This consists of a point from the CPS data for each place at which the bus came to a stop or very slow and therefore should contain the positions of the marked places plus stops at intersections and it should be possible to correlate the marked places from these files.

I have added a few of additional mark points to mark occurrences of odometer creep when the vehicle was not moving.

Tables beginning with CPS are the Mapinfo stored CPS position, time etc. CPS time is local.

Tables beginning with GPS are the Mapinfo stored GPS position, time etc. GPS time is UTC.

Files beginning with NMEA are the ASCII NMEA 0183 output of the CPS. These contain all of the information available from the CPS. The Mapinfo tables are parsed and contain selected information.

Please see the description of table and NMEA structure below.

Monday August 18, 1997.

Directory 81897

We left Ironbound Garage for Dunellen via North Ave. Data sets 'Iron to Dun via N Av 818'. At the start of the data set the CPS had just been installed and was learning its current position, heading and vehicle parameters. Note in Plainfield at Terrill and Front Streets odometer creep (newmark point 53) caused 50 m overshoot at the corner.

At the end of the previous run, odometer creep caused 284 meters offset at the beginning of the next run, 'Dun to

Iron Via S. Ave 818', Dunellen to Ironbound Garage via South Ave. The CPS recovered after its reset distance of 2 km. A creep of 30 meters occurred at the corner of Watchung and E. 5th St in Plainfield.

Tuesday August 19,1997.

Directory 81997am

We reinstalled the hardware in the bus and began run 'Ironbound to PA', to the Port Authority through the Lincoln Tunnel. As I noted at the time, we did not give the CPS very much time to adjust to the vehicle before entering the tunnel, about ten minutes. Nevertheless, the error at the end of the 2.43km tunnel was a very modest 30 meters offside.

The next two sets, 'PA to Cranford' and 'Cranford to Dun 819' run from the Port Authority to Dunellen. The end of the 'PA to Cranford run was when the CPS was affected by multiple starting of the bus. Recall that we had removed our protective power watch-dog device. I restarted the CPS with default parameters and it took a turn around Union and Springfield streets to recover (.7km.)

The next run 'Dun to PA via S 819' is Dunellen to the Port Authority via South Ave and through the Lincoln Tunnel, with logging beginning after the bus moved 315 meters (one block). Note an odometer creep of 25 meters at the corner of Bley and Liberty in Hillside. The second pass across the Tunnel was similar to the first.

Tuesday August 19, afternoon

Directory 81997pm

'PA to Newark' was from the Port Authority to Penn Station in Newark. One occasion of odometer creep was at newmark point 14, about 58 meters. Another odometer creep occurred while saving this run and starting the last run, 'Newark to Iron', of 340 meters. The CPS recovered in 2km despite very poor GPS coverage.

Aside from errors due to the odometer noise, which the current CPS algorithm could not filter due to the coarse odometer scale factor, the CPS stayed within a few meters RMS based on multiple runs in almost all areas.

Table Structure

Mapinfo tables, created by GPSMap from Honkus and Associates for GPS receivers.

The CPS table columns are:

Vehicle ID(=2), Time (seconds elapsed this day), Latitude (decimal degrees), Longitude, GPS Height (0), Speed(knots), Heading (degrees true), Note,'Datum'='Receiver output'.

GPS table columns:

Same. Note that GPS time is UTC while CPS time is local. In addition the columns speed and heading in the GPS tables cannot be filled from the GGA message which the CPS transmits from the internal GPS receiver. GPSMap copies the needed data from the CPS data.

Mark and newmark files are based on the CPS files. The Mark files have additional columns Description and Type (of event) added by GPSMap.

The NMEA files contain the two standard NMEA0183 message type GPGGA and GPRMC. In the case of the CPS, the GPRMC is based entirely on the CPS current position calculation. The GPGGA message is copied unchanged from the GPS receiver and can be used not only to indicate the GPS receiver uncorrected position but also the quality: No data, GPS or DGPS; and the age of differential corrections. Note a peculiarity of this and many other receivers that the quality indicator is very slow to change to a lower quality level. It is more reliable to look at age of differential data for DGPS quality and HDOP for presence of a useful GPS position.

The following description is taken from our CPS manual:

RMC OUTPUT

The GGA message syntax conforms to NMEA0183; however, the electrical interface is RS232-C and data rate is 9600 baud.