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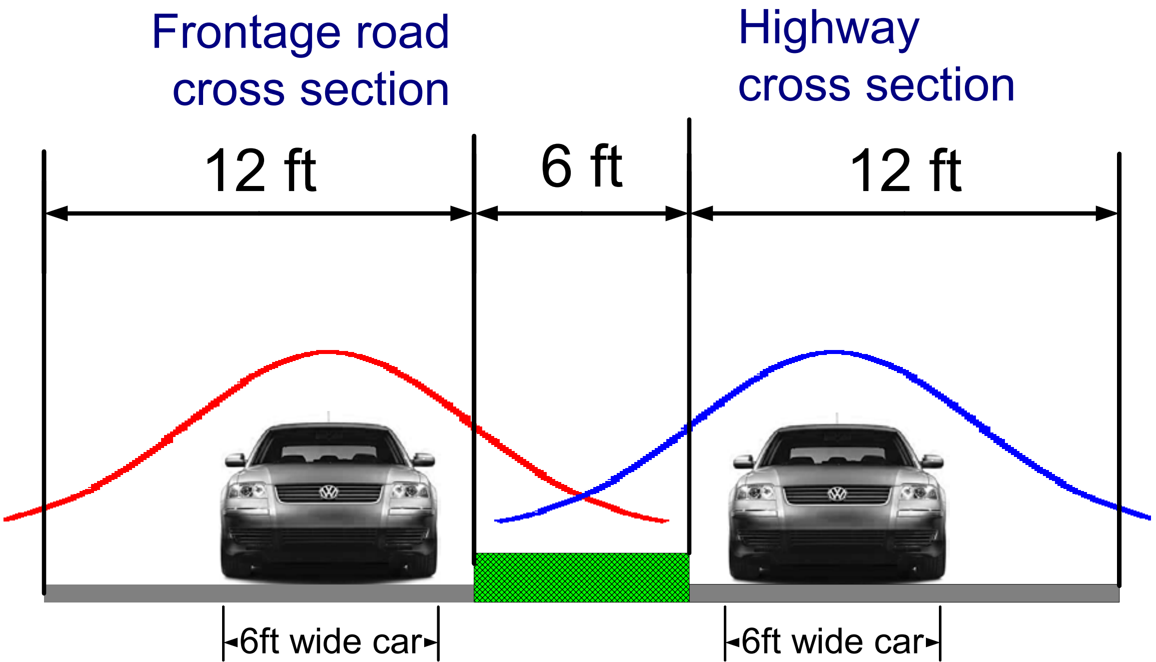
Final Report

# A New Approach to Assessing Road User Charges: Evaluation of Core Technologies



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16. Abstract (Limit: 200 words)

The main goal of this research was to develop the system requirements for the GPS and the digital map components that make up the core of an in-vehicle road user charging system. The focus was to evaluate both GPS and digital maps in the most difficult of environments – where roads of different jurisdictions and possibly different fee structures are located in close proximity to each other (a highway and a frontage road, for instance). In order for the system to be effective it must be able place the vehicle on the correct road.

GPS receivers that are commonly used by automotive navigation systems do not have sufficient accuracy for road user charging applications. However, the GPS-determined positions can be corrected, and thus made more accurate, using publicly and privately available wireless signals, namely, using differential GPS (DGPS). This experimental study based on road testing found that only certain DGPS receivers are capable of achieving the needed accuracy.

Extensive testing of existing digital maps found that they are also not accurate enough to be used for road user charging. There are however, new, higher accuracy digital maps (not yet publicly available) that are already being used for vehicle safety applications. By combining DGPS and such high accuracy digital maps, the ability to design a road user charging system with high geographical resolution can become a reality.

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# A New Approach to Assessing Road User Charges: Evaluation of Core Technologies

## Final Report

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# Executive Summary

## *Background*

With advances in modern technology, vehicles are becoming less dependent on traditional fossil fuels. With less fuel consumption, state and federal income from motor fuel taxes is reduced, decreasing the revenue available to maintain and improve the transportation infrastructure. To keep pace with future transportation needs under these circumstances, a new funding mechanism is needed in the long term to supplement or replace the current road financing mechanism. One possible approach is to charge for road use based directly on travel on public roadways, using a "users pay" principle rather than a flat fuel tax.

The type of system under consideration involves an on-board computer system that would use a differential GPS (DGPS) receiver, digital road maps, and map-matching software as the basis for computing charges. The charges would be computed in real time and would be based on such parameters as miles traveled, time of travel, road jurisdiction, and road type. For many applications, it is desirable that such systems resolve jurisdictional boundaries smaller than the county level – perhaps at levels down to individual road segments or even specific lanes.

The main goal of this research project was to develop the system requirements for the DGPS and digital maps for an on-board computer system that will allow location resolution down to the road segment level. Our focus was to evaluate both DGPS and digital maps in the most difficult environment, with special concern for minimal errors when roads of different jurisdictions are located close to each other. If only a Vehicle Miles Traveled (VMT) based charge were the objective, then much simpler technologies could serve that function.

## *Objectives*

For the research on the GPS component, the objectives are the following:

- Evaluate accuracies of different DGPS technologies for road user charge applications, particularly in locations where problems are likely to arise, and document the differences among them;
- Examine and document dynamic effects (i.e., of vehicle speed) on the accuracies of GPS receivers;
- Examine and document the effect of elevation and changes in elevation on the accuracies of GPS receivers;
- Document the GPS coverage in a downtown environment where multipath effects are the most significant;
- Identify the least expensive GPS technology presently available that would meet the needs of road user charge applications;
- Identify limitations of GPS technology and possible means to overcome these limitations.

For the research on the digital map component, the objectives are as follows:

- Survey and acquire digital road maps for testing;
- Select test routes for the evaluations of GPS and digital maps;
- Evaluate the positional accuracies of the acquired digital maps;
- Evaluate the map matching accuracies of the acquired digital maps.

This study also recommends the minimum required accuracy for the GPS and for the digital map based on the road separation distance associated with a specified requirement to distinguish roads running in close proximity from each other.

## *Key Findings*

In this project, five GPS receivers using three different DGPS technologies were evaluated. The five receivers evaluated were the Trimble AgGPS 132 receiver, the CSI GBX-12R receiver, the JRC DGPS 212 receiver, the NavCom SF-2050M receiver and the Garmin GPS 76 receiver. Among the receivers evaluated, the Trimble, CSI, and JRC receivers use correction signals from the Nationwide DGPS (NDGPS) services to improve their accuracies. The NavCom receiver uses a proprietary global DGPS correction services and the Garmin receiver uses the Wide Area Augmentation System (WAAS) service provided by the Federal Aviation Administration (FAA). All prices listed below are for single quantities (in 2002).

The main results of the GPS evaluations are listed as follows:

- The NavCom SF-2050M receiver has the highest overall accuracy among the GPS receivers tested. The receiver is able to distinguish between two roads with a separation of 1.2 m (4 ft) at a confidence level of 99.73%. However, it is unlikely that the present cost of the receiver ($6,000) and the annual subscription fee ($850) can be reduced to the extent that it could be used for road user charging applications in the near term.
- The Trimble AgGPS 132 receiver has the highest accuracy among DGPS receivers that utilize publicly available correction signals. It is capable of distinguishing between two roads with a separation distance of 1.8 m (6 ft) at a 99.73% confidence level.
- The Garmin GPS 76 receiver has the best price/performance ratio among the GPS receivers tested. At $200, this receiver can distinguish between two adjacent roads with a separation of 6.1m (20 ft) at 99.73%. It is a good candidate for most of the road user charging applications that do not require lane-level road pricing.
- The accuracies of the NDGPS receivers are relatively insensitive to the distance of the vehicle from the reference station.
- On rare occasions, a GPS receiver would drift out of the normal course for few seconds and then converge back. This problem can be corrected by using an inexpensive inertial measurement sensor.
- The positional accuracies of GPS receivers are not affected by vehicle speeds. This is consistent for all receivers and across the range of speeds tested.
- The accuracies of GPS receivers are not affected by a change of elevation. Results have shown that the accuracy of a GPS receiver does not degrade when a vehicle travels on hilly terrain as long as the GPS receiver has enough satellites in view to compute position solutions.

- The GPS coverage in a downtown environment is spotty. We are particularly referring to areas where tall buildings on both sides of streets create an urban canyon. Urban canyons present serious multipath problems which are difficult to overcome. It is very difficult for a GPS receiver to function accurately in a downtown environment. Secondary sensors (e.g., an odometer) are needed to track mileage traveled in a downtown area.

For the digital map component, digital maps from both the private sector and the public sector (Mn/DOT basemap and City of Minneapolis road map) were evaluated.

Map positional accuracies can be quantified by the percentage of roads described by a digital map, which are "located" within a specified range of the physical roadway. Map matching accuracy is quantified by the percentage of roads traveled that are correctly identified.

The main findings of the digital map evaluations are:

- For the commercial map, the overall positional accuracy in the Twin Cities Metropolitan Area can be summarized as follows: 60% of the roads in the map were within ± 12 m (40 ft) of the actual roads and 80% were within ± 46 m (150 ft). 65% of highways were within ± 12 m (40 ft) of the actual highways.
- For the Mn/DOT basemap, the positional accuracy in the Twin Cities Metropolitan Area is as follows: 83% were within ± 12 m (40 ft) and 90% were within ± 15 m (50 ft). For interstate highways, 87% were within ± 12 m (40 ft) of their correct locations.
- For the Mn/DOT basemap, the overall positional accuracy in Duluth (an area with significant elevation changes): 91% of roads were within ± 12 m (40 ft).
- Positional accuracy of the digital map in the downtown area from the City of Minneapolis: 91% of the municipal streets in downtown Minneapolis were within ± 12 m (40 ft).
- Using the Mn/DOT basemap resulted in a better map matching accuracy than using the commercial map (87% vs. 73%).

In an analysis of the seven counties that encompasses the Twin Cities metropolitan area, the research found that 5% of the Interstate highways and 2.5% of the Minnesota state highways are within 15 m (50 ft) of another road with a different jurisdiction. This implies that existing digital road maps are NOT adequate for most of the road user charging applications. They are not designed for distinguishing roads at the level required by a road usage charging system and may lead to inaccurate and unfair charges.

Although there are clearly candidate GPS receiver technologies that can be used for a road user charging system, the same cannot be said for digital maps presently available from the public or private sectors. It is our contention that higher accuracy digital maps do already exist but these have not yet become commonly available. Such digital maps exhibit accuracies in the decimeter range and can be readily acquired as needed. By combining GPS receivers and such newer digital maps, the ability to design a road user charging system with good lateral resolutions becomes possible. Given that digital maps of higher accuracies have not yet entered the mainstream, a broad based field operational test is recommended to evaluate a road user charging system that would take advantage of this new technology.

# Chapter 1
# Introduction

This report presents a study design to develop a new approach for charging vehicles for travel on public roads. The new approach applies intelligent transportation system (ITS) technology that incorporates Global Positioning System (GPS) and geographic information system (GIS) to compute road usage and assess user charges in real-time. Although this approach is simple in concept, several technological issues need to be resolved. This project examines the accuracy of GPS and GIS and how this affects their use as the primary "sensor" for determining user charges.

## *1.1 Background*

Motor fuel tax has been a major source for financing public roadways in the United States for many years. Placing an excise tax on fuel charges road use as a utility. This tax is used to approximate the distance driven by a given vehicle user or roughly the amount of road usage. In recent years, the correlation between fuel consumption and road usage has changed dramatically with high efficiency internal combustion engines and newly introduced "green" cars. While these cars are still in the minority, there is a growing movement by automobile manufacturers to respond to the ever-increasing environmental restrictions placed by both federal and state governments on vehicle emissions. This development in automobile technology leads to new vehicles that are more independent of traditional fuels and thus revenues from motor fuel taxes would be reduced. The advance of fuel cell technology will further contribute to a sharp drop in the revenues that pay for much of the construction and maintenance of our road and highway system.

Another impact on the transportation infrastructure is the growth of vehicles and the corresponding congestion caused by too great a demand by the growing number of vehicles that is out-pacing the supply of road space. The most obvious evidence of this is in urban areas where increasing demand has caused severe congestion and increased pollution as vehicles crawl on interstate highways at average speeds of less than 20 MPH during rush hours (e.g., Los Angeles, New York). This vehicle growth and congestion problem will continue to add pressure to governments and legislatures for increased road capacity and better maintenance.

In order to keep pace with future transportation needs under these circumstances, a new funding mechanism is needed to supplement or replace the current road financing mechanism for the longer term. Instead of a flat fuel tax, users would be charged for road use based directly on their travel on public roadways, and also perhaps for the added congestion they contribute to the system.

Lately, technological innovation has allowed governments to look at new approaches to charge vehicles for road usage. GPS was originally developed by the Department of Defense (DoD) to enhance the navigation and timing ability for armed forces. After the tragedy of Korean Airlines Flight 007 in 1983, GPS was made available to civilian applications internationally. Currently, it is employed around the world for many applications from air traffic control, precision agriculture, to vehicle navigation. An adjunct to GPS is GIS, an advanced digital map which attaches different attributes (e.g., jurisdiction, pricing, and congestion level) to each road segment. Together, GPS and GIS are making the road user charges a reality. Road usage can be priced just like any other utility. The charge can be based on the distance traveled plus other externalities like environmental charges, time of day charges, and location charges. Such a system can be utilized to generate revenues that could continue to fund the transportation needs of the future.

## *1.2 Other Road User Charge Projects*

The shortfall of revenues from motor fuel taxes and the increase in congestion and demand are not problems that only the U.S. needs to face. In fact, many parts of the world have more serious problems than the U.S. does and there is a global movement to charge road usage as a utility.

In New Zealand, public roadways are financed through levies in the price of fuels and road user charges [I-1]. Commercial vehicles are charged not only by the weight carried but also by the distance traveled. In 2002, the Ministry of Transport (of New Zealand) also started to investigate ways of calculating and collecting such road user charges electronically.

In Singapore, Electronic Road Pricing (ERP) has been implemented for years [I-2]. This is an automatic electronic system of road pricing. Charges are levied on a per-pass basis when a vehicle passes the ERP gantry. These charges can vary according to time and congestion levels. With ERP, motorists are more aware of the true cost of driving. Therefore, drivers may carpool, use public transportation, or choose a different route, destination, or time of travel.

In Japan, an experimental Electronic Toll Collection (ETC) service was started in 2000 [I-3]. This ETC system is designed to be used on all toll roads in Chiba. The purpose of this experimental system is “to verify the function of ETC equipment and the effects of ETC on the smoothness of traffic flow.” This system, however, does not select GPS as the position sensor. It uses a two-way radio communication system at the entrances and exits to compute the road usage for vehicles.

In Europe, there is a demonstration road pricing project, PRoGR€SS (Pricing Road user for Greater Responsibility, Efficiency and Sustainability in citieS), that is currently underway [I-4]. This project is led by the Bristol City Council (U.K.), with 28 partners from 8 cities in Europe. The goal of this project is to demonstrate and evaluate the effectiveness and acceptance of integrated urban transportation pricing schemes to achieve transportation goals and raise revenue. The participating cities include Bristol (U.K.), Edinburgh (U.K.), Copenhagen (Denmark), Genoa (Italy), Gothenburg (Sweden), Helsinki (Finland), Rome (Italy) and Trondheim (Norway). Each city has a different role in the project. Some are researching different types of road pricing schemes, some through demonstrations with volunteer drivers, and others by implementing full, real road user charges.

In Copenhagen, the PRoGR€SS demonstration project is to test whether road user taxes are an efficient means to change the travel behavior of motorists [I-5]. A GPS-based vehicle positioning system is used to track vehicles in zones divided by the city. The city may apply road charges based on the distance traveled, and/or with different levels of charges across different zones. A display inside the vehicle would keep the motorist up to date with all the charges accumulated. To simulate a situation where reduced driving is equal to money saved, each motorist is given an account with a fixed cash amount. A motorist is allowed to cash the amount left on the account at the end of the project. This will allow a person to cash a larger amount if he/she reduces the driving compared to no change in driving behavior.

Within PRoGR€SS, Genoa plans to test a zone pricing scheme that is designed to protect the historical center and the downtown [I-6]. Fees are collected at the entrance in the protected zones and fares are varied according to day of the week, time of day, user type and environmental conditions. The technology adopted in the Genoa demonstration is based on license plate recognition and central data processing. The main goal of this road pricing application is to manage demand in the protected areas and at the same time promote public transportation for better access to central locations. Rome's activities in the PRoGR€SS are very similar to the road pricing demonstration in Genoa [I-7].

In Germany, the government plans to implement an automatic road-tolling system for commercial trucks [I-8]. This system which begins its rollout in May 2003 uses GPS-equipped on-board units to measure truck movements along roads. Once a vehicle begins to move, the GPS receiver on-board automatically identifies the road on which the vehicle is traveling. As soon as the truck enters a toll road, the on-board unit will send the truck's configuration (e.g., number of axles and emission class) and the distance traveled to the Toll Collect Center. The center then arranges payment of the toll with the shipping company. The system claims to be able to distinguish roads that are in close proximity and parallel to each other.

In London (U.K.), the city government has implemented a "Traffic Management Zone" that would charge motorists £5 per trip for entering the zone [I-9]. Similar to the technology adopted in Genoa, computerized cameras scan the license plates of all vehicles entering the zone and the processing center deducts the fees automatically from motorists' accounts at the end of a day. Penalty for late and non-payment is significant. Within three weeks of turning on the system, the traffic in the management zone has fallen by 20%. Although still early, the results thus far seem to indicate that a road pricing application not only can be used to raise revenues but can also be used to manage demands. What is interesting is that the congestion at the periphery of the managed area has increased significantly.

While each country is different, several common trends are emerging. It is clear that revenues from traditional fuel taxes are likely to decrease significantly in the future and the use of alternative fuels are expected to increase significantly in the years to come. In addition, pressures on road transportation demand are calling for more road transportation expenditures. These revenue implications have forced countries all over the world to find alternative funding sources. One potential source that is popular in many countries is based on the "user pays" principle. Several countries and cities have introduced electronic road pricing, distance-based charging, and higher urban zone charges. These systems are enabled by the advances of the ITS technologies in recent years. With lessons learned from other road user charging projects around the world, it is certain that new approaches for charging road users will be developed using technologies already available today.

## *1.3 Accuracy and Error*

All measurements from sensors contain errors. By definition, accuracy is a degree of conformity of a measure to a standard or a true value. In other words, accuracy is used to describe errors of measurements made by a sensor. This section discusses errors introduced by GPS receivers and errors contained in digital maps. Both must be considered since the output of a GPS receiver is the position expressed in the degrees of latitude and longitude on the earth. One must match this position with the location on a digital map to determine the position needed for road user charging.

### 1.3.1 GPS Errors

In GPS, the accuracy of an estimated or measured position of a body (vehicle, aircraft, person, or vessel) at a given time is the degree of conformance of that position with the true position of the body at that time. Since readings from a GPS receiver vary with time for a particular location, GPS accuracy needs to be treated as a statistical measure of performance and expressed statistically. For a fixed location, GPS measurements need to be made periodically and recorded over an extended period of time. Statistical analysis of the recorded data is then performed to compare against the previously known coordinates of the same location. Finally, the result of the statistical analysis represents the accuracy of the GPS receiver for a fixed location.

For applications that require the understanding of the dynamic performance of GPS receivers, a different approach needs to be taken. If a body's direction of travel is known, the errors of the on-board GPS can be separated into three components: positional error, lateral error and longitudinal error. Figure 1.1 illustrates the three error components. The positional error is the distance between the GPS position and the reference position (i.e., ground truth). The longitudinal and lateral errors are the corresponding vector components of the positional error in the direction of travel and perpendicular to the direction of travel, respectively.

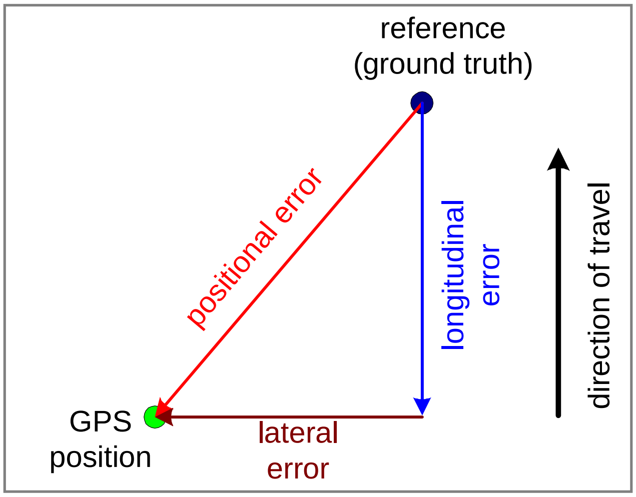


Figure 1.1 Error components of a GPS measurement

For road user charging applications, the lateral accuracy of a GPS receiver is more significant than the longitudinal accuracy. When a vehicle travels on a road, the lateral accuracy of the on-board GPS receiver is the parameter which will most affect the ability of the receiver to determine its correct location on a road, in particular for situations in which roads are in close proximity to each other. It also determines which jurisdiction the road belongs to. This issue is most significant when adjacent roads belong to different jurisdictions or are rated differently. It is often the case that congestion will lead to diversion of traffic to roads running parallel to the congested road. Being able to correctly determine the vehicle's position on a road allows the rate structure to factor in different traffic management strategies and, most importantly, will not lead to unfair charges due to incorrect readings. In addition, these incorrect road charges may result in revenues collected being distributed incorrectly among government agencies, which have jurisdiction over these roads. Over time, errors in the system will cause the general public to lose confidence in the road user charging system and eventually cause the system to fail. On the other hand, the longitudinal accuracy of a GPS receiver is not as important as the lateral accuracy because the road jurisdiction (or the road type) generally does not change very often over its length. The exception of course is for travel crossing municipal, county or state boundaries. Therefore, this project will focus on the lateral accuracies of GPS receivers.

### 1.3.2 Map Errors

Map accuracy is defined as the degree to which information on a map or in a digital database matches true or accepted values. The map accuracy is an issue related to the data quality and the number of errors contained in a dataset or a digital map. In discussing digital road maps, most commonly considered are horizontal and vertical accuracies with respect to geographic positions, as well as attribute, and logical accuracy. For road user charging applications, it is most important to evaluate the positional accuracy of a digital map. The level of accuracy required for a particular application varies greatly. Formally, the traditional positional accuracy of a digital road map includes two components: lateral accuracy and longitudinal accuracy. Figure 1.2 illustrates the lateral accuracy and the longitudinal accuracy of a digital map.

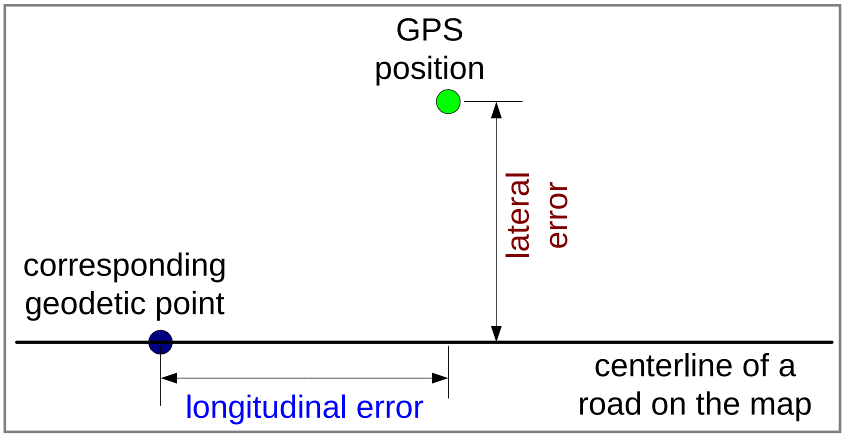


Figure 1.2 Definition of map positional accuracy

For road user charging applications, the lateral accuracy of a digital map is also more important than its longitudinal accuracy. As discussed earlier, this is because of the need to distinguish one road from a parallel road nearby. Very often such roads belong to different jurisdictions and as such need to be categorized differently for charging purposes.

In this report, both metric and English units will be used. In Part I, the GPS component, parameters will be provided in the metric units primarily with English units in parenthesizes since metric units are the primary units used for GPS specifications. For Part II, the digital map component, we will reverse that since English units are most commonly used for describing maps and road lane geometry in the U.S.

## *1.4 Desired Accuracies for Road User Charge Applications*

### *1.4.1 Desired Accuracy of GPS*

As mentioned previously, one of the most important factors in considering a GPS receiver for road user charging applications is its lateral accuracy and the ability to locate vehicles on roads in close proximity. The mean ($\mu$) and standard deviation ($\sigma$) in a GPS receiver's position distribution decide the minimum separation required for two roads. Consider the worst-case scenario shown in Figure 1.3. Vehicle A (6 ft wide) is traveling on the left-most lane of Road A and Vehicle B (6 ft wide) is traveling on the right-most lane of Road B.

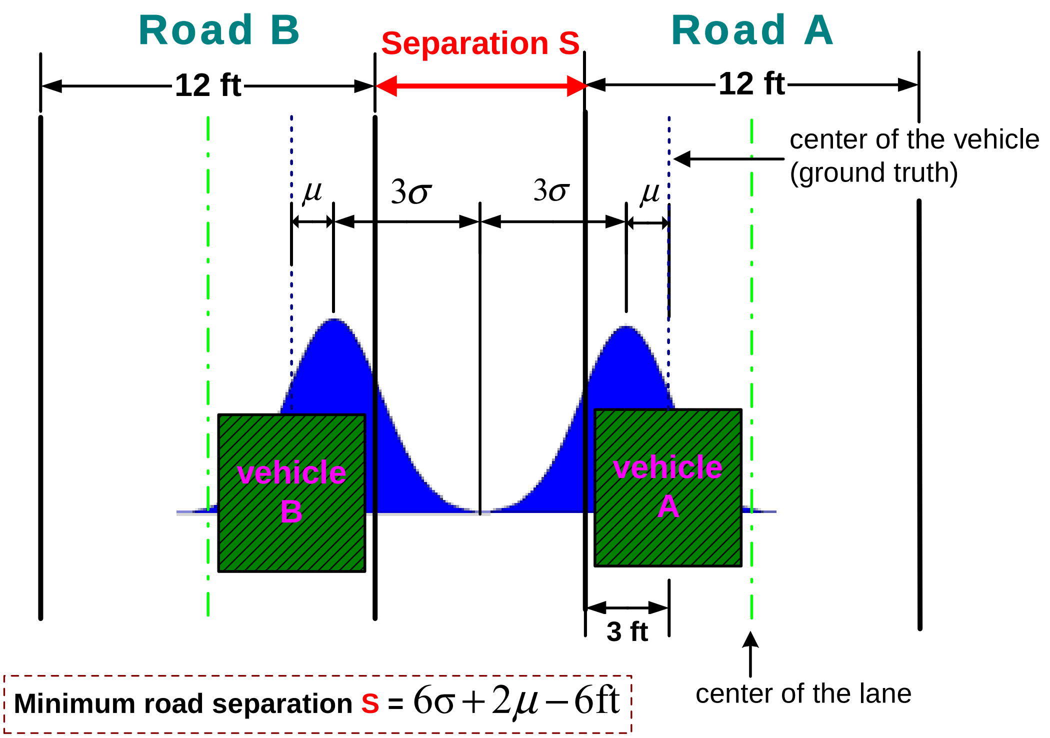


Figure 1.3 Desired Accuracy of GPS in a road user charge application. The Gaussian curves represent the statistical spread of the data captured from vehicles traveling on Road A or Road B in closest proximity to each other

If a confidence level of 99.73% (i.e., 3σ) were required to distinguish the location of Vehicle A on Road A from Vehicle B on Road B, then the minimum road separation *S* required would be

$$S = 6\sigma + 2\mu - 1.8\text{m} \quad \text{or} \tag{1.1a}$$
$$S = 6\sigma + 2\mu - 6\text{ft} \tag{1.1b}$$

If a confidence level of 95% (i.e., 2σ) were required, then the minimum road separation *S* required becomes

$$S = 4\sigma + 2\mu - 1.8\text{m} \quad \text{or} \tag{1.2a}$$
$$S = 4\sigma + 2\mu - 6\text{ft} \tag{1.2b}$$

In Equations 1.1 and 1.2, generally as demonstrated in this report, the absolute value of the mean (μ) is smaller than the standard deviation (σ) for all GPS receivers.

Obviously, the higher the confidence level is, the larger the minimum road separation is. Thus, if one standard deviation (σ) for the GPS receiver were less than 0.3m (1 ft) in Equation 1.1 then the minimum road separation required would be zero, i.e., the GPS receiver is capable of lane-level discrimination. If the standard deviation (σ) is less than 0.3m (1 ft), then generally the mean (μ) would be small enough to ignore. If, however, the 95% level of confidence is acceptable, then the GPS receiver must exhibit a standard deviation (σ) of 0.5m (1.5 ft) or less.

For example, if the mean (μ) and standard deviation (σ) of a GPS receiver were 0.3m (1 ft) and 1.2 m (4 ft), respectively. Then, the minimum road separation required for this road user charge application is $S = 6 \times 4 + 2 - 6 = 20\text{ft}$, if this GPS receiver were chosen as the position sensor. Roads closer than 6m (20 ft) will be difficult for this GPS receiver to distinguish and may cause inaccurate road charges and improper billings.

From another perspective, the required minimum road separation also determines the desired accuracy of a GPS receiver for a road user charge application. For example, if the minimum road separation is known to be 6 m (20 ft) and a confidence level of 99.73% (3σ) is required for a road user charge implementation, then the GPS receiver chosen for this application should have a mean accuracy of less than 0.3 m (1 ft) with a standard deviation (σ) less than 1.2 m (4 ft). Any GPS receiver with a lower accuracy will increase the chance of locating the vehicle incorrectly and thus increase the probability of generating inaccurate road usage.

### 1.4.2 Desired Accuracy of Digital Maps

The most important factor for implementing a digital map in a road user charge application is its lateral accuracy. With a higher accuracy digital map, the on-board computer will have the ability to distinguish roads in close proximity at a higher confidence level. Figure 1.4 illustrates an example for determining what the desired accuracy of a digital map should be for a road user charge application. In the figure, the co-location distance is the distance between two centerlines of the roads. This is the minimum allowable distance of road pairs for the particular road user charging application. It also represents the geographical resolution desired and how well an on-board computer can distinguish between two roads in close proximity. From the figure, the separation distance (*S*) between two roads is

$$S = \text{co-location distance} - \tfrac{1}{2}(\text{Road 1 width}) - \tfrac{1}{2}(\text{Road 2 width}) \qquad (1.3)$$

where the road width includes all the lanes captured by the road and its centerline.

Thus, the maximum allowable map positional error (E) is

$$E = \tfrac{1}{2} \times S \qquad (1.4)$$

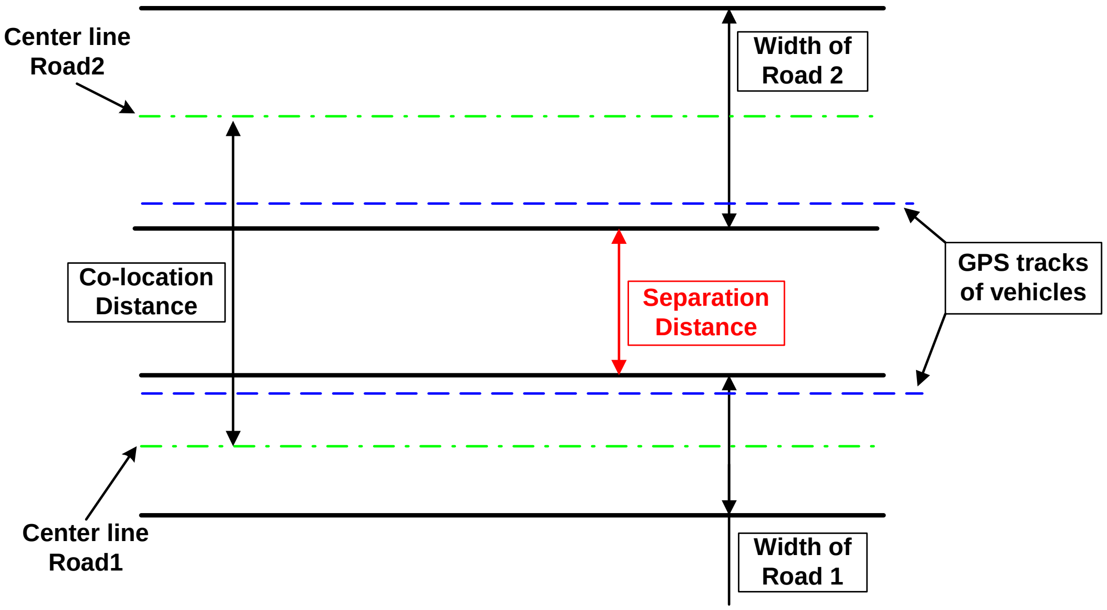


Figure 1.4 Desired accuracy of a digital map in a road user charge application. GPS tracks are based on the assumption that the vehicles are traveling in the lane closest to the adjacent road.

The following example explains how to determine the desired accuracy of a digital map in a road user charge application. Assume that both Road 1 and Road 2 have the same width (2 lanes each) of 7.3 m (24 ft) and the co-location distance is 15.2 m (50 ft). From Equation 1.3, the separation distance (S) can be computed as:

$$S = 15.2\text{m} - 3.6\text{m} - 3.6\text{m} = 8\text{m} \quad \text{or} \qquad (1.5\text{a})$$
$$S = 50\text{ ft} - 12\text{ ft} - 12\text{ ft} = 26\text{ ft} \qquad (1.5\text{b})$$

Thus, the maximum allowable map positional error (E) should be

$$E = \tfrac{1}{2} \times 8\text{m} = 4\text{m} \quad \text{or} \qquad (1.6\text{a})$$
$$E = \tfrac{1}{2} \times 26\text{ ft} = 13\text{ ft} \qquad (1.6\text{b})$$

Please note that from Equations 1.3 and 1.4, one can also determine that if a smaller co-location distance or separation distance is required by a road user charging application, then a higher accuracy digital map would be desired to achieve the same level of confidence in computing the road usage.

### 1.4.3 Desired Overall Accuracy

In previous subsections, the desired accuracies for both the GPS and the digital map are discussed. It should be noted that the error of the digital map is not included (i.e., a perfect digital map is assumed) in the consideration of the desired accuracy of the GPS and neither is the GPS error included (i.e., perfect GPS is assumed) in the consideration of the desired accuracy of a digital map. However, it is impossible to obtain perfect GPS and a perfect digital map in reality.

More importantly, the on-board computer needs to interact with both components in order to compute the correct road usage for charging. Therefore, a road user charge system needs to meet all the requirements specified from Equations 1.1 ~ 1.4 in order to achieve the stated confidence level on computing road usage.

For example, if a confidence level of 99.73% is required for a road user charge application and the minimum road separation is known to be 6 m (20 ft). From Equations 1.1 ~ 1.4, it is found that the GPS receiver chosen for this particular application should have a mean accuracy of 0.3m (1 ft) with a standard deviation of 1.2m (4 ft) and the digital map should have a positional accuracy of 3m (10 ft) or less. If a less accurate GPS receiver or digital map is used for this road user charge application, then the confidence level would decrease and the incorrect computation of road usage may occur more frequently than desired.

This analysis treats the GPS receiver and the digital map as independent measures. It is indeed true that one can develop algorithms that combine the two (often called map matching) that may improve the situation. However, as will be seen in this study, if the digital map does not have sufficient accuracy, even the best commercially available GPS receiver today (capable of achieving centimeter level accuracy) cannot correctly classify the road more than about 73% ~ 87% of the time.

## *1.5 Research Questions and Report Overview*

The goal of this project is to evaluate the core technologies, namely GPS and digital maps that hold the most potential for providing the location, distance traveled and time of day that form the base of a road user charge system. There have been many studies on the accuracy of GPS and digital maps. The study described here focuses on the following questions:

- How accurate must these technologies be to correctly identify a vehicle’s location when roads are in close parallel proximity to each other?
- How often are roads located in close proximity? How “close” is “close”?
- Are existing GPS and digital map technologies available to meet these specifications? If so, which are they? If not, can alternatives be proposed that overcome their limitations?

Since GPS and digital maps are technologically different, each of these two components of the road charging system is tackled individually for better understanding the nature of the problems. Therefore, the report is structured to present the research and discussion on each component separately:

- **Part I - GPS Component**: evaluate different DGPS technologies and identify possible candidates for road user charge applications;
- **Part II – Digital Map Component**: survey and evaluate digital maps for road user charge applications and develop methodologies needed to quantify the map accuracy.

# PART I

# GPS Component

# Chapter 2
# Research Design of the GPS Component

## *2.1 Problem Description and Objectives*

GPS is a technology that can provide real-time information on a vehicle’s position. A receiver onboard can track the vehicle as it moves. The track record can then be used to generate an electronic log of a trip for billing. The GPS technology is an attractive solution for road user charging applications because it is an approach that is independent of roadside devices and can readily be implemented to cover a very large region or even the entire country.

It is important to stress that a GPS receiver picks up signals from the GPS satellites that orbit the Earth. Each receiver uses these signals to calculate the position of the receiver’s antenna. The antenna may be physically connected to the receiver as one piece, or may be separated. It is important to state categorically that the traveler’s privacy is not affected by the presence of “GPS” on board a vehicle. The computed position information and related parameters stays resident in the GPS receiver unless communicated via a separate device (e.g., wireless modem) to other entities. The GPS satellites themselves have no ability to receive information from the GPS equipped vehicles.

The necessary accuracy of the on-board GPS receiver depends upon the detailed level of the road user charges that need to be implemented. For example, in order to use GPS technology as a means for assessing street-level road charges (assuming a road separation of 6m or 20 ft in Equation 1.1), it is necessary to resolve vehicle position accurately to the ± 1 ~ 2 m level (at a confidence level of 67%). This is to ensure that a vehicle can be correctly located as traveling on a frontage road or the adjacent freeway, where under some conditions, the separation between the boundary of one road and the boundary of the adjacent road may be as small as few meters. Figure 2.1 illustrates one possible “worst” scenario. Assuming one vehicle traveling on the left-most lane of a highway and the other vehicle traveling on the right-most lane of the frontage road adjacent to the highway with only 1.8 m (6 ft) of separation between them. If the accuracy of the GPS receiver on-board is 2.4 m (8 ft) at 95% level of confidence, then one can find from the figure that it is possible that the GPS would position the vehicles incorrectly on the road that they are not on. This would incorrectly charge the vehicle user.

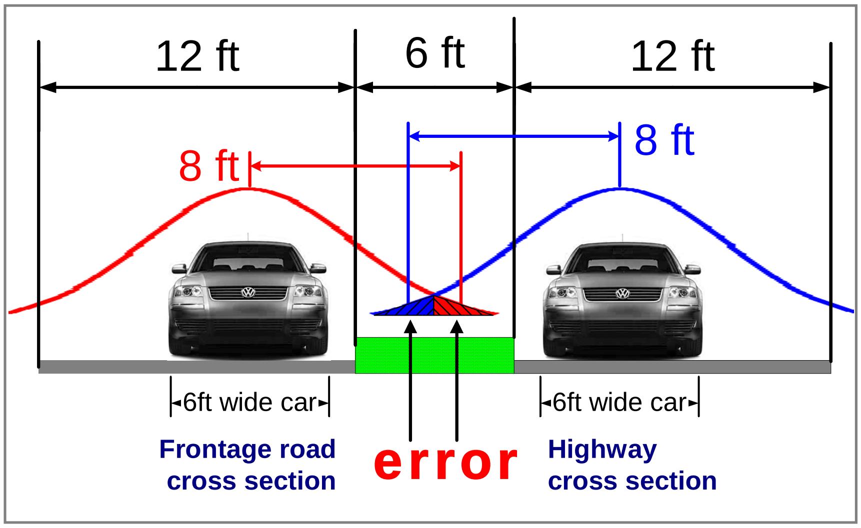


Figure 2.1 One scenario that would cause incorrect road charges

Currently, the positioning accuracy offered by GPS without correction is not accurate to 1 ~ 2 m. Therefore, differentially corrected GPS should be considered and examined. Differential GPS (DGPS) is now the primary means for achieving higher accuracy than regular GPS. DGPS is generally done by transmitting locally generated error correction signals over the air. One correction that is publicly available today is based on the Nationwide Differential Global Positioning System (NDGPS). The claimed accuracy for NDGPS is somewhat better than 1 m at the reference station site, with errors growing by 1 m every 150 km. The range of coverage varies based on the broadcasting power at each site and the ground conductivity in the area. Commercial DGPS services also exist which can achieve even better accuracies. However, these DGPS services do not presently conform to any standard and are only available to paying customers. Additionally, the government provided services offer an integrity function to GPS receivers that indicates which, if any, satellites should not be used to calculate solutions.

The problem with the accuracies specified above is that they are for stationary receivers. The specifications have not been verified for moving vehicles. Furthermore, dramatic change of elevation and multipath (resulting from signal reflections from adjacent structures) may affect the vehicle’s GPS-based position computation. For any proposed new road financing approach to work based on GPS, accurate, repeatable, and reliable location measurements are needed for vehicles moving at legal speeds on a variety of roads.

The objectives of this project are listed as follows:

- Evaluate accuracies of different DGPS technologies for road user charge applications, particularly in locations where problems are likely to arise, and document the differences between them;
- Examine and document dynamic effects (i.e., vehicle speed) on the accuracies of GPS receivers;

- Examine and document the effect of elevation and changes in elevation on the accuracies of GPS receivers;
- Study and record the GPS coverage in a downtown environment where multipath effects are the worst;
- Identify the least expensive GPS technology that would meet the needs of road user charge applications;
- Identify limitations of GPS technology and possible means to overcome these limitations.

## *2.2 Research Design and Scope*

There are two main components of the on-board road user charge system: GPS and GIS digital maps. For the GPS component, the main objective is to find a practical solution that would meet the accuracy requirement specified by governments and legislature. In addition, the system needs to work reliably in all environments and under all conditions nationwide.

The following outlines the research design of the GPS portion of the study whose goal is to find a practical solution for road user charging application by evaluating different GPS receivers available today:

1. Research currently available GPS and DGPS services;
2. Establish the baseline (i.e., reference) for GPS evaluations;
3. Evaluate accuracies of GPS receivers on highways;
4. Evaluate accuracies of GPS receivers on city streets;
5. Examine and document dynamic effects (i.e., vehicle speed) on the accuracies of GPS receivers;
6. Examine and document the effect of elevation and changes in elevation on the accuracies of GPS receivers;
7. Study and record the GPS coverage in a downtown environment where multipath effects are the worst.

# Chapter 3
# Evaluation of GPS

The GPS receiver is an essential part of the on-board user charge system. It provides location and time information in real-time and helps to accurately track vehicle mileage. In conjunction with digital maps, the GPS can also determine the road jurisdiction irrespective of the local political boundaries, and distinguish different road types if required.

This chapter discusses the requirements of the GPS system for the purpose of road user charging, the differences between different DGPS systems, definition of GPS errors, and the algorithm used to compute GPS errors.

## *3.1 Requirements*

Since the on-board user charge system is designed to charge vehicles traveling on public roadways, the GPS system needs to meet the following criteria:

1. Be able to work nationwide;
2. Be able to work in different environments (e.g., urban, rural, open plain, mountainous etc);
3. Be reliable and robust;
4. Have the ability to identify jurisdiction on roads in close proximity;
5. Be as low cost as possible.

## *3.2 GPS Basics*

GPS is the shortened form of NAVSTAR GPS, which stands for NAVigation System with Time And Ranging Global Positioning System. GPS is a satellite-based system that uses a constellation of 24 satellites to facilitate the calculation of an “accurate” position of a receiver located where on the earth (as long as a sufficient number of satellite signals can be picked up by the receiver). It is important to note that “accurate” is a relative term for different applications. To a hiker, 15 m (49 ft) is accurate enough, however, to a land surveyor, “accurate” means 1 cm (0.4 in) or less. GPS can be used to achieve those accuracies, the difference being the type of GPS receiver used and the technique employed.

The GPS configuration is comprised of three distinct segments:

- The Space Segment: satellites orbiting the earth that broadcast an array of signals;
- The Control Segment: stations positioned on the earth’s equator to control the satellites;
- The User Segment: anyone that receives and uses the GPS signals.

The Space Segment is designed to consist of 24 satellites orbiting the earth at approximately 20,200km (12,551 miles) every 11 hours and 58 minutes. It is designed to have 4 satellites in 6 orbital planes. As of May 2003, there are 27 satellites in orbit, of which 23 are in service and 4 are spares. One of the spares is gradually being shifted to fill the empty slot located in the orbital plane E, slot 2 (resulting from a satellite failure).

The satellites broadcast two carrier waves in the L-Band:

- The L1 signal is broadcast at 1575.42 MHz,
- The L2 signal is broadcast at 1227.60 MHz.

The L1 signal has two codes modulated on it. The Coarse/Acquisition (C/A) code is modulated at 1.023 MHz and the Precision (P) code is modulated at 10.23 MHz. The L2 signal has only the P code modulated at 10.23 MHz. The P code can only be decrypted by military GPS receivers. Civilian GPS receivers can only use the C/A code and they do not have the ability to fully decode the P code.

The positioning accuracy offered by GPS varies depending upon the type of service and equipment available. For security reasons, only the Standard Positioning Service (SPS) is available for civilian applications. The mean positioning accuracy of SPS is about 13 m at 95% level of confidence [I-11].

Starting in 2003, the GPS system will be modernized [I-10]:

- A new civil signal will be added to the L2 signal, i.e., L2C;
- A new L5 signal will be added to the system.

GPS receivers can start taking advantage of the new L2C signal when 18 satellites capable of broadcasting the new signal are in orbit (by about 2007). At that time, the GPS accuracy is expected to be improved to 5 m (16 ft) without correction. Figure 3.1 shows the deployment plans for the new GPS signals.

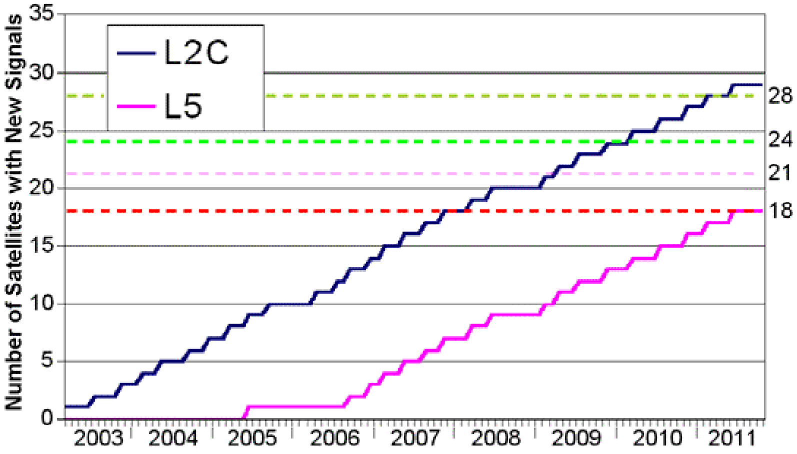


Figure 3.1 Deployment of the new GPS signals.

## *3.3 Use of Differential GPS*

For road user charging purposes, an accuracy of ±13 m by using GPS is generally not sufficient to distinguish roads in close proximity. Thus, differential positioning techniques were examined. The purpose of differential GPS (DGPS) is to remove the effects of atmospheric errors, timing errors and satellite orbit errors, while enhancing system integrity.

## *3.4 Sources of DGPS*

One method of providing DGPS involves setting up a reference GPS receiver at a fixed point with known coordinates. This reference receiver makes distance measurements to each of the GPS satellites in real-time. It then calculates what the true range should be, without errors, knowing its coordinates and those of each satellite. By comparing the calculated range and the measured range, a correction term can be determined for each satellite. The corrections are broadcast and applied to the satellite measurements at each user’s location. This method provides a good navigation solution for the user and is the method employed by the Nationwide DGPS (NDGPS) service.

The above method is also incorporated into the Federal Aviation Administration’s (FAA) Wide Area Augmentation System (WAAS) for GPS. In this system, a network of GPS reference stations are used to calculate GPS corrections. The corrections are then relayed to geostationary satellites and broadcast to users.

In order to achieve better performance and higher accuracy, some private companies have also set up their own network of reference stations, have leased satellite channels and broadcast the encrypted correction signals to designated users. Users need to purchase special GPS equipment and pay subscription fees in order to decode the proprietary correction messages.

### 3.4.1 Nationwide DGPS

The NDGPS service is an expansion of the U.S. Coast Guard's Maritime DGPS service [I-12]. The signals are not encrypted and are broadcast in the 285 and 325 KHz maritime radiobeacon band. Anyone with a beacon radio can pick up the correction signals to improve the GPS accuracy. The predictable accuracy of the NDGPS service within the coverage areas is better than 10 m at the 95% level of confidence. Generally, the accuracy at each broadcast site is better than 1 m and the achievable accuracy degrades at an approximate rate of 1 m per 150 km distance from the broadcast site. High-end dual-frequency receivers are able to achieve accuracies significantly better than 1 m throughout the entire coverage area by compensating for ionospheric errors  using additional signals broadcast by the GPS satellites.

When completed as expected by December 2005, the NDGPS service will provide uniform differential GPS coverage for the continental U.S. and part of Hawaii and Alaska. Figure 3.2 shows the current coverage of the NDGPS service as of December 2002. There are three NDGPS reference stations located near the state of Minnesota: Alma (Wisconsin), Pine River (Minnesota), and Wisconsin Point (Wisconsin). The Alma, WI site is always referenced as St. Paul in all NDGPS literature. Figure 3.3 shows the locations of these three reference stations and their distances to Twin Cities, Minnesota.

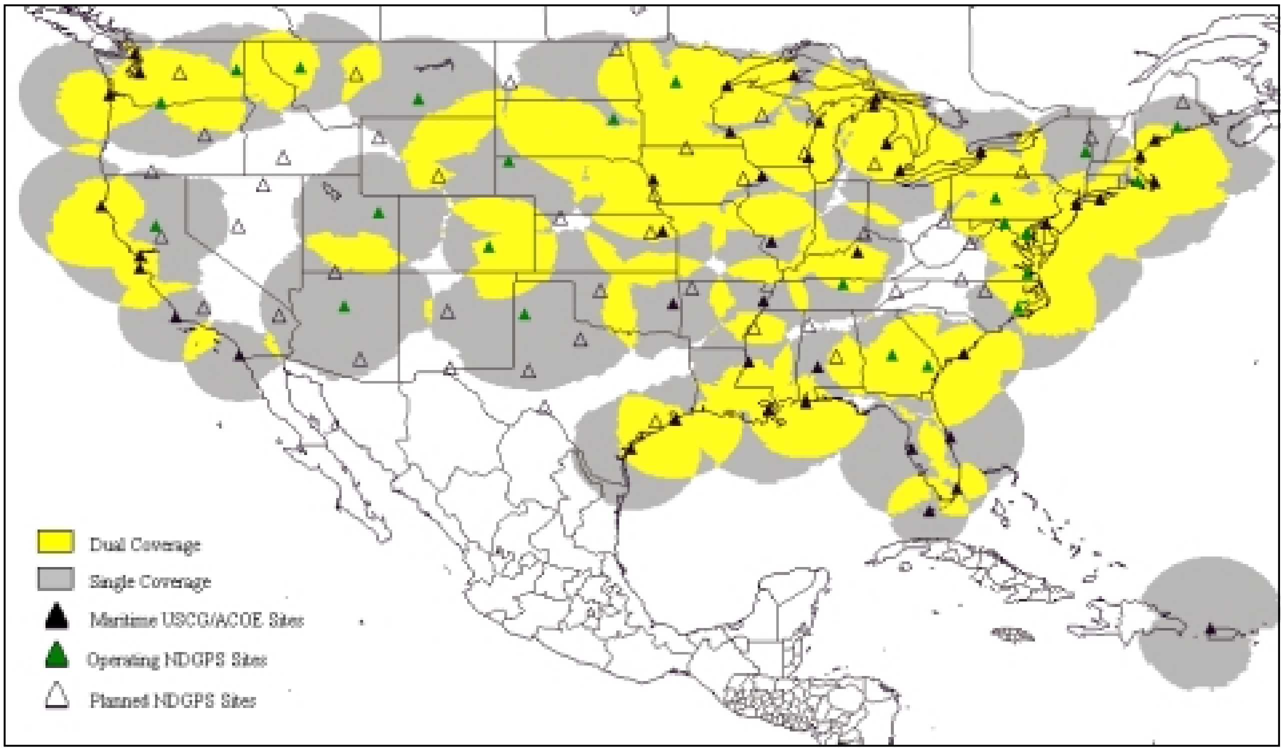


Figure 3.2 Current coverage of NDGPS Service (as of December 2002).

Figure 3.3 NDGPS reference stations located near Minnesota.

### 3.4.2 WAAS

The WAAS is a satellite-based GPS augmentation system and designed to provide precision guidance to aircrafts for navigation and landing in North America [I-13]. The goal of WAAS is to improve the accuracy and ensure the integrity of information coming from GPS satellites.

Unlike ground-based navigation aids, WAAS covers a more extensive service area. Twenty-five precisely surveyed ground reference stations are linked to form a WAAS network. Each station in the network receives signals from GPS satellites and compute errors in the signals. The messages are then sent to one of two master stations to compute correctional information for specific geographical areas. A correction message is then prepared and uplinked to a geostationary satellite. This message is broadcast on the same frequency as GPS (L1 at 1575.42 MHz) and is not encrypted. The WAAS improves basic GPS accuracy to approximately 2 to 3 m horizontally (at the 95% level of confidence).

Figure 3.4 shows the WAAS architecture and the network.

Figure 3.4 WAAS architecture and the network.

### 3.4.3 Satellite-Based DGPS Systems

To obtain global DGPS coverage and sub-meter accuracy over the entire coverage area, several companies have set up their own network of global satellite-based DGPS services. Similar to WAAS, these systems also utilize the GPS satellite system, L-band communication satellites, and a worldwide network of reference stations to deliver real-time high precision positioning. The method used to compute GPS corrections and uplink the data to geostationary satellites is very similar to WAAS. What is unique to these global DGPS services is the incorporation of precise satellite orbits and their proprietary differential processing techniques used to generate differential correction data for each satellite in the GPS constellation. This proprietary wide area DGPS algorithm is optimized for dual-frequency receivers in which dual-frequency ionospheric measurements are available at both the reference receivers and the user receivers. The use of dual-frequency receivers at both the reference and user sides, plus the proprietary processing algorithms make it possible to produce the sub-meter or even higher accuracy throughout the entire globe.

Currently, the companies that have established global DGPS services include NavCom Technology Inc. [I-14], OmniSTAR [I-15], and Thales Landstar [I-16] etc. Among them, NavCom Technology claims the highest accuracy of 10 cm globally. The DGPS service is available to paying users only and users need to use proprietary equipment to receive the signals. Figure 3.5 shows the coverage map of the NavCom global DGPS service.

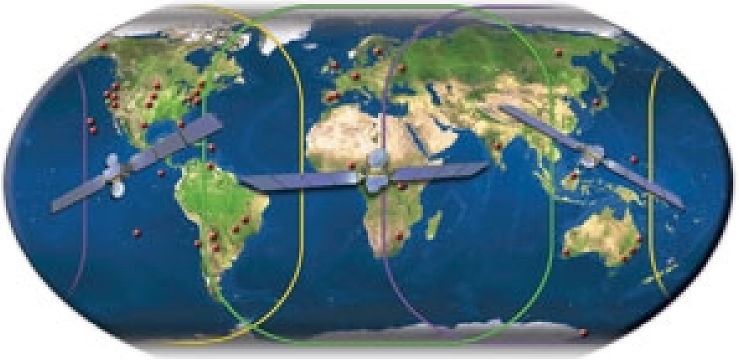


Figure 3.5 Coverage map of the NavCom global DGPS service.

## *3.5 Dynamic Evaluation of High Accuracy Differential GPS*

### 3.5.1 Background

The best way to evaluate the accuracy of a GPS receiver (both statically and dynamically) is to compare its solution outputs against the ground truth. However, this method is rather complicated especially if one wants to measure the accuracy of a GPS receiver dynamically (i.e., when the vehicle is moving). For road user charging purposes, the use of GPS receivers with centimeter level accuracy is not needed. Since the accuracy required for road user charging is on the order of meters, a dual-frequency GPS receiver with centimeter level accuracy can replace the ground truth as a baseline (i.e., as a “gold standard”) to evaluate the meter-level GPS receivers.

Before this high accuracy, dual-frequency DGPS receiver can be used as a “gold standard” to evaluate the low-end GPS receivers, its accuracy and dynamic performance needs to be measured and confirmed. The following section describes an experiment performed to quantify the dynamic performance (position accuracy and latency) of a dual-frequency carrier phase RTK DGPS system [I-17].

### 3.5.2 Experimental Design

The high-accuracy dual-frequency GPS receiver under evaluation was the Trimble MS-750 receiver. The position solutions were measured against ground truth using image-processing techniques. To measure against ground truth, a high-resolution calibrated digital camera with an externally controlled shutter was mounted coaxially beneath the center of the DGPS antenna and pointed at the ground. A series of accurately positioned reference points were used to position and align square tiles that were used as ground truth references. Figure 3.6 shows the setup of the experiment.

Figure 3.6 Set up of the experiment and data collection system.

As the test vehicle is driven over the tiles, the camera shutter is synchronized with the timing signal of the GPS receiver (pulse per second signal). If a tile is captured in the field of view of an image, the physical location of the antenna with respect to the tile can be determined from the camera calibration. The position of the antenna as computed by the GPS receiver at the time the shutter is triggered can be compared to the position of the camera to provide an error measurement. Repeatedly driving over multiple tiles can provide statistically relevant information regarding the error associated with the DGPS system.

To better understand the GPS performance dynamically, data at different speeds of 10, 20, 30 MPH were collected. Also the base station that provided correction signals to the GPS receiver under evaluation was placed at both 1 km and 15 km away to test the effects of short and long baselines.

Please note that in this experiment, the dynamic performance of the GPS receiver were measured only with the position solutions with the highest quality (i.e., “RTK fix”). Position solutions with lower qualities (e.g., “RTK float”, or “DGPS”) were not included in the data analysis.

### 3.5.3 Data Collection

Figure 3.7 shows the setup of the data collection system. Synchronization of the computer systems while recording the DGPS data and images is critical to accurately evaluate GPS accuracy. The pulse-per-second (PPS) output on the Trimble MS-750 receiver is used to ensure synchronization. When a PPS pulse from the GPS receiver is detected, the camera is triggered, and the time from the real-time clock on the Neutrino computer (N-PC) is written to the data log. When a GPS solution is received by the N-PC, the time is also recorded for latency calculation. The images captured by the camera are stored on a Windows PC (W-PC). Each image file is correspondent to a unique identifier created based on the GPS solution time.

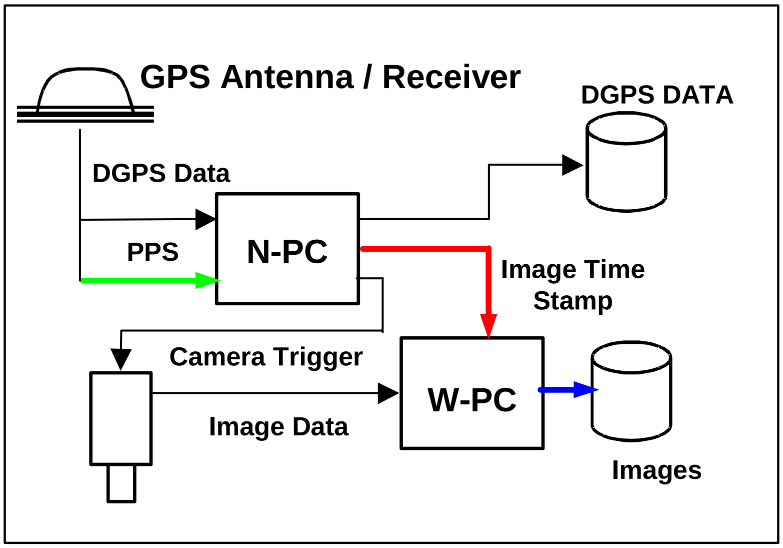


Figure 3.7 Setup of the data collection system.

### 3.5.4 Experimental Results

On the processed images, the pixel coordinates of the image center and the GPS position are used to compute the positional error of the GPS computed position. Also, since the direction of travel is known, the lateral error is defined as the difference in the ***x*** pixel coordinates of the image center and of the GPS point. Likewise, the longitudinal error is defined by the difference in the ***y*** values of these points. Figure 3.8 describes the calculation of these errors. The reference point represents the accurately surveyed ground truth, the image center represents the location of the GPS antenna center and the DGPS location represents the position computed from the DGPS receiver corresponding to the captured image. The error values are then converted from a pixel count to real distance using the measured pixel width based on the known dimension of the square tile.

The following tables (Tables 3.1 ~ 3.4) statistically summarize the position and latency performance of the Trimble MS-750 GPS receiver.

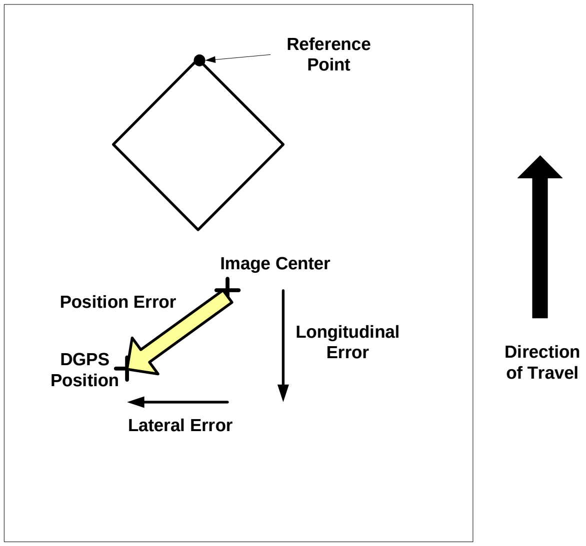


Figure 3.8 Location of GPS data on the captured image.

| Speed (MPH) | Mean error (cm) | Standard Deviation (cm) | Average Latency (msec) |
|---|---|---|---|
| 10 | 6.0 | 9.3 | 40.5 |
| 20 | 3.2 | 1.1 | 37.0 |
| 30 | 15.4 | 16.8 | 45.0 |

Table 3.1 Positional errors for short baseline.

| Speed (MPH) | Lateral error, mean (cm) | Lateral error, Std Dev (cm) | Longitudinal error, mean (cm) | Longitudinal error, Std Dev (cm) |
|---|---|---|---|---|
| 10 | -0.6 | 10.0 | -2.5 | 3.9 |
| 20 | 0.1 | 0.9 | -3.0 | 1.1 |
| 30 | 4.5 | 20.5 | -6.2 | 6.7 |

Table 3.2 Lateral and Longitudinal errors for short baseline.

| Speed (MPH) | Mean error, (cm) | Standard Deviation (cm) | Average Latency (msec) |
|---|---|---|---|
| 10 | 7.9 | 3.8 | 42.4 |
| 20 | 9.6 | 8.3 | 46.0 |
| 30 | 8.9 | 7.8 | 39.5 |

Table 3.3 Positional errors for long baseline.

| Speed (MPH) | Lateral error, mean (cm) | Lateral error, Std Dev, (cm) | Longitudinal error, Mean (cm) | Longitudinal error, Std Dev (cm) |
|---|---|---|---|---|
| 10 | -0.5 | 5.7 | -6.6 | 1.3 |
| 20 | 2.5 | 10.7 | -6.2 | 2.0 |
| 30 | -4.5 | 9.3 | -5.6 | 1.6 |

Table 3.4 Lateral and longitudinal error for long baseline.

### 3.5.5 Conclusions

In this experiment, three error components: positional, lateral, and longitudinal errors, of a DGPS system are defined. The positional error is the distance between the GPS position and the reference position. The lateral and longitudinal errors are the corresponding radial and tangential vector components of the positional error in the direction of travel.

We found that the Trimble MS-750 GPS receiver exhibits sub-decimeter dynamic accuracy at different speeds when its solution quality is “RTK fix”. Thus, a Trimble MS-750 receiver can be used as a “gold standard” to evaluate meter-level accuracy of GPS receivers when its position outputs possess the quality of “RTK fix”.

In this experiment, the Trimble MS-750 data with the quality of “RTK float” was not evaluated. The accuracy of “RTK float” is not defined in the Trimble reference manual. However, because data with “RTK fix” is relatively difficult to obtain in the metropolitan area, data with both “RTK fix” and “RTK float” was used to perform the digital map evaluation. From our experience, it is reasonable to believe that the Trimble MS-750 data with the quality of “RTK float” exhibits an accuracy somewhere between 0.3m (1 ft) to 1 m (3.3 ft). Given that commercially available digital maps have accuracies on the order of 25 m (82 ft), it is not unreasonable to use GPS data with the “RTK float” criterion for evaluating maps. For the GPS evaluations, only data with the quality “RTK fix” was used.

## *3.6 Dynamic Evaluation of GPS Receivers*

### 3.6.1 GPS for Road User Charging

As a part of the road user charging system, the function of a GPS receiver is to compute and track the locations of a vehicle. The GPS receiver needs to be accurate enough to distinguish if a vehicle is on a highway or on a frontage road adjacent to the highway. For road user charging to be feasible, accurate and reliable location measurements are needed for vehicles moving at different speeds on different types of roads. Thus, one of the most important tasks in this project is to evaluate the dynamic performance of different DGPS systems (particularly in locations where problems are likely to arise) and to identify the least expensive technology that is suitable. The evaluation will also try to identify limitations of each DGPS system and suggest means to overcome them.

From Section 3.4, it is known that the currently available DGPS services include NDGPS, WAAS, and global satellite-based DGPS service. Among these, NDGPS and WAAS are free services provided by the U.S. government while the global satellite-based DGPS service is only available to designated users by subscription. Since performance specifications and prices for NDGPS receivers vary widely, three NDGPS receivers were purchased and evaluated in this project. The Trimble AgGPS 132 is a high-end NDGPS receiver. It costs about $5,000, has 12 parallel GPS channels to track satellites, can decode L1 C/A code and filter carrier phase signals, and outputs solutions at 10 Hz. The beacon radio embedded into the Trimble AgGPS 132 receiver has two independent channels to search signals from two different reference stations based on either the signal strength, distance to base stations or manually. The CSI GBX-12R GPS receiver is a mid-to-low end NDGPS receiver. It costs about $850, has 12 parallel channels to track GPS satellites, decodes L1 C/A code, and outputs solutions at 1 Hz. The beacon radio in the CSI GPS receiver has two channels, however, only one base station can be locked. The user can adjust the beacon radio manually or let the radio search for the strongest signals in the area. The JRC DGPS 212 is a low-end NDGPS receiver. It costs about $550, has 12 channels to track satellites, decodes L1 C/A code, and outputs solutions at 1 Hz. The beacon radio in the JRC DGPS receiver has one channel and will automatically search for the strongest NDGPS signals in the area and use it as correction. User adjustment of the radio frequency is not an option on the JRC DGPS 212 receiver.

The WAAS receiver purchased for evaluation was a $200 Garmin GPS 76 receiver. This unit has 12 differential-ready channels and will pick up WAAS signals automatically. The Garmin 76 GPS receiver updates every second, however, it only outputs NMEA location strings at 0.5 Hz (every 2 seconds). NMEA is a communication standard established by the National Marine Electronics Association (NMEA) and is adopted by all GPS manufacturers.

For the global satellite-based DGPS service, NavCom Technology Inc.’s StarFire service was selected. The StarFire has the highest accuracy service among all global satellite-based DGPS services and its GPS receivers are priced among the lowest. The SF-2050 receiver purchased for evaluation is their second-generation StarFire GPS receiver that is designed to be rugged and lightweight for mobile applications. The unit costs $6,000 and the subscription costs $850 annually. The SF-2050 GPS sensor is a dual-frequency high-end GPS receiver that can track L1 and L2 code plus the carrier phase signals. This SF-2050 receiver takes about 1 ~ 2 minutes to lock the correction signals from the Inmarsat satellite and can output solutions up to 25 times per second. One major drawback of the SF-2050 receiver is that it takes about 30 minutes or longer to converge and reach its claimed accuracy of 10 cm. A planned software upgrade will facilitate faster convergence.

Table 3.5 summarizes the features for all the DGPS receivers discussed above and Figure 3.9 shows what they look like.

| | **Trimble MS-750** | **Trimble AgGPS 132** | **CSI GBX-12R** | **JRC DGPS 212** | **Garmin GPS 76** | **NavCom SF-2050** |
|---|---|---|---|---|---|---|
| Channels | 9 L1 & 9 L2 | 12 L1 | 12 L1 | 12 L1 | 12 L1 | 12 L1 & 12 L2 |
| Resolution | 0.00000001’ (0.018 mm) | 0.000001’ (0.18 cm) | 0.0001’ (18 cm) | 0.001’ (1.8 m) | 0.0001’ (18 cm) | 0.000001’ (0.18 cm) |
| Update rate | Up to 20 Hz | Up to 10 Hz | 1 Hz | 1 Hz | 0.5 Hz | Up to 25 Hz |
| Beacon mode | N/A | Auto power, auto range, and manual | Auto power and manual | Auto power | N/A | N/A |
| Beacon channels | N/A | 2 | 2 | 1 | N/A | N/A |
| WAAS ability | No | No | No | No | Yes | No |
| StarFire ability | No | No | No | No | No | Yes |
| Cost | $12,000 | $5,000 | $850 | $550 | $200 | $6,000 |

Table 3.5 Summary of DGPS receivers evaluated.

**Trimble MS-750** **Trimble AgGPS 132** **CSI GBX-12R**

**JRC DGPS 212** **Navcom SF-2050** **Garmin GPS 76**

Figure 3.9 Pictures of all the DGPS receivers that were evaluated.

### 3.6.2 Experimental Design

The goal of the experiments is to quantify the dynamic accuracies of DGPS receivers on different types of roads, under different kinds of environments, and particularly in locations where problems are likely to arise. One of the major concerns in road user charging is the ability to distinguish if a vehicle is on a highway or on the frontage road next to the highway with only a few meters of separation. Thus, a majority of the experiments were conducted on highways and on city streets close to highways in the Twin Cities area. Experiments were also performed in the downtown Minneapolis area to examine the “multipath” effects caused by tall buildings and structures, and in the Duluth, Minnesota area to study the effect of significant rapid elevation change steep hills to the accuracy of GPS receivers. In addition, experiments were conducted to study the accuracies of GPS receivers at various vehicle speeds.

In order for GPS receivers to be evaluated at the same time and compared using the same baseline (“gold standard”), they were mounted on a bar running across the top of a vehicle (Figure 3.10). The outputs of all GPS receivers were recorded on a data-collection computer via a multiport RS-232 serial hub in real-time. The computer also had a touch-screen interface to control the experiments and show the incoming GPS data in real-time. The interface is a good tool to check if the system is functioning correctly and would warn the operator if any GPS receiver fails.

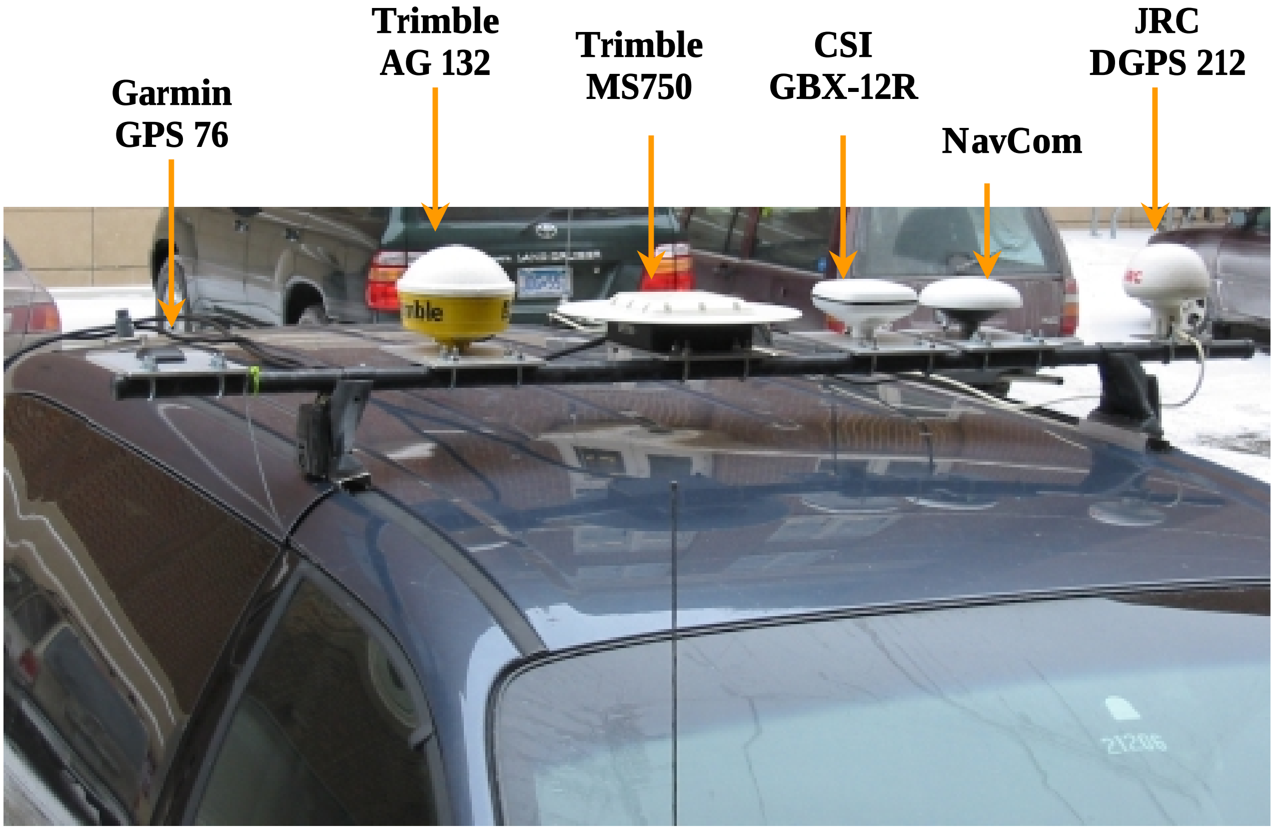


Figure 3.10 Experimental setup of the GPS evaluation.

### 3.6.3 Route Selection

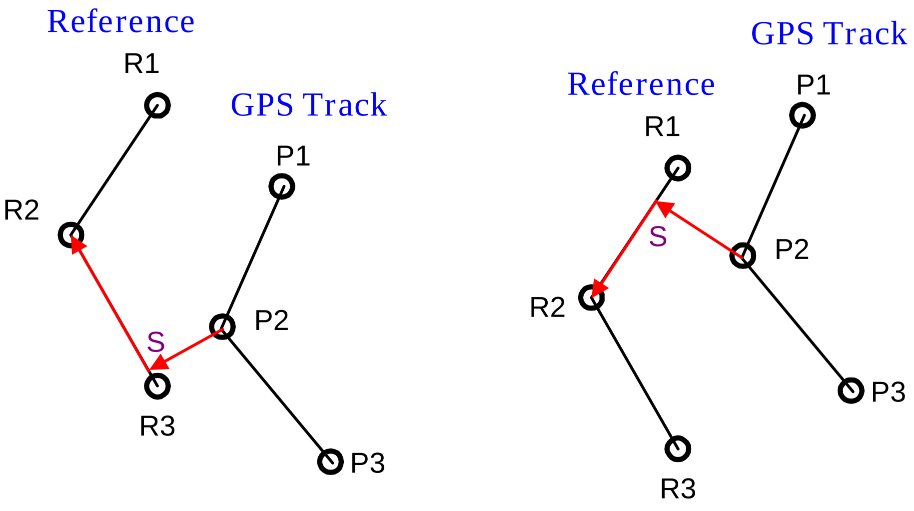
Routes were selected that would highlight the problem associated with distinguishing between roads that were parallel and adjacent to each other. An extensive study (documented in Chapter 8) describes the methodology (co-location mining) that was used to identify such roads. Several routes were then chosen and the GPS receivers were evaluated on these routes.

### 3.6.4 Data Analysis: Calculation of Dynamic Lateral/Longitudinal Distance Errors

Experimental data was sorted by time, travel route, receiver type, correction source, and GPS solution quality. All GPS data was converted from latitude and longitude in the NAD-83 datum plane to X and Y coordinates (unit: meter) in the Minnesota State Plane for comparison.

The algorithm to compute GPS errors compares two GPS tracks and calculates the positional, lateral, and longitudinal errors. Figure 3.11 illustrates how the algorithm works. GPS points **R** are reference points (i.e., the “gold standard” against which the comparison is made), and GPS points **P** are from the GPS receiver under evaluation. Points $\mathbf{R}_1$, $\mathbf{R}_2$, and $\mathbf{R}_3$ and points $\mathbf{P}_1$, $\mathbf{P}_2$, and $\mathbf{P}_3$ in the figure are three consecutive GPS points from the reference track **R** and the GPS track **P**, respectively. In addition, points $\mathbf{R}_1$, $\mathbf{R}_2$, and $\mathbf{R}_3$ in the reference track all need to have the solution quality of “RTK fix”. To compute the dynamic positional/lateral/longitudinal errors of $\mathbf{P_2}$ (vs. $\mathbf{R_2}$), the following procedure is applied:

1. Find the point $\mathbf{R_2}$, which has the same GPS time stamp as the point $\mathbf{P_2}$, in the reference track **R**;
2. Check if the vehicle is moving above the velocity threshold if such is specified;
3. Find the smaller distance of $\overline{P_2R_1}$ and $\overline{P_2R_3}$ (to check if $\mathbf{P_2}$ is lagging [Figure 3.11(a)] or leading [Figure 3.11(b)]);
4. Find the intersection point **S** of the perpendicular to $\overline{R_1R_2}$ or $\overline{R_2R_3}$ based on the result of (2);
5. Compute the positional error $\overline{P_2R_2}$ (scalar);
6. Compute the lateral error $\overrightarrow{P_2S}$ (which is a vector; it is > 0 if on the left side, or < 0 if on the right side);
7. Compute the longitudinal error $\overrightarrow{SR_2}$ (which is a vector; it is > 0 if leading, or < 0 if lagging).



(a) GPS lagging (b) GPS leading

Figure 3.11 Calculation of dynamic lateral/longitudinal distance errors

The above procedure is repeated until all the data points in the GPS track **P** are processed. Since accuracy is a statistical measure of performance, statistical software is then used to further analyze the position errors and present the final results in statistical terms. Please note that the calculated GPS errors (i.e., accuracies) are a combination of several factors. They are comprised of errors caused by instability of the transmitted signal, effects of physical changes in the propagation medium, errors in the receiving equipment, and errors introduced by humans, etc. Since none of these errors can be measured individually, it is impossible to quantify how much each factor contributes to the total error. Note that the above algorithm cannot be applied when the vehicle is not moving (i.e., speed = 0). In this case, the only GPS error component that can be defined and computed is the positional error ( $\overline{P_2R_2}$ ).

Please also note that the position error (a scalar) will always be larger than either the lateral or longitudinal errors (which are each vectors). Generally, the longitudinal errors are larger than the lateral errors unless the GPS receiver can compensate the computational latency internally. Keep in mind that it is the lateral error with which we are most concerned.

# Chapter 4
# Results of the GPS Evaluation

In this chapter, results of different GPS evaluations are presented. These include evaluations done on highways and local streets. Experiments were also performed to study the effects of vehicle speed and change of elevation on the accuracies of GPS receivers. In addition, issues on the GPS coverage in a downtown environment are also discussed.

## *4.1 Evaluations of the NDGPS Service: Highways*

Evaluations of the NDGPS service were first performed on the interstate and state trunk highways in the metropolitan Twin Cities area. The DGPS receivers under evaluation were the Trimble AgGPS 132, the CSI GBX-12R, and the JRC DGPS 212. Figure 4.1 shows all four routes tested. These routes covered most of the major highways in the Twin Cities and had a total length of about 991 km (616 miles). However, since there were a lot of bridges, over-passes, and CDPD wireless signal holes, etc. on highways, only 196 km (122 miles or 20%) of the Trimble MS-750 data had the solution quality of “RTK fix”. The Trimble MS-750 data with “RTK fix” and the corresponding data segments from other DGPS receivers were extracted for data analysis. The average travel speed for all routes was 21 m/sec (46 MPH). All routes were driven at least twice and the experiments were performed in April and May of 2002.

The results for each testing route are presented in each subsection and the overall results of the highway evaluation are summarized and discussed at the end of this section.

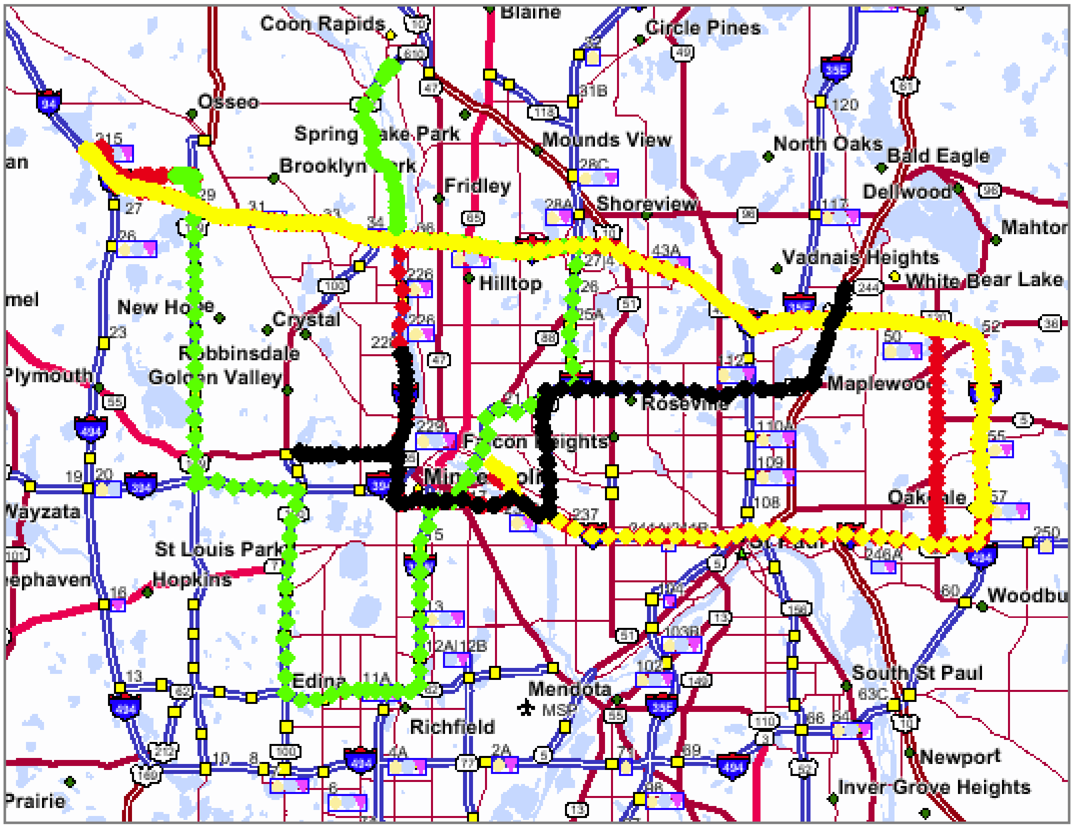


Figure 4.1 Test routes for the highway evaluation.

### 4.1.1 Results of the NDGPS Evaluation on Highway Route I

Highway Route I included MN Highway 252 and MN Highway 610 in the northwest Twin Cities metropolitan area. The total mileage for the route was 25.5 km (15.8 miles) and the mileage for “RTK fix” data was 14.3 km (8.86 miles, or 56%). The average travel speed on the route was 16 m/sec (37 MPH). The St Paul NDGPS base station was used as the correction source for this evaluation.

Figure 4.2 shows the route on a digital map and the results are presented in Table 4.1 and Figure 4.3. Gaps in the data of Figure 4.3 represent locations along the road in which “RTK fix” was not available.

Figure 4.2 Highway Route I

| Correction [St Paul] | Positional mean error | σ | Lateral mean error | σ | Longitudinal mean error | σ |
|---|---|---|---|---|---|---|
| **Trimble AgGPS132** | 0.96 m (3.15 ft) | 0.36 m (1.18 ft) | -0.18 m (-0.59 ft) | 0.36 m (1.18 ft) | 0.01 m (0.03 ft) | 0.70 m (2.30 ft) |
| **CSI GBX-12R** | 16.43 m (53.89 ft) | 4.21 m (13.81 ft) | -0.35 m (-1.15 ft) | 1.30 m (4.26 ft) | -16.38 m (53.73 ft) | 4.22 m (13.84 ft) |
| **JRC DGPS 212** | 21.94 m (71.96 ft) | 5.07 m (16.63 ft) | -0.55 m (-1.80 ft) | 1.35 m (4.43 ft) | 19.76 m (64.81 ft) | 16.54 m (35.13 ft) |

Table 4.1 Results of the NDGPS Evaluation on Highway Route I at an average speed of 16 m/sec (37 MPH)

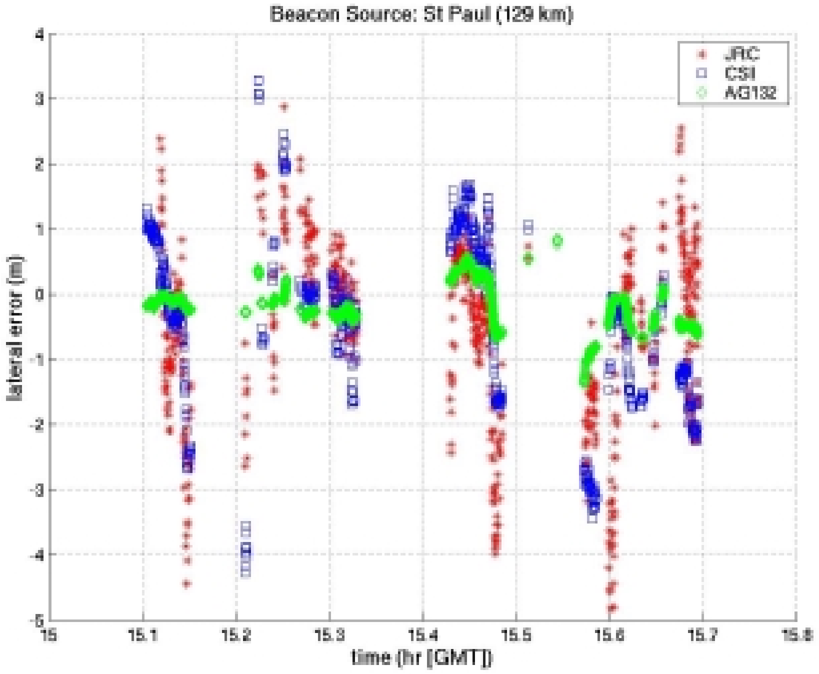


Figure 4.3 Results of the NDGPS Evaluation on Highway Route I

### 4.1.2 Results of the NDGPS Evaluation on Highway Route II

Highway Route II included U.S. Highway 169, Highway I-394, MN Highway 100, MN Highway 62, Highway I-35W, and Highway I-694 in the western Twin Cities metropolitan area. The total mileage for the route was 154.8 km (96.2 miles) and the mileage for “RTK fix” data was 30.5 km (18.97 miles, or 20%). The average travel speed on the route was 23 m/sec (51 MPH). The St Paul NDGPS base station was used as the correction source for this evaluation.

Figure 4.4 shows the route on a digital map and the results are presented in Table 4.2 and Figure 4.5.

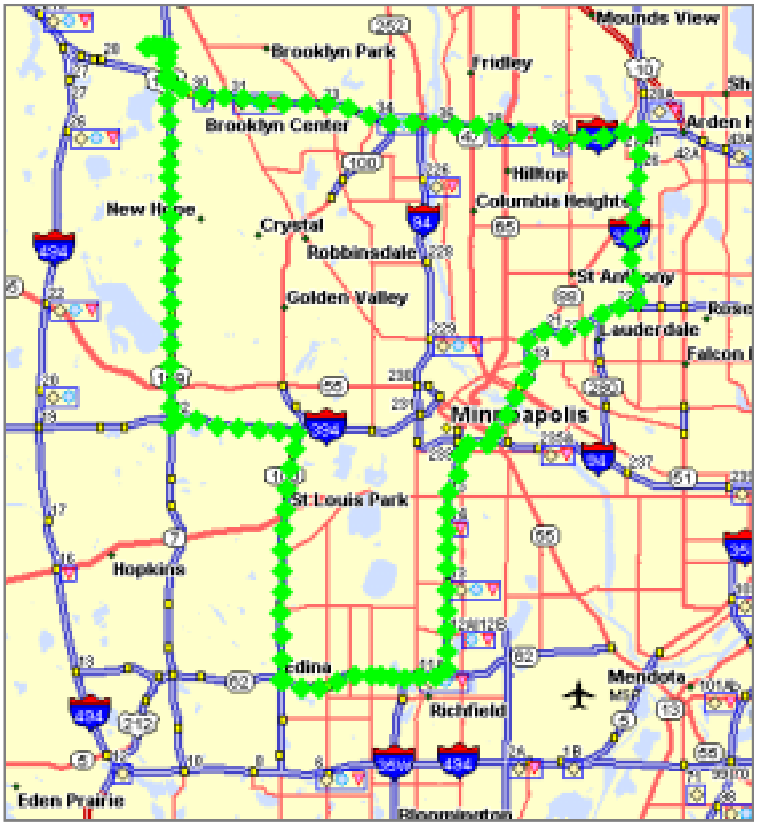


Figure 4.4 Highway Route II

| **Correction [St Paul]** | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|
| **Trimble AgGPS132** | 0.82 m (2.70 ft) | 0.56 m (1.83 ft) | -0.17 m (-0.54 ft) | 0.50 m (1.65 ft) | 0.01 m (0.03 ft) | 0.53 m (1.74 ft) |
| **CSI GBX-12R** | 2.13 m (7.00 ft) | 0.88 m (2.90 ft) | -0.43 m (-1.39 ft) | 1.52 m (4.99 ft) | -0.37 m (-1.20 ft) | 1.69 m (5.56 ft) |
| **JRC DGPS 212** | 15.02 m (49.27 ft) | 17.01 m (55.79 ft) | -0.38 m (-1.25 ft) | 1.57 m (5.15 ft) | 13.56 m (44.48 ft) | 18.13 m (59.45 ft) |

Table 4.2 Results of the NDGPS Evaluation on Highway Route II at an average speed of 23 m/sec (51 MPH)

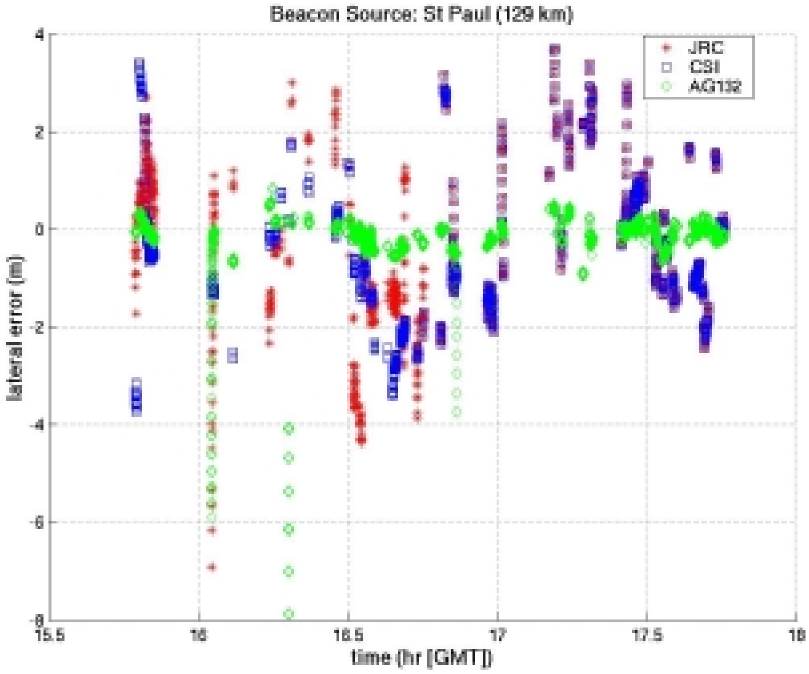


Figure 4.5 Results of the NDGPS Evaluation on Highway Route II

### 4.1.3 Results of the NDGPS Evaluation on Highway Route III

Highway Route III included MN Highway 55, Highway I-94, MN Highway 280, MN Highway 36 and U.S. Highway 61 in the Twin Cities. The total mileage for the route was 219.5 km (135.3 miles) and the mileage for “RTK fix” data was 45.5 km (28.3 miles, or 21%). The average travel speed on the route was 21 m/sec (46 MPH). In this evaluation, all three NDGPS reference stations near Minnesota (St Paul, Pine River, and Wisconsin Point) were used as correction sources to test the effects of different baselines on GPS accuracies. Please note that the JRC DGPS 212 receiver was excluded from this evaluation because it does not have the ability to manually adjust the beacon frequency and thus one cannot tune to a particular base station.

Figure 4.6 shows the route on a digital map and the results are presented in Table 4.3 and Figures 4.7 ~ 4.11.

Figure 4.6 Highway Route III

| Correction | Receiver | Positional mean error | σ | Lateral mean error | σ | Longitudinal mean error | σ |
|---|---|---|---|---|---|---|---|
| **St Paul** | **Trimble AgGPS132** | 0.69 m (2.25 ft) | 0.62 m (2.03 ft) | -0.26 m (-0.85 ft) | 0.43 m (1.42 ft) | -0.05 m (-0.18 ft) | 0.57 m (1.88 ft) |
| | **CSI GBX-12R** | 5.19 m (17.02 ft) | 6.40 m (20.98 ft) | 0.01 m (0.03 ft) | 1.75 m (5.73 ft) | -2.49 m (-9.79 ft) | 7.47 m (24.50 ft) |
| **Pine River** | **Trimble AgGPS132** | 0.86 m (2.83 ft) | 0.37 m (1.21 ft) | -0.05 m (-0.16 ft) | 0.39 m (1.28 ft) | 0.22 m (0.72 ft) | 0.24 m (0.79 ft) |
| | **CSI GBX-12R** | 1.15 m (3.76 ft) | 0.58 m (1.91 ft) | -0.51 m (-1.68 ft) | 0.85 m (2.79 ft) | -0.15 m (-0.50 ft) | 0.93 m (3.05 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | 0.63 m (2.04 ft) | 0.39 m (1.29 ft) | -0.58 m (-1.89 ft) | 0.53 m (1.74 ft) | 0.19 m (0.63 ft) | 0.39 m (1.30 ft) |
| | **CSI GBX-12R** | 1.80 m (5.90 ft) | 0.97 m (3.18 ft) | -0.48 m (-1.58 ft) | 1.78 m (5.83 ft) | 0.09 m (0.30 ft) | 0.99 m (3.25 ft) |

Table 4.3 Results of the NDGPS Evaluation on Highway Route III at an average speed of 21 m/sec (47 MPH)

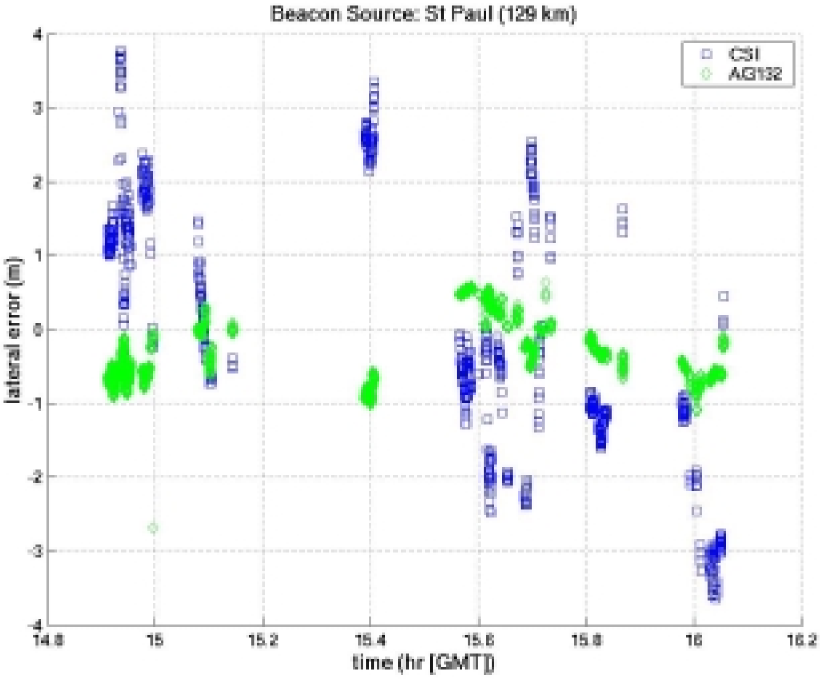


Figure 4.7 Results of the NDGPS Evaluation on Highway Route III (St Paul base station)

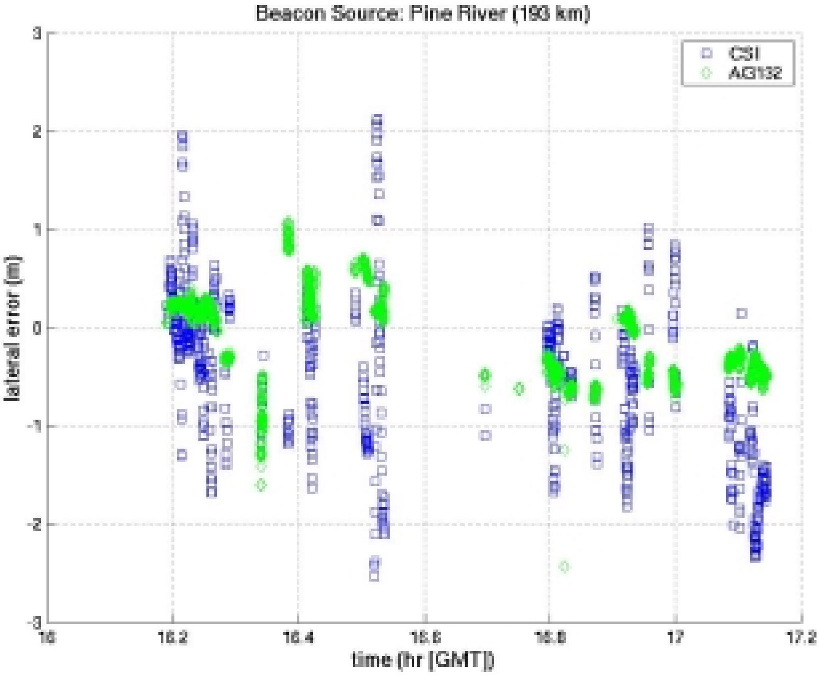


Figure 4.8 Results of the NDGPS Evaluation on Highway Route III (Pine River base station)

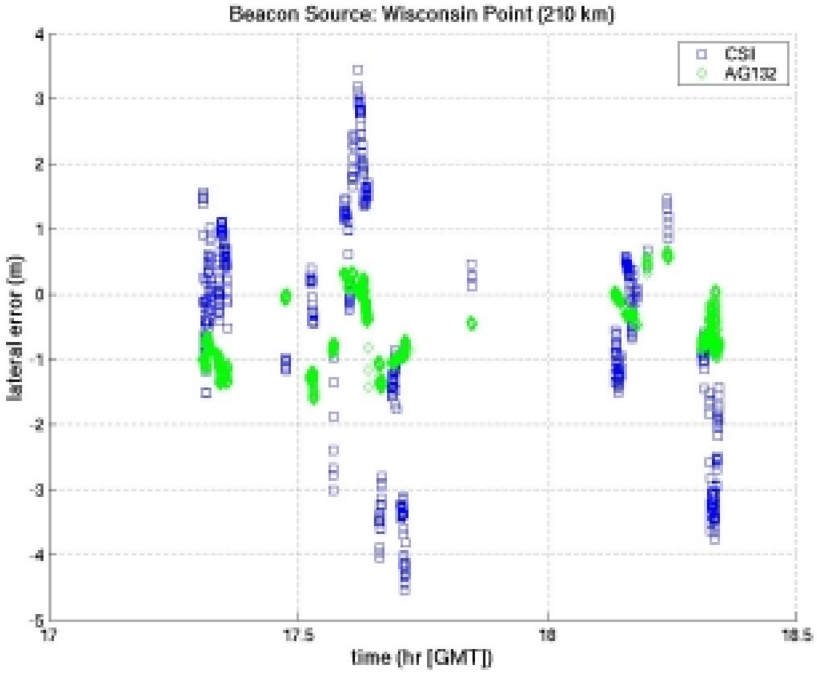


Figure 4.9 Results of the NDGPS Evaluation on Highway Route III (Wisconsin Point base station)

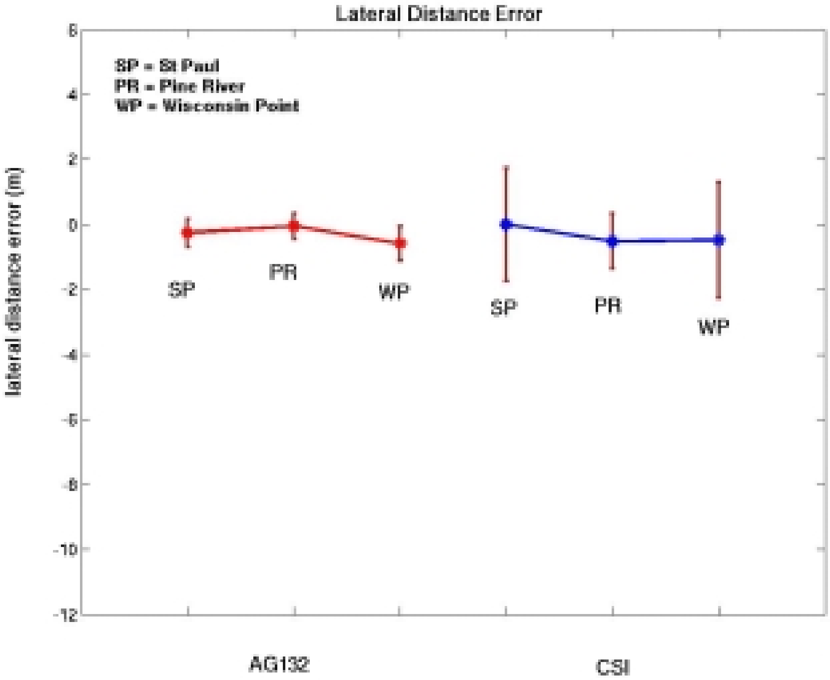


Figure 4.10 Comparison of the lateral distance errors for different NDGPS base stations (Highway Route III)

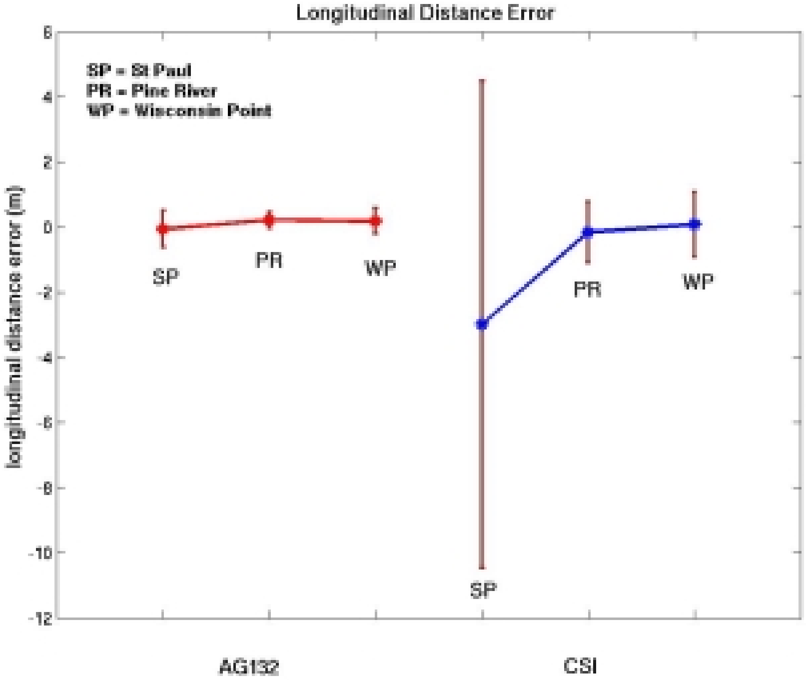


Figure 4.11 Comparison of the longitudinal distance errors for different NDGPS base stations (Highway Route III)

### 4.1.4 Results of the NDGPS Evaluation on Highway Route IV

Highway Route IV included the Highway I-94 and Highway I-694 loop in the Twin Cities. The total mileage for the route was 591.2 km (367.1 miles) and the mileage for "RTK fix" data was 106 km (65.8 miles, or 18%). The average travel speed on the route was 23 m/sec (51MPH). In this evaluation, all three NDGPS reference stations near Minnesota (St Paul, Pine River, and Wisconsin Point) were used as correction sources to test the effects of different baselines on GPS accuracies. Again, the JRC DGPS 212 receiver was excluded from this evaluation because it does not have the ability to manually adjust the beacon frequency and thus one cannot tune to a particular base station.

Figure 4.12 shows the route on a digital map and the results are presented in Table 4.4 and Figures 4.13 ~ 4.15. Two results in Table 4.4 (identified in red) are discussed further.

Figure 4.12 Highway Route IV

| Correction | Receiver | Positional mean error | σ | Lateral mean error | σ | Longitudinal mean error | σ |
|---|---|---|---|---|---|---|---|
| **St Paul** | **Trimble AgGPS132** | 1.67 m (5.48 ft) | 5.30 m (17.37 ft) | -0.47 m (-1.54 ft) | 4.56 m (14.95 ft) | 0.47 m (1.55 ft) | 3.11 m (10.21 ft) |
| | **CSI GBX-12R** | 22.87 m (75.01 ft) | 4.68 m (15.36 ft) | 0.25 m (0.81 ft) | 1.15 m (3.76 ft) | -22.83 m (-74.89 ft) | 4.69 m (15.39 ft) |
| **Pine River** | **Trimble AgGPS132** | 1.24 m (4.08 ft) | 0.54 m (1.79 ft) | 0.31 m (1.01 ft) | 0.55 m (1.80 ft) | 0.15 m (0.50 ft) | 0.46 m (1.50 ft) |
| | **CSI GBX-12R** | 22.46 m (73.67 ft) | 5.86 m (19.21 ft) | -0.71 m (-2.34 ft) | 1.26 m (4.13 ft) | -22.41 m (-73.52 ft) | 5.88 m (19.28 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | 1.91 m (6.27 ft) | 4.77 m (15.66 ft) | 0.75 m (2.47 ft) | 4.74 m (15.55 ft) | 0.12 m (0.39 ft) | 1.20 m (3.93 ft) |
| | **CSI GBX-12R** | 22.58 m (77.33 ft) | 4.50 m (14.76 ft) | 0.27 m (0.87 ft) | 1.28 m (4.19 ft) | -23.52 m (-77.13 ft) | 4.60 m (15.10 ft) |

Table 4.4 Results of the NDGPS Evaluation on Highway Route IV at an average speed of 23 m/sec (51 MPH)

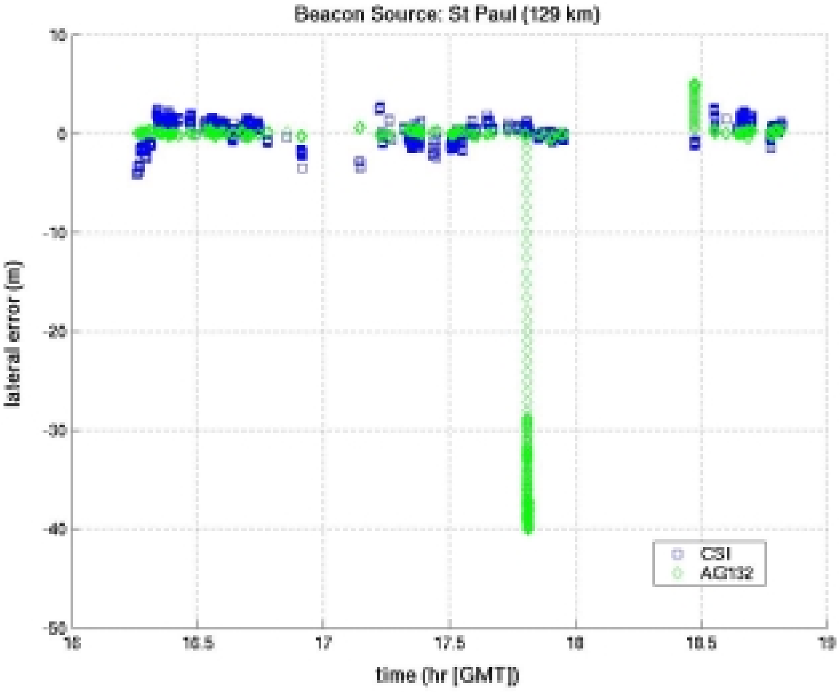


Figure 4.13 Results of the NDGPS Evaluation on Highway Route IV (St Paul base station)

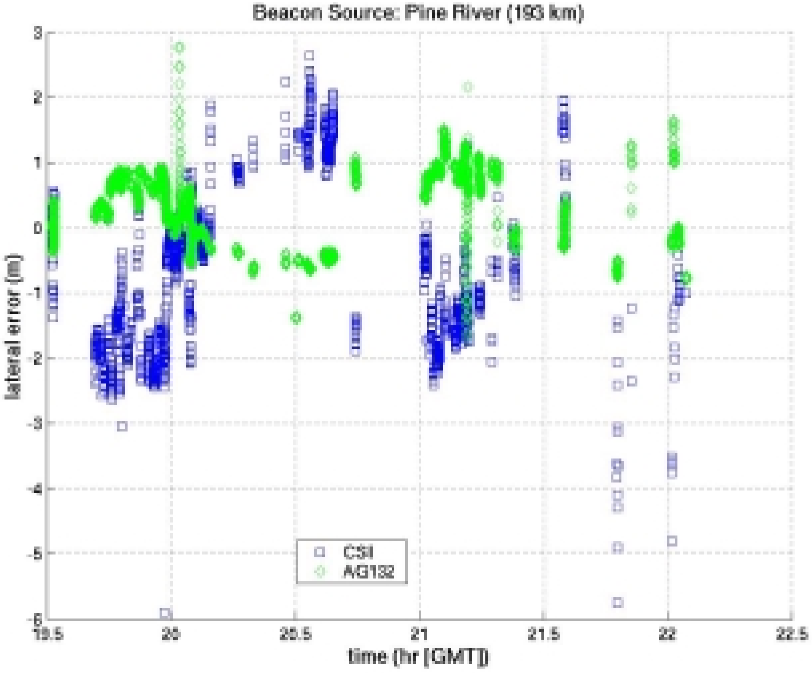


Figure 4.14 Results of the NDGPS Evaluation on Highway Route IV (Pine River base station)

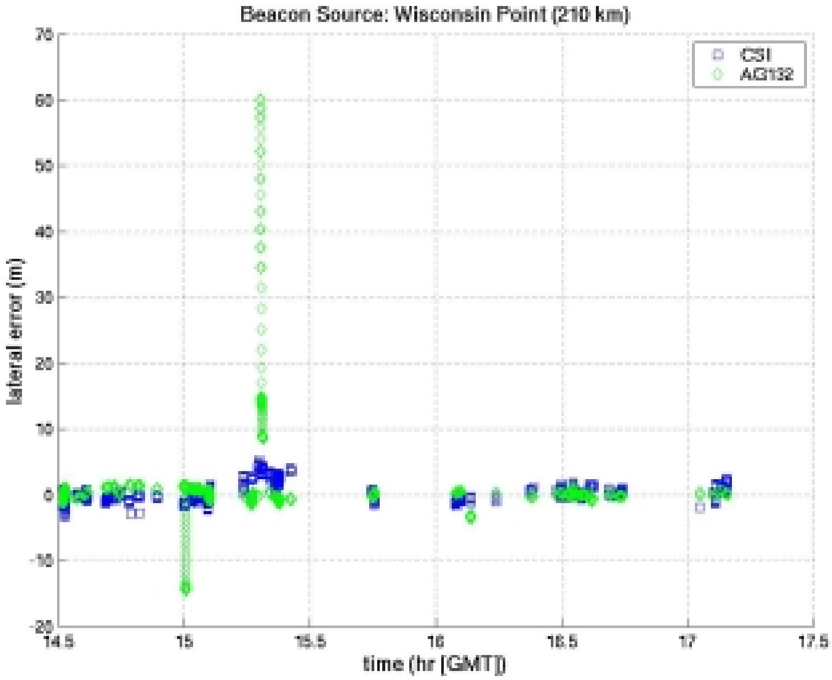


Figure 4.15 Results of the NDGPS Evaluation on Highway Route IV (Wisconsin Point base station)

From Table 4.4, Figure 4.13, and Figure 4.15, it is found that there were abnormal spikes on the lateral errors from the Trimble AgGPS 132 receiver. Further investigation showed that the GPS receiver drifted out of the normal course for a brief period of time. In Figure 4.13 where the St Paul base station was used as the correction source, the Trimble AgGPS 132 receiver drifted out of the normal course for 25.2 seconds. In Figure 4.15 where the Wisconsin Point base station was used as the correction source, there were two episodes of drift which lasted for a total of 30.9 seconds. An example of such GPS drift is shown in Figure 4.16. The duration of all GPS drifts (56.1 seconds total) on this testing route can be ignored when compared to the total data collection time of 478.2 minutes. This constituted less than 0.2% of the data on this highway route.

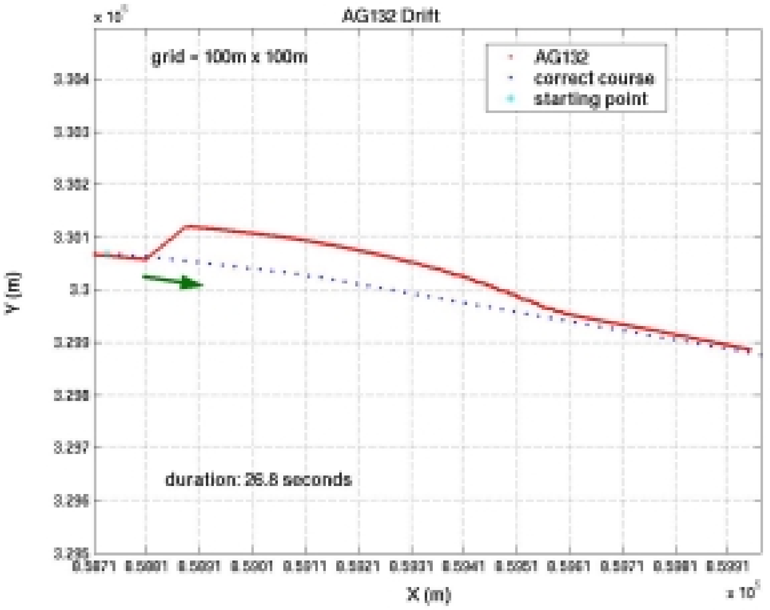


Figure 4.16 Abnormal drift of the Trimble AgGPS 132 receiver on Highway Route IV

The reasons for the drifts are not certain. It may be because of a satellite constellation change occurring in which one satellite drops out of the view of the GPS receiver and/or the other satellite is emerged from the horizon and causes the GPS receiver to recompute its positions based on the new constellation. It might also be because the vehicle comes out from under a bridge and the GPS receiver takes longer than usual to compute its new positions due to unforeseeable environmental variables such as multipath effect, interruption of correction signals, and topography etc. Fortunately, such anomalies are easy to detect. With an inexpensive inertial measurement sensor (e.g., a gyroscope or a lateral accelerometer with an appropriately designed filter), the on-board road user charge system will be able to tell when a GPS drift occurs and can ignore the solution for a brief period of time (until it converges back to the correct course).

The interesting issue is that this normally only occurred in the Trimble AgGPS 132 and not to any of other receivers that were collecting data at the same time.

The accuracy of the Trimble AgGPS 132 receiver is pretty much in agreement with the results presented in previous subsections after the abnormal drift is removed from the data. The results without the drift included are shown in Table 4.5 and Figures 4.17 ~ 4.20.

| **Correction** | **Receiver** | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|---|
| **St Paul** | **Trimble AgGPS132** | 1.00 m<br>(3.28 ft) | 0.48 m<br>(1.57 ft) | 0.10 m<br>(0.33 ft) | 0.35 m<br>(1.15 ft) | 0.10 m<br>(0.33 ft) | 0.48 m<br>(1.57 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | 1.28 m<br>(4.20 ft) | 0.86 m<br>(2.82 ft) | 0.22 m<br>(0.72 ft) | 0.97 m<br>(3.18 ft) | 0.26 m<br>(0.85 ft) | 0.48 m<br>(1.57 ft) |

Table 4.5 Results of the accuracy of the Trimble AgGPS 132 receiver without drift on Highway Route IV

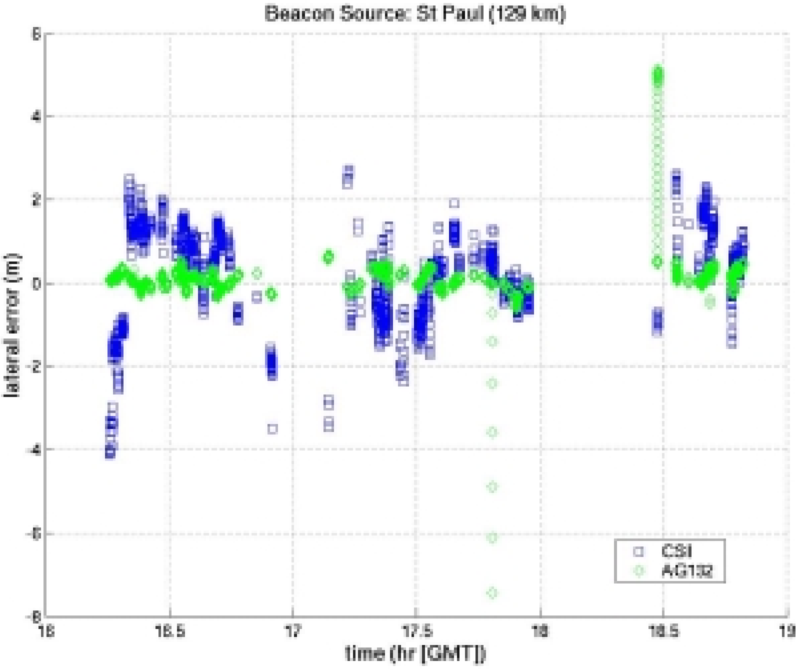


Figure 4.17 Results of the NDGPS Evaluation without drift included on Highway Route IV (St Paul base station)

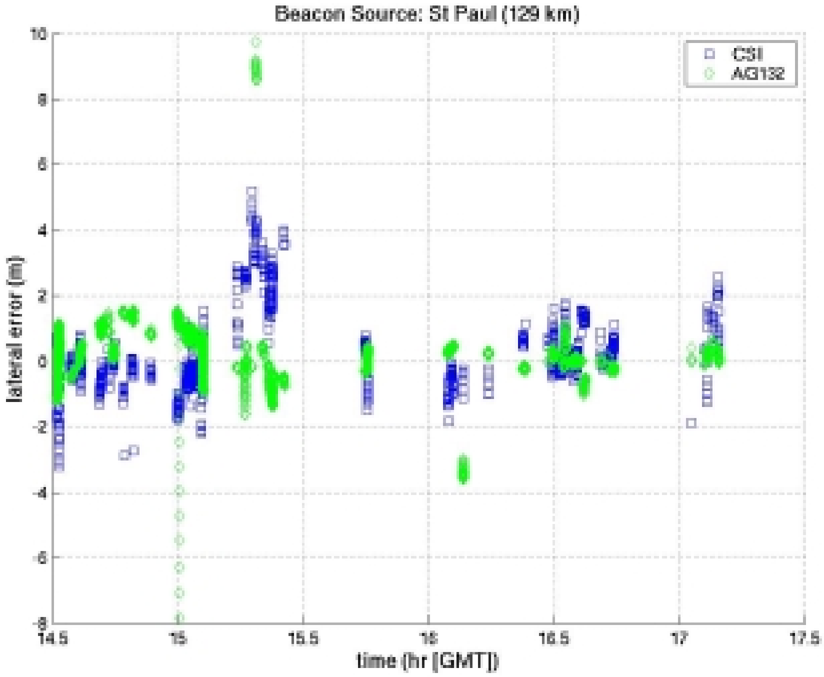


Figure 4.18 Results of the NDGPS Evaluation without drift included on Highway Route IV (Wisconsin Point base station)

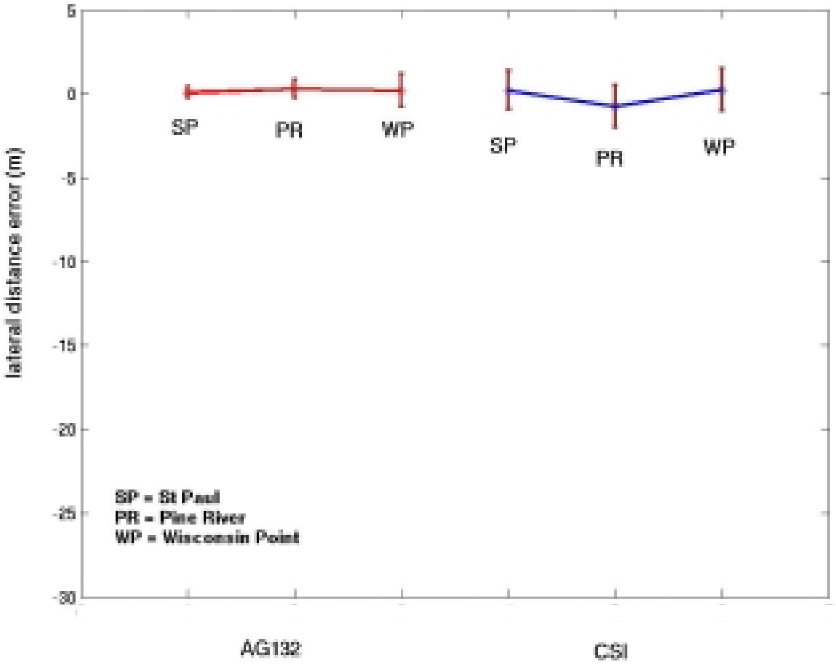


Figure 4.19 Comparison of the lateral distance errors with different NDGPS base stations (without drift included, Highway Route IV)

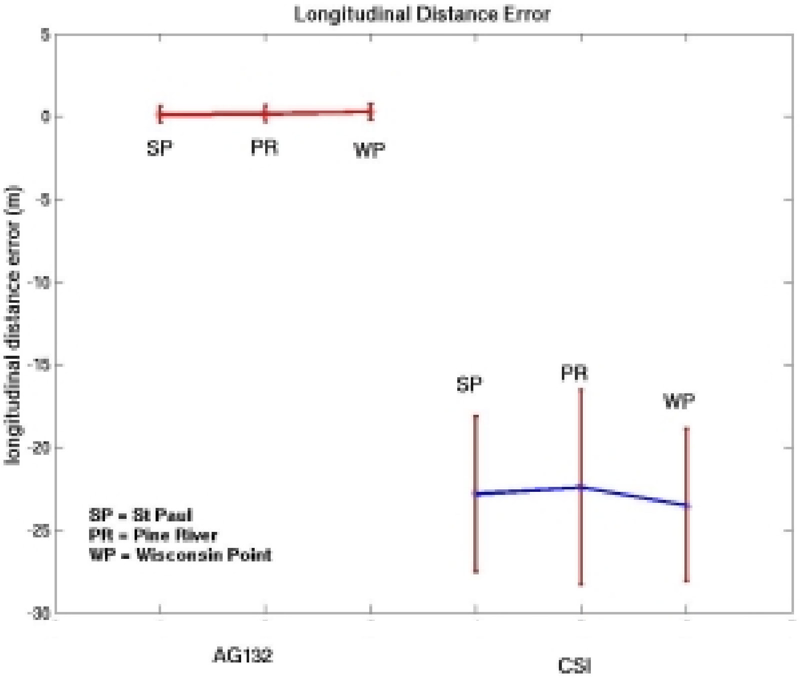


Figure 4.20 Comparison of the longitudinal distance errors with different NDGPS base stations (without drift included, Highway Route IV)

### 4.1.5 Summary and Discussion of the NDGPS Evaluation on Highways

The following summarizes the results presented in Sections 4.1.1 ~ 4.1.4:

- The Trimble AgGPS 132 has the highest accuracy among all GPS receivers tested. Overall, it has a mean positional error of 0.99 m (3.24 ft) with a standard deviation ($\sigma$) of 0.60 m (1.97 ft). The mean lateral error and its standard deviation are 0.01 m (0.03 ft) and 0.61 m (1.99 ft), respectively. The overall accuracies for all highway routes for all three GPS receivers tested are shown in Table 4.6.
- The effects of different baselines do not play a significant role on the accuracies of GPS receivers. All three NDGPS base stations near Minnesota with baselines ranged from 129 km (80 miles) to 210 km (130 miles) were used in the highway evaluation. However, the accuracy of the same GPS receiver on the same route does not improve by using a closer NDGPS base station. In some instances, a GPS receiver even has worse accuracy by using the closer NDGPS base station. For example, it is found from Table 4.8 that the CSI GBX-12R GPS receiver has a better positional accuracy using the Wisconsin Point base station that has a longer baseline of 210 km (130 miles) than using the St Paul base station with the shorter baseline of 129 km (80 miles). This may be due to the range rate correction in the NDGPS service to compensate for the long baseline from the base station so that a higher accuracy can be achieved.
- The abnormal drift of the Trimble AgGPS receiver can be corrected by using an inexpensive inertial measurement sensor. The drift rarely happens and can be considered

an anomaly. A drift of more than 10 m (32.8 ft) laterally only occurred for a total of 56.1 seconds out of the total 841.06 minutes of experimental data. This represents less than 0.1% of the data on all highway routes.

| | Positional mean error | σ | Lateral mean error | σ | Longitudinal mean error | σ |
|---|---|---|---|---|---|---|
| **Trimble AgGPS132** | 0.99 m (3.24 ft) | 0.60 m (1.97 ft) | 0.01 m (0.03 ft) | 0.61 m (1.99 ft) | 0.11 m (0.37 ft) | 0.51 m (1.66 ft) |
| **CSI GBX-12R** | 14.27 m (46.79 ft) | 10.63 m (34.86 ft) | -0.22 m (-0.73 ft) | 1.40 m (4.60 ft) | -13.56 m (-44.48 ft) | 11.43 m (37.49 ft) |
| **JRC DGPS 212** | 17.62 m (57.80 ft) | 14.19 m (46.56 ft) | -0.45 m (-1.46 ft) | 1.49 m (4.89 ft) | 15.89 m (52.11 ft) | 16.03 m (52.59 ft) |

Table 4.6 Summary of the results of the NDGPS Evaluation on Highway routes (not including the short term drift results for the Trimble AgGPS 132 receiver)

## *4.2 Evaluations of the NDGPS Service: City Streets*

Evaluations of the NDGPS service were also performed on city streets in the metropolitan Twin Cities area. The DGPS receivers tested were the same as those evaluated on the highway routes. They are the Trimble AgGPS 132, the CSI GBX-12R, and the JRC DGPS 212. Figure 4.21 shows all five routes tested. These routes covered about 365 km (226 miles). However, since there were buildings, structures, and trees on the sides of streets, and CDPD wireless signal holes along the way, only 126 km (78 miles or 34%) of the Trimble MS-750 data had the quality of "RTK fix". By using the same procedure, the Trimble MS-750 data with "RTK fix" and the corresponding data segments from other DGPS receivers were extracted for data analysis. The average travel speed for all routes was 8.5 m/sec (19 MPH). The experiments on city streets were performed in May 2002.

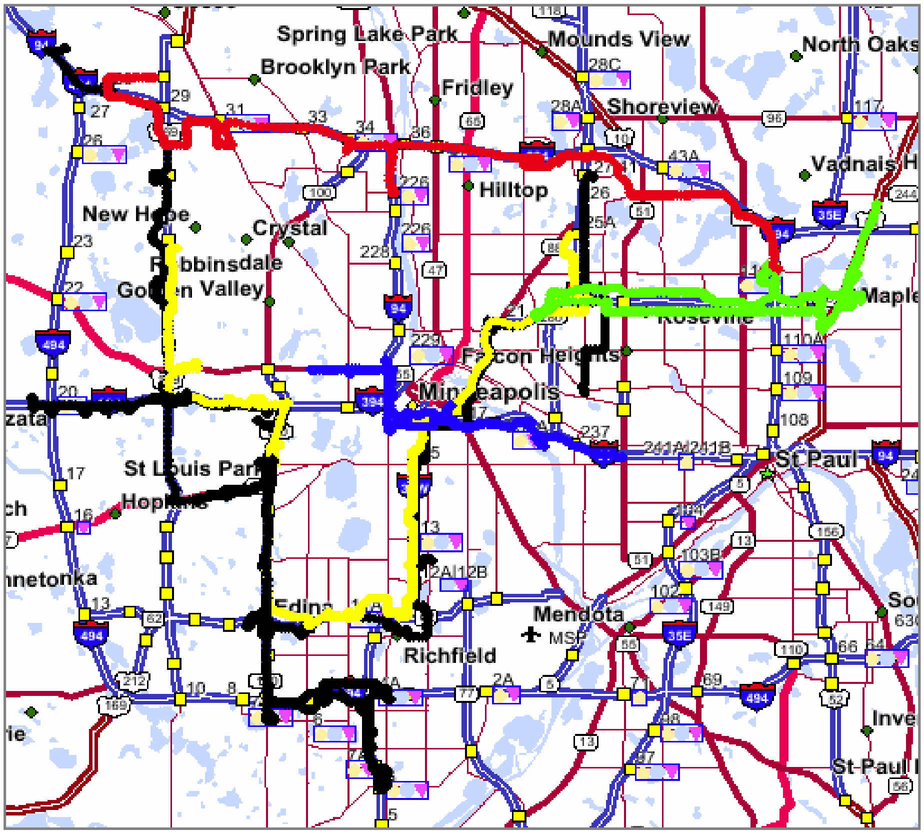


Figure 4.21 Testing routes of the NDGPS evaluation on city streets

The selections of these local routes are based on the worst-case scenarios that are possible for the application of road user charging. All local routes are along major highways. They are either the frontage roads of highways or city streets running parallel to highways. Some roads are separated from highways with islands that are only 2 ~ 3 meters wide. The other roads are under elevated highways with one side of the view of the sky totally blocked by highways or sound walls. By testing these worst-case scenarios, one will be able to find how well each GPS receiver works and thus design a road user charging system that would work under most conditions. Please note that the charging system can ignore segments when no data is available. This is reasonable if such events are not common.

The results of each testing route are presented in each subsection and the overall results of the evaluation on city streets are summarized and discussed at the end of this section.

### 4.2.1 Results of the NDGPS Evaluation on Local Route I

Local Route I ran along the Highway Route II. Most of them were frontage roads of the highways on the Highway Route II. The total mileage for the route was 170 km (106 miles) and the mileage for "RTK fix" data was 58.5 km (19 miles, or 34%). The average travel speed on the route was 8.5 m/sec (19 MPH). The St Paul NDGPS base station was used as the correction source for this evaluation.

Figure 4.22 shows the route on a digital map and the results are presented in Table 4.7 and Figure 4.23.

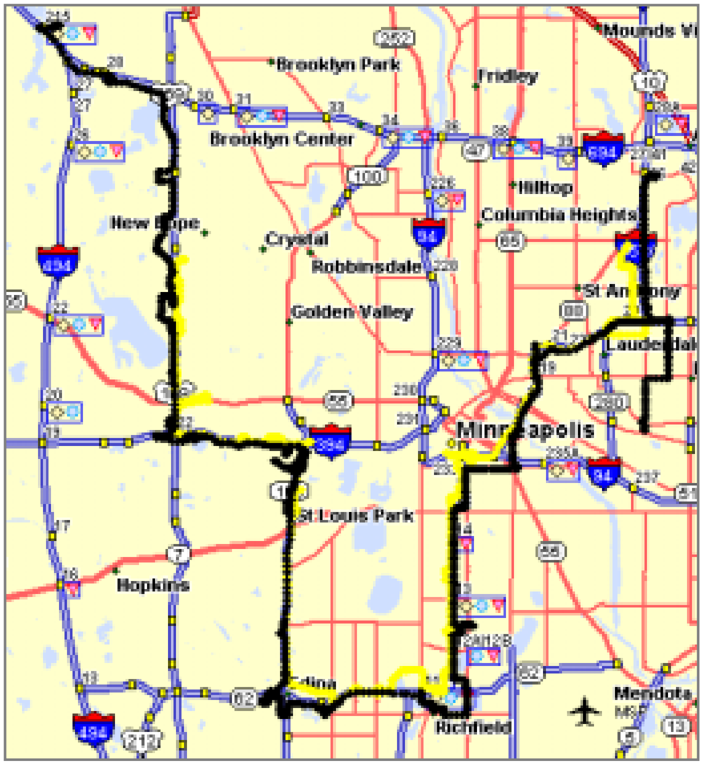


Figure 4.22 Local Route I

| Correction [St Paul] | Positional mean error | σ | Lateral mean error | σ | Longitudinal mean error | σ |
|---|---|---|---|---|---|---|
| **Trimble AgGPS132** | 0.96 m (3.16 ft) | 1.09 m (3.57 ft) | -0.09 m (-0.28 ft) | 1.02 m (3.35 ft) | 0.05 m (0.16 ft) | 0.70 m (2.31 ft) |
| **CSI GBX-12R** | 2.20 m (7.22 ft) | 0.97 m (3.17 ft) | -0.17 m (-0.57 ft) | 1.73 m (5.66 ft) | -0.33 m (-1.07 ft) | 1.64 m (5.37 ft) |
| **JRC DGPS 212** | 19.80 m (64.96 ft) | 8.80 m (28.85 ft) | -0.28 m (-0.91 ft) | 2.02 m (6.63 ft) | 19.61 m (64.33 ft) | 8.94 m (29.34 ft) |

Table 4.7 Results of the NDGPS Evaluation on Local Route I at an average speed of 12 m/sec (27 MPH)

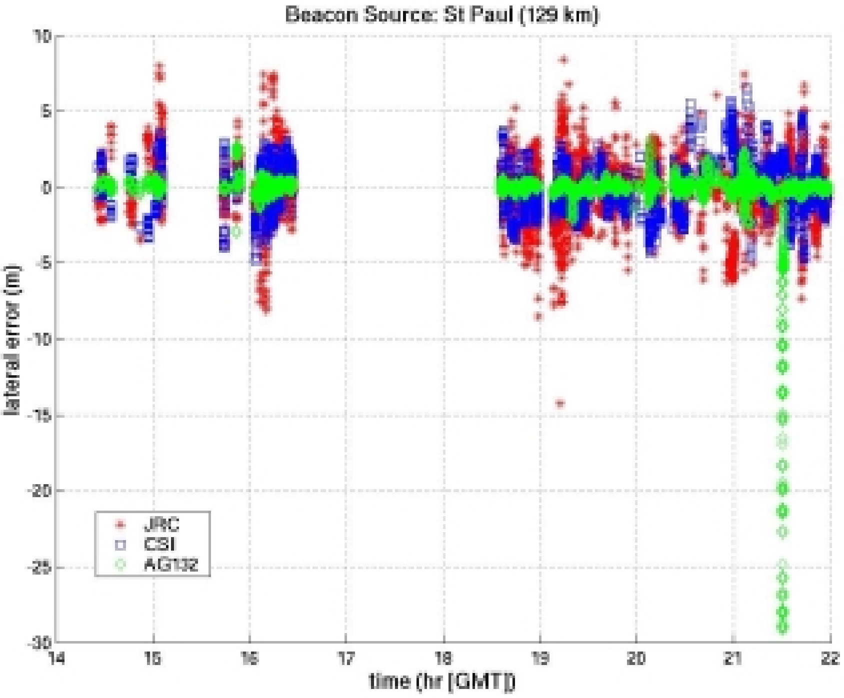


Figure 4.23 Results of the NDGPS Evaluation on Local Route I

From Table 4.7 and Figure 4.23, it is found again that the Trimble AgGPS 132 receiver had another abnormal spike for lateral errors. Figure 4.24 shows that the Trimble AgGPS 132 receiver drifted out of the course for 56.2 seconds. Comparing with the total experimental data of 457 minutes on this route, this drift was very brief and only represented less than 0.2% of the data.

After correcting the abnormal drift, the revised results are presented in Table 4.8 and Figure 4.25.

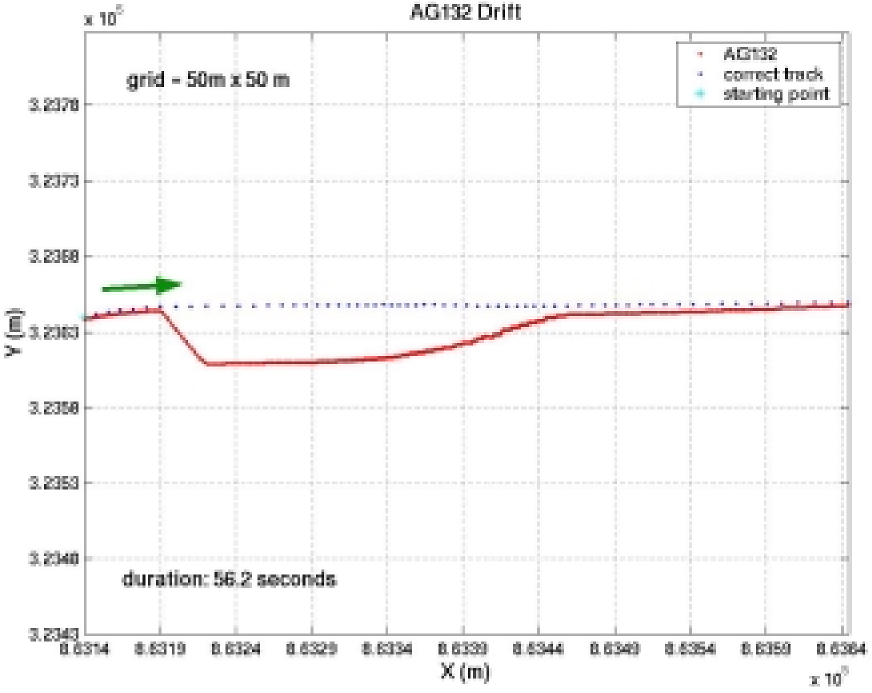


Figure 4.24 Abnormal drift of the Trimble AgGPS 132 receiver on Local Route I

| **Correction [St Paul]** | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|
| **Trimble AgGPS132** | 0.91m (3.00 ft) | 0.64 m (2.09 ft) | -0.03 m (-0.09 ft) | 0.35 m (1.13 ft) | 0.06 m (0.20 ft) | 0.68 m (2.22 ft) |

Table 4.8 Accuracy of the Trimble AgGPS 132 receiver without drift on Local Route I

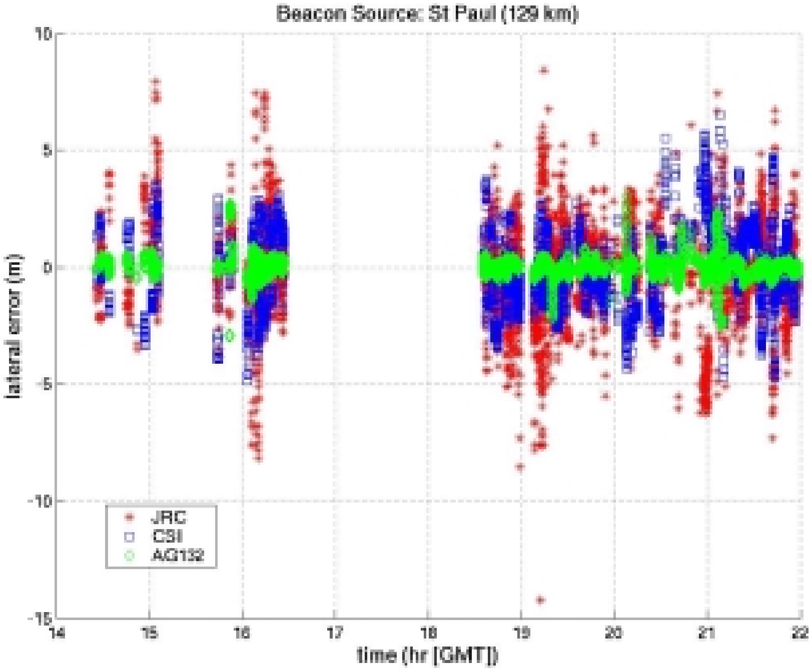


Figure 4.25 Results of the NDGPS Evaluation without drift on Local Route I

### 4.2.2 Results of the NDGPS Evaluation on Local Route II

Local Route II covered the southwest Twin Cities area and ran on the frontage roads and city streets along major state and interstate highways. The total mileage for the route was 79 km (49 miles) and the mileage for “RTK fix” data was 35 km (22 miles, or 44%). The average travel speed on the route was 8.7 m/sec (19 MPH). The St Paul NDGPS base station was used as the correction source for this evaluation.

Figure 4.26 shows the route on a digital map and the results are presented in Table 4.9 and Figure 4.27.

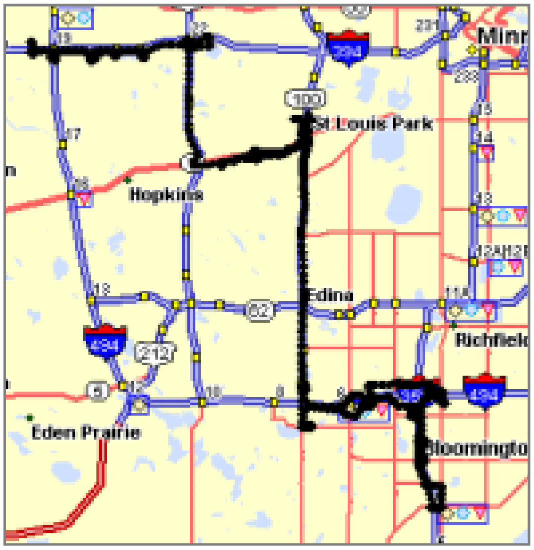


Figure 4.26 Local Route II

| **Correction [St Paul]** | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|
| **Trimble AgGPS132** | 0.84 m (2.75 ft) | 0.29 m (0.94 ft) | -0.04 m (-0.13 ft) | 0.29 m (0.96 ft) | 0.02 m (0.08 ft) | 0.25 m (0.81 ft) |
| **CSI GBX-12R** | 1.81 m (5.94 ft) | 0.60 m (1.96 ft) | -0.34 m (-1.12 ft) | 1.44 m (4.72 ft) | -0.03 m (-0.10 ft) | 1.25 m (4.10 ft) |
| **JRC DGPS 212** | 15.40 m (50.52 ft) | 9.14 m (29.99 ft) | 0.24 m (0.79 ft) | 2.35 m (7.39 ft) | 14.98 m (48.84 ft) | 9.61 m (31.52 ft) |

Table 4.9 Results of the NDGPS Evaluation on Local Route II at an average speed of 11 m/sec (25 MPH)

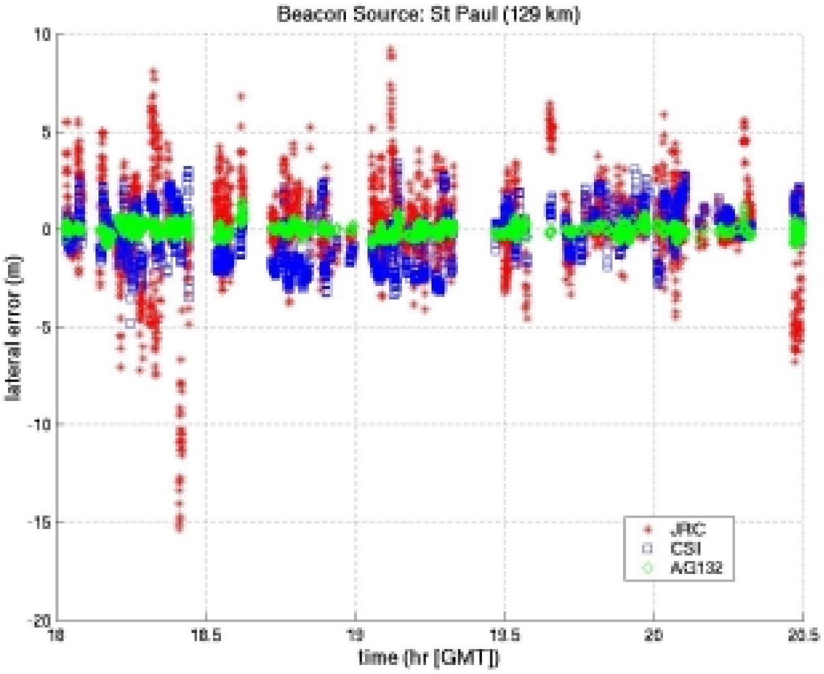


Figure 4.27 Results of the NDGPS Evaluation on Local Route II

### 4.2.3 Results of the NDGPS Evaluation on Local Route III

Local Route III covered the area right outside of downtown Minneapolis and ran on the frontage roads and city streets along the western part of the Highway Route III. The total mileage for the route was 29 km (18 miles) and the mileage for "RTK fix" data was 6 km (4 miles, or 22%). The average travel speed on the route was 6 m/sec (13 MPH). The St Paul NDGPS base station was used as the correction source for this evaluation.

Figure 4.28 shows the route on a digital map and the results are presented in Table 4.10 and Figure 4.29.

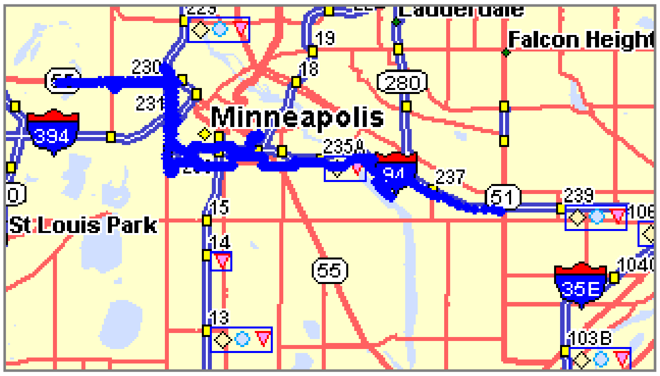


Figure 4.28 Local Route III

| Correction [St Paul] | Positional mean error | σ | Lateral mean error | σ | Longitudinal mean error | σ |
|---|---|---|---|---|---|---|
| **Trimble AgGPS132** | 0.97 m (3.18 ft) | 0.43 m (1.41 ft) | 0.06 m (0.19 ft) | 0.44 m (1.44 ft) | 0.02 m (0.06 ft) | 0.36 m (1.17 ft) |
| **CSI GBX-12R** | 2.19 m (7.18 ft) | 1.22 m (4.00 ft) | 0.20 m (0.64 ft) | 1.75 m (5.73 ft) | 0.22 m (0.72 ft) | 1.72 m (5.64 ft) |
| **JRC DGPS 212** | 15.13 m (49.64 ft) | 6.43 m (21.08 ft) | 0.65 m (2.13 ft) | 1.99 m (6.53 ft) | 14.86 m (48.73 ft) | 6.51 m (21.37 ft) |

Table 4.10 Results of the NDGPS Evaluation on Local Route III at an average speed of 9 m/sec (20 MPH)

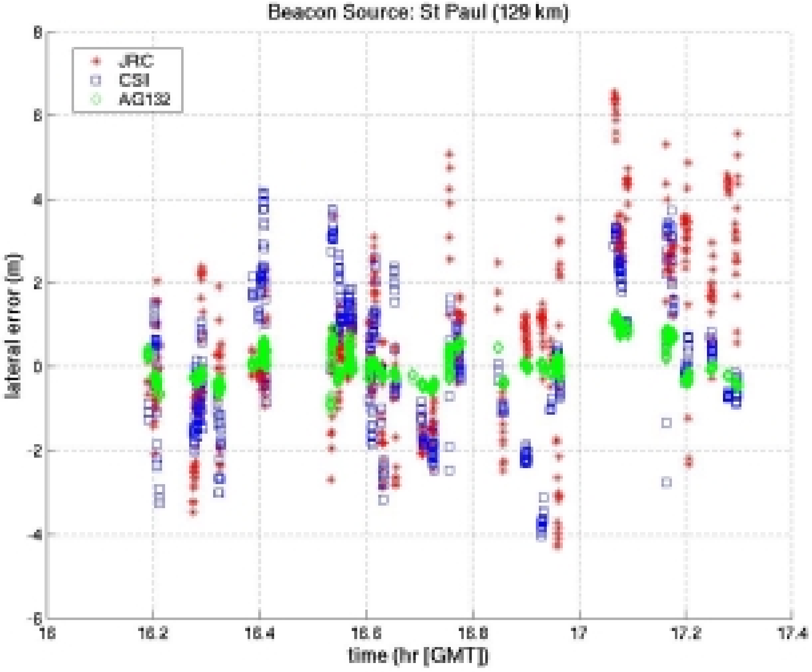


Figure 4.29 Results of the NDGPS Evaluation on Local Route III

### 4.2.4 Results of the NDGPS Evaluation on Local Route IV

Local Route IV covered the north Twin Cities area and ran on the frontage roads and city streets along the Highway Route IV. The total mileage for the route was 45 km (28 miles) and the mileage for “RTK fix” data was 14 km (9 miles, or 31%). The average travel speed on the route was 12 m/sec (26 MPH). The St Paul NDGPS base station was used as the correction source for this evaluation.

Figure 4.30 shows the route on a digital map and the results are presented in Table 4.11 and Figure 4.31.

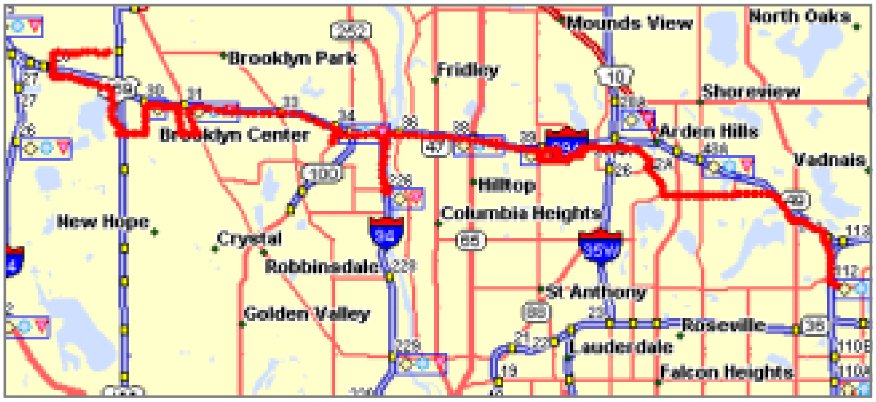


Figure 4.30 Local Route IV

| **Correction [St Paul]** | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|
| **Trimble AgGPS132** | 0.85 m (2.78 ft) | 0.25 m (0.82 ft) | -0.04 m (-0.12 ft) | 0.27 m (0.88 ft) | 0.14 m (0.47 ft) | 0.21 m (0.70 ft) |
| **CSI GBX-12R** | 3.26 m (10.68 ft) | 3.87 m (12.68 ft) | -0.01 m (-0.03 ft) | 1.87 m (6.13 ft) | -0.79 m (-2.60 ft) | 4.62 m (15.16 ft) |
| **JRC DGPS 212** | 22.45 m (73.65 ft) | 9.81 m (32.18 ft) | 1.44 m (4.71 ft) | 2.06 m (6.74 ft) | 22.16 m (72.69 ft) | 9.91 m (32.51 ft) |

Table 4.11 Results of the NDGPS Evaluation on Local Route IV at an average speed of 14 m/sec (31 MPH)

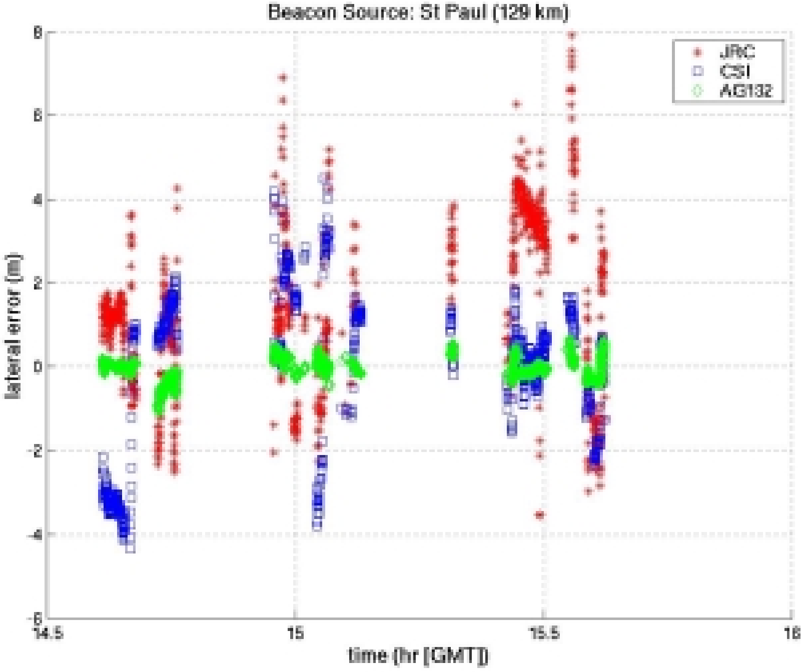


Figure 4.31 Results of the NDGPS Evaluation on Local Route IV

### 4.2.5 Results of the NDGPS Evaluation on Local Route V

Local Route V covered the area northeast of the city of Minneapolis and ran on the frontage roads and city streets along the eastern portion of the Highway Route III. The total mileage for the route was 42 km (26 miles) and the mileage for "RTK fix" data was 12 km (7 miles, or 29%). The average travel speed on the route was 8 m/sec (18 MPH). The St Paul NDGPS base station was used as the correction source for this evaluation.

Figure 4.32 shows the route on a digital map and the results are presented in Table 4.12 and Figure 4.33.

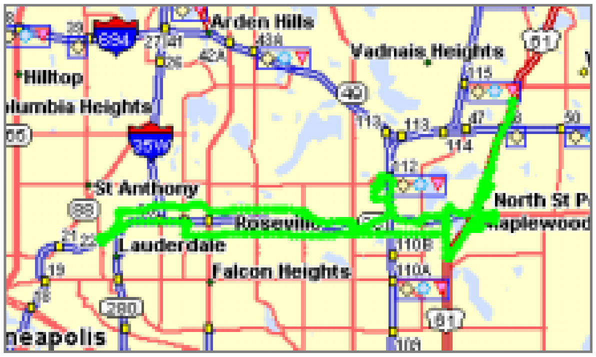


Figure 4.32 Local Route V

| Correction [St Paul] | Positional mean error | σ | Lateral mean error | σ | Longitudinal mean error | σ |
|---|---|---|---|---|---|---|
| **Trimble AgGPS132** | 1.03 m (3.38 ft) | 0.28 m (0.91 ft) | 0.15 m (0.50 ft) | 0.27 m (0.87 ft) | 0.05 m (0.18 ft) | 0.29 m (0.96 ft) |
| **CSI GBX-12R** | 1.93 m (6.32 ft) | 1.43 m (4.69 ft) | -0.46 m (-1.49 ft) | 1.95 m (6.41 ft) | -0.42 m (-1.39 ft) | 1.32 m (4.32 ft) |
| **JRC DGPS 212** | 12.22 m (40.07 ft) | 6.38 m (20.91 ft) | 0.92 m (3.00 ft) | 1.66 m (5.43 ft) | 11.56 m (37.92 ft) | 7.04 m (23.09 ft) |

Table 4.12 Results of the NDGPS Evaluation on Local Route V at an average speed of 11 m/sec (25 MPH)

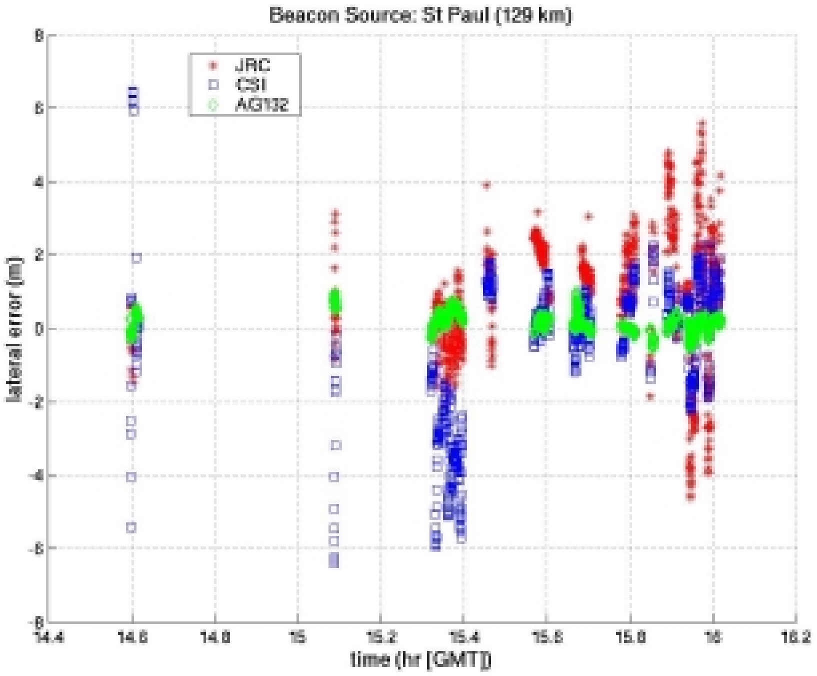


Figure 4.33 Results of the NDGPS Evaluation on Local Route V

### 4.2.6 Summary and Discussion of the NDGPS Evaluation on City Streets

The following summarizes the results presented in Sections 4.2.1 ~ 4.2.5:

- The Trimble AgGPS 132 again has the highest accuracy among all GPS receivers tested on city streets. Overall, it has a mean positional error of 0.90 m (2.95 ft) with a standard deviation (σ) of 0.49 m (1.59 ft). The mean lateral error and its standard deviation are –0.01 m (–0.03 ft) and 0.33 m (1.08 ft), respectively. The JRC DGPS 212 receiver still has the least accuracy of the units tested. Its lateral accuracy is on par with the CSI GBX-

12R receiver. However, it has a very large longitudinal error. The overall accuracies on local routes for all three GPS receivers tested are shown in Table 4.13. The comparison of lateral and longitudinal accuracies of all three GPS receivers on local routes is shown in Figures 4.34 and 4.35.

- The effects of different baselines of the NDGPS service were not evaluated in this experiment. From the highway evaluations, it is found that the accuracies of the NDGPS receivers are relatively insensitive to baseline distance or changes of base stations. Therefore, it is not necessary to repeat the experiments again using different NDGPS base stations. Only the nearest NDGPS base station in Alma, Wisconsin was used as the correction source for GPS evaluations on city streets.
- Once again, an abnormal drift of the Trimble AgGPS 132 receiver occurred on Local Route I. The GPS receiver drifted out of the course for a total of 56.2 seconds. There was more than 846 minutes of experimental data on local routes and the drift represented less than 0.1% of the data.  If warranted, the drift can be corrected using an inexpensive inertial measurement sensor.

| | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|
| **Trimble AgGPS132** | 0.90 m (2.95 ft) | 0.49 m (1.59 ft) | -0.01 m (-0.03 ft) | 0.33 m (1.08 ft) | 0.05 m (0.18 ft) | 0.50 m (1.63 ft) |
| **CSI GBX-12R** | 2.15 m (7.06 ft) | 1.53 m (5.01 ft) | -0.21 m (-0.69 ft) | 1.69 m (5.55 ft) | -0.26 m (-0.84 ft) | 2.01 m (6.59 ft) |
| **JRC DGPS 212** | 17.71 m (58.10 ft) | 9.17 m (30.08 ft) | 0.21 m (0.67 ft) | 2.14 m (7.00 ft) | 17.37 m (56.97 ft) | 9.48 m (31.11 ft) |

Table 4.13 Summary of the results of the NDGPS Evaluation on local routes

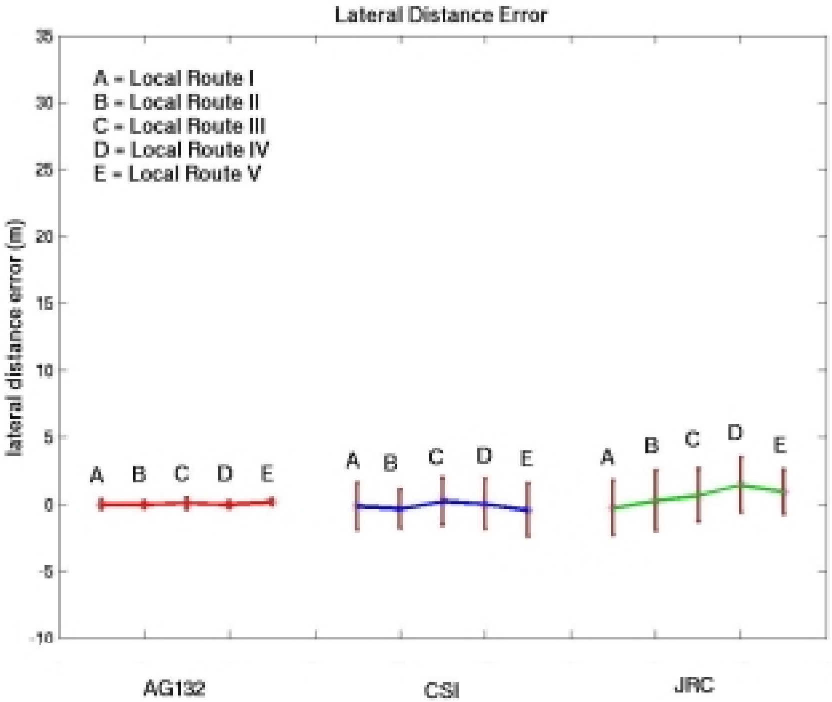


Figure 4.34 Comparison of lateral accuracies of GPS receivers on local routes

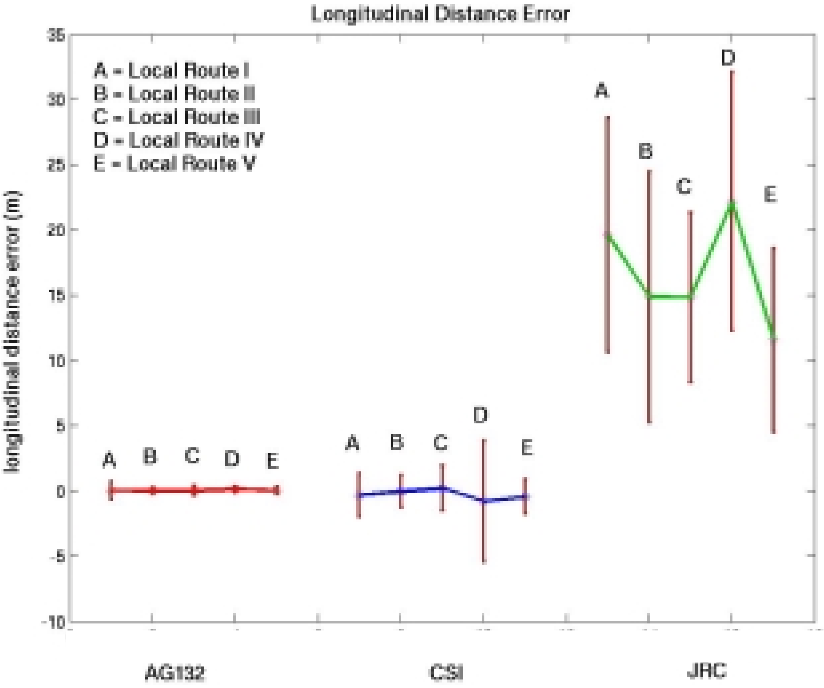


Figure 4.35 Comparison of longitudinal accuracies of GPS receivers on local routes

## *4.3 Evaluation of DGPS Accuracies at Different Speeds*

Experiments were also performed to test GPS accuracies at different speeds. The goals of experiments were threefold, comprising (1) evaluate the newly released (October 2002) NavCom SF-2050M GPS receiver and the WAAS enabled Garmin GPS 76 receiver, (2) examine the lateral accuracy of each GPS receiver and its ability to distinguish two roads in close proximity, and (3) study how vehicle speeds affect the longitudinal accuracy of each GPS receiver.

In addition to the new NavCom SF-2050M and Garmin GPS 76 receivers, two of the NDGPS receivers, the Trimble AgGPS 132 and the CSI GBX-12R, were also included in the experiments. The JRC DGPS 212 receiver was excluded because of its poor performance shown in the experiments conducted on highways and city streets. In these experiments, different NDGPS base stations were also used to test the effects of different baselines on GPS accuracies. The Garmin GPS 76 receiver was evaluated under both its regular GPS mode (no correction) and the WAAS mode. Under the regular GPS mode, the Garmin receiver did not use any correction signal to improve its computation on locations.

Experiments were performed at speeds of 15, 25, 40, and 60 MPH so that the GPS performance can be characterized over the normal speed ranges of everyday driving. The results of experiments at each speed are presented in each subsection below and the overall results are summarized and discussed at the end of this section. Please note that these experiments were conducted in January and February of 2003.

### 4.3.1 DGPS Evaluation at 15 MPH

The experiments for DGPS evaluation at 15 MPH were performed on the low volume road at Mn/ROAD. Mn/ROAD is a Minnesota Department of Transportation research facility located near Albertville, MN. It is a closed outdoor pavement test track with an extensive sensor network used to study the effects of weather and heavy commercial truck traffic on various pavement materials and designs. The continuous low volume test track consists of two long straight roadways connected by looped sections. Mn/ROAD is an ideal area for testing because it provides a controlled environment with no traffic, allowing for various tests while avoiding interactions with other vehicles. Figure 4.36 shows the Mn/ROAD tracks and the section where the experiments were conducted. Each direction of the section was driven at least 30 times. The mileage covered in this evaluation is 77.4 km (48.1miles). The data from the Trimble MS-750 receiver that had the quality of “RTK fix” and thus can be used for data analysis covered 77.2 km (48.0 miles or 99.7 %). The actual mean speed of the vehicle in this evaluation was 6.4 m/sec (14.2 MPH).

Table 4.14 shows the accuracies of all GPS receivers at 15 MPH.

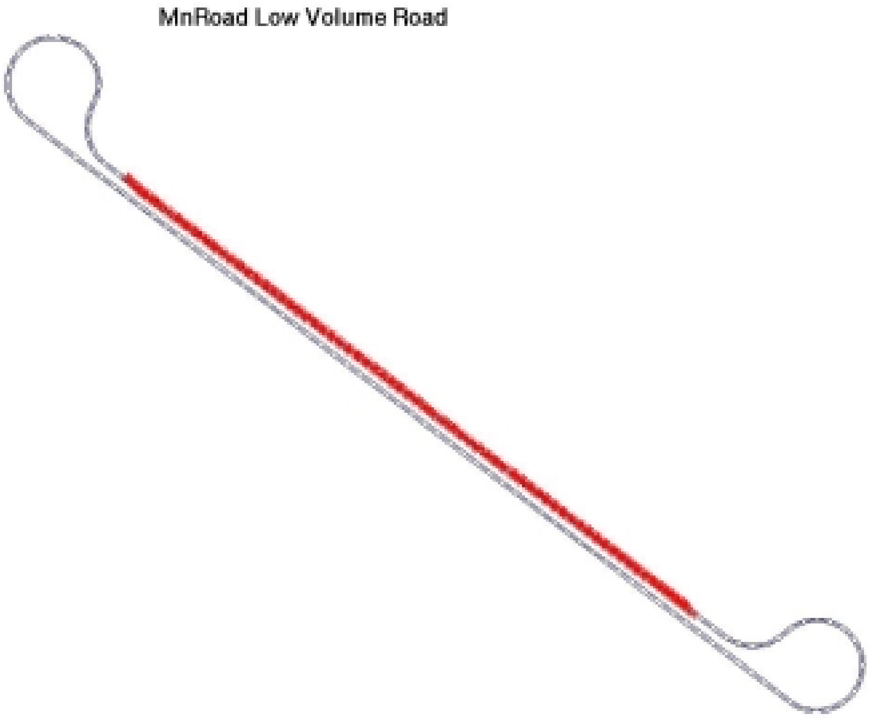


Figure 4.36 Mn/ROAD tracks and the section where the evaluation was performed.

| Correction Source | Receiver | Positional mean error | σ | Lateral mean error | σ | Longitudinal mean error | σ |
|---|---|---|---|---|---|---|---|
| **Satellite** | **NavCom SF-2050M** | 1.04 m (3.40 ft) | 0.60 m (1.95 ft) | 0.01 m (0.03 ft) | 0.94 m (3.08 ft) | -0.01 m (-0.03 ft) | 0.60 m (1.97 ft) |
| **St Paul** | **Trimble AgGPS132** | 1.18 m (3.89 ft) | 0.38 m (1.25 ft) | 0.01 m (0.03 ft) | 0.55 m (1.80 ft) | -0.01 m (-0.03 ft) | 1.06 m (3.47 ft) |
| **Pine River** | **Trimble AgGPS132** | 0.62 m (2.03 ft) | 0.39 m (1.26 ft) | 0.05 m (0.17 ft) | 0.58 m (1.89 ft) | 0.03 m (0.11 ft) | 0.33 m (1.08 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | 0.56 m (1.83 ft) | 0.33 m (1.09 ft) | 0.04 m (0.12 ft) | 0.44 m (1.44 ft) | 0.01 m (0.03 ft) | 0.36 m (1.17 ft) |
| **St Paul** | **CSI GBX-12R** | 2.12 m (6.95 ft) | 1.91 m (6.26 ft) | 0.15 m (0.49 ft) | 1.76 m (5.77 ft) | -0.27 m (-0.88 ft) | 2.19 m (7.18 ft) |
| **Pine River** | **CSI GBX-12R** | 7.06 m (23.15 ft) | 1.69 m (5.55 ft) | -0.13 m (-0.42 ft) | 1.40 m (4.58 ft) | -6.93 m (-22.72 ft) | 1.64 m (5.38 ft) |
| **Wisconsin Point** | **CSI GBX-12R** | 2.31 m (7.58 ft) | 0.82 m (2.67 ft) | 0.38 m (1.25 ft) | 1.58 m (5.18 ft) | 0.59 m (1.92 ft) | 1.66 m (5.45 ft) |
| **No Correction** | **Garmin GPS 76** | 3.20 m (10.51 ft) | 1.41 m (4.64 ft) | -0.30 m (-1.00 ft) | 1.72 m (5.63 ft) | -0.35 m (-1.16 ft) | 2.85 m (9.33 ft) |
| **WAAS** | **Garmin GPS 76** | 1.66 m (5.44 ft) | 1.20 m (3.94 ft) | 0.51 m (1.69 ft) | 1.28 m (4.18 ft) | 0.29 m (0.94 ft) | 1.62 m (5.31 ft) |

Table 4.14 Accuracies of GPS receivers at 15 MPH

### 4.3.2 DGPS Evaluation at 25 MPH

The experiments of DGPS evaluation at 25 MPH were also performed on the low volume road at Mn/ROAD. The mileage covered in this evaluation is 78.8 km (48.9 miles). The data from the Trimble MS-750 receiver with the quality of "RTK fix" that can be used for data analysis covered 76.2 km (47.3 miles or 96.8 %). The actual mean speed of the vehicle in this evaluation was 12.1 m/sec (27.1 MPH).

Table 4.15 shows the accuracies of all GPS receivers at 25 MPH.

| **Correction Source** | **Receiver** | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|---|
| **Satellite** | **NavCom SF-2050M** | 0.66 m (2.18 ft) | 0.35 m (1.13 ft) | 0.17 m (0.55 ft) | 0.53 m (1.75 ft) | -0.01 m (-0.03 ft) | 0.34 m (1.11 ft) |
| **St Paul** | **Trimble AgGPS132** | 0.90 m (2.96 ft) | 0.27 m (0.88 ft) | 0.02 m (0.06 ft) | 0.27 m (0.87 ft) | -0.01 m (-0.03 ft) | 0.53 m (1.72 ft) |
| **Pine River** | **Trimble AgGPS132** | 0.64 m (2.10 ft) | 0.23 m (0.75 ft) | 0.02 m (0.06 ft) | 0.27 m (0.87 ft) | -0.01 m (-0.03 ft) | 0.53 m (1.72 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | 0.75 m (2.45 ft) | 0.42 m (1.38 ft) | 0.02 m (0.06 ft) | 0.61 m (1.99 ft) | 0.01 m (0.03 ft) | 0.50 m (1.64 ft) |
| **St Paul** | **CSI GBX-12R** | 2.62 m (8.58 ft) | 1.23 m (4.03 ft) | 0.16 m (0.51 ft) | 2.54 m (8.33 ft) | 0.04 m (0.13 ft) | 1.32 m (4.33 ft) |
| **Pine River** | **CSI GBX-12R** | 12.76 m (41.84 ft) | 1.81 m (5.95 ft) | 0.10 m (0.35 ft) | 0.43 m (1.41 ft) | -12.74 m (-41.80 ft) | 1.82 m (5.96 ft) |
| **Wisconsin Point** | **CSI GBX-12R** | 3.75 m (12.31 ft) | 1.82 m (5.97 ft) | 0.26 m (0.87 ft) | 3.79 m (12.42 ft) | -0.47 m (-1.55 ft) | 1.61 m (5.27 ft) |
| **No Correction** | **Garmin GPS 76** | 2.69 m (8.83 ft) | 0.99 m (3.25 ft) | 0.10 m (0.32 ft) | 1.76 m (5.78 ft) | -0.38 m (-1.23 ft) | 2.13 m (7.00 ft) |
| **WAAS** | **Garmin GPS 76** | 4.04 m (13.25 ft) | 15.04 m (49.34 ft) | 1.73 m (5.67 ft) | 12.30 m (40.34 ft) | -0.84 m (-2.75 ft) | 9.47 m (31.06 ft) |

Table 4.15 Accuracies of GPS receivers at 25 MPH

From Table 4.15, one can find that the Garmin GPS 76 receiver had an abnormally large lateral mean error and standard deviation (σ) when WAAS was used as the correction source. Further research found that the Garmin GPS 76 receiver drifted out of the course for about 1.7 minutes (about 2.5% of the total data at 25 MPH). Unlike the drift found on the Trimble AgGPS 132 receiver (Figures 4.16 and 4.24) in which the receiver slowly drifted out of the course and then slowly converged back, the Garmin GPS 76 receiver just "jumped" about 65 meters to the left (Figure 4.37) and then "jumped" back to the correct course after 1.7 minutes. The reasons for the drift are not clear. However, examination of the raw GPS data during the time when the drift occurred found that the Garmin GPS receiver stopped outputting solutions for 10 seconds before the "jump" occurred. For some reason, the Garmin GPS receiver was not able to track enough satellites and stopped computing positions for 10 seconds. After the Garmin GPS receiver regained tracking of satellites, the new solutions were not of good initially. It took the Garmin GPS receiver about 1.7 minutes to converge back to “normal”. All other three GPS receivers were functional at the time and output correct position solutions when the “jump” happened. Even though more research is needed to find the real reasons for the jump on the Garmin GPS 76 receiver, the problem can be corrected by using an inexpensive inertial measurement sensor. Even an inexpensive inertial measurement sensor can detect whether the vehicle is really moving a large lateral distance in a short period of time. Obviously, this is physically impossible according to the laws of dynamics. The on-board computer can thus ignore the data until the GPS receiver outputs correct solutions again. In addition, if the on-board computer finds that the GPS receiver has stopped computing solutions due to a lack of satellites, it can ignore the incoming data for few minutes after the GPS receiver regains tracking of satellites. This will prevent the “bad” data from being applied to the calculation of road user charges.

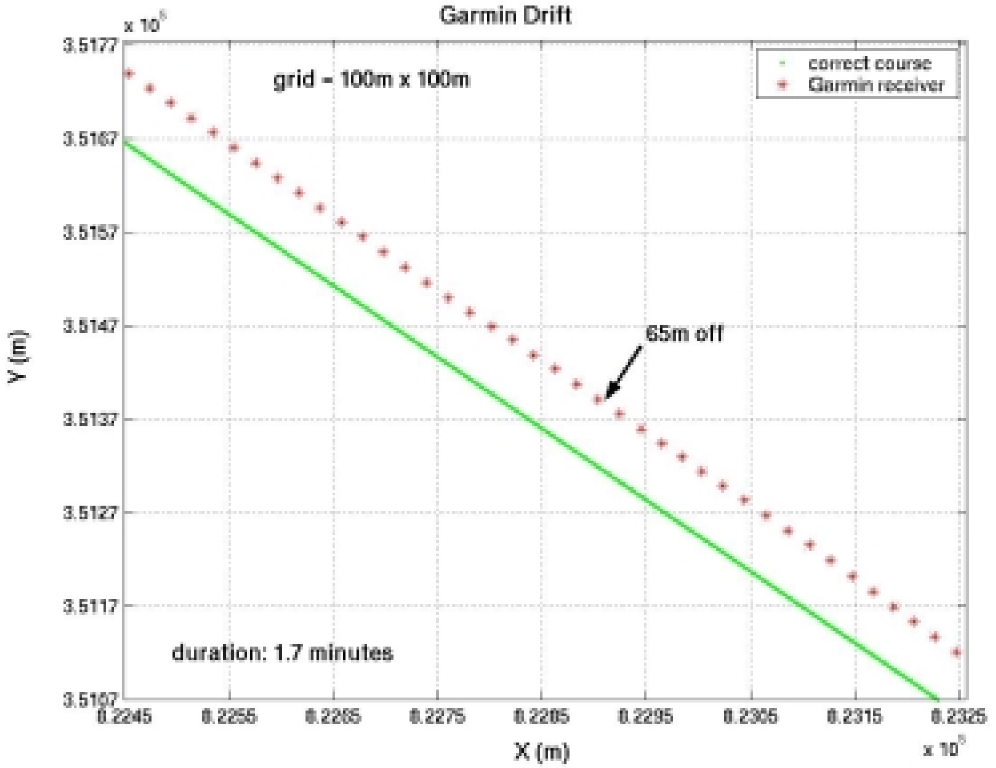


Figure 4.37 Abnormal jump of the Garmin GPS 76 receiver at 25 MPH

After correcting the drift problems on the Garmin GPS 76 receiver, the new results are presented in Table 4.16.

| Correction Source | Receiver | Positional mean error | σ | Lateral mean error | σ | Longitudinal mean error | σ |
|---|---|---|---|---|---|---|---|
| **WAAS** | **Garmin GPS 76** | 1.54 m<br>(5.05 ft) | 0.82 m<br>(2.68 ft) | -0.03 m<br>(-0.09 ft) | 1.14 m<br>(3.75 ft) | -0.33 m<br>(-1.08 ft) | 1.02 m<br>(3.33 ft) |

Table 4.16 Accuracy of the Garmin GPS 76 receiver with drift event excluded from analysis at 25 MPH

### 4.3.3 DGPS Evaluation at 40 MPH

The experiments for DGPS evaluation at 40 MPH were also performed on the low volume road at Mn/ROAD. The mileage covered in this evaluation was 84.6 km (52.5 miles). The data from the Trimble MS-750 receiver with the quality of “RTK fix” that was used for data analysis was 84.5 km (52.4 miles or 99.9%) in length. The actual mean speed of the vehicle in this evaluation was 20.3 m/sec (45.4 MPH).

Table 4.17 shows the accuracies of all GPS receivers at 40 MPH.

| Correction Source | Receiver | Positional mean error | σ | Lateral mean error | σ | Longitudinal mean error | σ |
|---|---|---|---|---|---|---|---|
| **Satellite** | **NavCom SF-2050M** | 0.52 m<br>(1.72 ft) | 0.14 m<br>(0.46 ft) | 0.02 m<br>(0.06 ft) | 0.15 m<br>(0.51 ft) | 0.01 m<br>(0.03 ft) | 0.26 m<br>(0.85 ft) |
| **St Paul** | **Trimble AgGPS132** | 0.59 m<br>(1.94 ft) | 0.15 m<br>(0.50 ft) | 0.04 m<br>(0.14 ft) | 0.16 m<br>(0.51 ft) | 0.01 m<br>(0.03 ft) | 0.50 m<br>(1.64 ft) |
| **Pine River** | **Trimble AgGPS132** | 0.53 m<br>(1.74 ft) | 0.21 m<br>(0.68 ft) | 0.04 m<br>(0.13 ft) | 0.25 m<br>(0.83 ft) | -0.01 m<br>(-0.03 ft) | 0.40 m<br>(1.32 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | 0.53 m<br>(1.73 ft) | 0.27 m<br>(0.88 ft) | 0.02 m<br>(0.08 ft) | 0.37 m<br>(1.22 ft) | -0.01 m<br>(-0.03 ft) | 0.32 m<br>(1.05 ft) |
| **St Paul** | **CSI GBX-12R** | 2.38 m<br>(7.79 ft) | 1.10 m<br>(3.60 ft) | 0.23 m<br>(0.75 ft) | 2.05 m<br>(6.71 ft) | -0.01 m<br>(-0.03 ft) | 1.56 m<br>(5.11 ft) |
| **Pine River** | **CSI GBX-12R** | 20.19 m<br>(66.21 ft) | 2.57 m<br>(8.44 ft) | 0.18 m<br>(0.58 ft) | 0.53 m<br>(1.74 ft) | -20.17 m<br>(-66.17 ft) | 2.58 m<br>(8.45 ft) |
| **Wisconsin Point** | **CSI GBX-12R** | 2.34 m<br>(7.67 ft) | 0.93 m<br>(3.05 ft) | 0.14 m<br>(0.45 ft) | 2.16 m<br>(7.07 ft) | -0.13 m<br>(-0.44 ft) | 1.23 m<br>(4.05 ft) |
| **No Correction** | **Garmin GPS 76** | 2.50 m<br>(8.20 ft) | 0.81 m<br>(2.65 ft) | -0.21 m<br>(-0.70 ft) | 1.56 m<br>(5.13 ft) | -0.51 m<br>(-1.66 ft) | 1.81 m<br>(5.94 ft) |
| **WAAS** | **Garmin GPS 76** | 1.42 m<br>(4.65 ft) | 0.50 m<br>(1.65 ft) | -0.20 m<br>(-0.64 ft) | 0.50 m<br>(1.65 ft) | -0.25 m<br>(-0.81 ft) | 1.03 m<br>(3.39 ft) |

Table.4.17 Accuracies of GPS receivers at 40 MPH

### 4.3.4 DGPS Evaluation at 60 MPH

The experiments for DGPS evaluation at 60 MPH were performed on the interstate highway I-94 between exit #205 (St. Michael) and exit #202 (Albertville). This section of the I-94 is outside of the Twin Cities metropolitan area and has much less traffic than the interstate highways in the metro area. More importantly, there is no bridge and overpass on this section of the I-94 highway and thus make it an ideal environment for GPS experiments. Figure 4.38 shows the section of I-94 where the DGPS evaluations at 60 MPH were performed. Each direction of this section of I-94 was driven at least 60 times. The total mileage covered in this evaluation was 588 km (365 miles). The data from the Trimble MS-750 receiver with the quality of "RTK fix" that was used for data analysis was 571 km (354.6 miles or 97%) in length. The actual mean speed of the vehicle in this evaluation was 28.3 m/sec (63.4 MPH).

Table 4.18 shows the accuracies of all GPS receivers at 60 MPH.

Figure 4.38 Interstate Highway I-94 and the section where the evaluation was performed (approximately 35 miles northwest from Minneapolis, MN)

| **Correction Source** | **Receiver** | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|---|
| **Satellite** | **NavCom SF-2050M** | 0.49 m (1.62 ft) | 0.15 m (0.49 ft) | 0.02 m (0.05 ft) | 0.15 m (0.49 ft) | 0.01 m (0.03 ft) | 0.21 m (0.68 ft) |
| **St Paul** | **Trimble AgGPS132** | 1.03 m (3.39 ft) | 0.31 m (1.01 ft) | 0.01 m (0.03 ft) | 0.52 m (1.70 ft) | 0.02 m (0.06 ft) | 0.88 m (2.89 ft) |
| **Pine River** | **Trimble AgGPS132** | 0.50 m (1.65 ft) | 0.22 m (0.71 ft) | 0.01 m (0.03 ft) | 0.27 m (0.90 ft) | -0.01 m (-0.03 ft) | 0.31 m (1.03 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | 0.57 m (1.86 ft) | 0.45 m (1.49 ft) | 0.03 m (0.10 ft) | 0.51 m (1.66 ft) | 0.02 m (0.05 ft) | 0.41 m (1.34 ft) |
| **St Paul** | **CSI GBX-12R** | 15.82 m (51.90 ft) | 13.01 m (42.68 ft) | 0.18 m (0.60 ft) | 1.99 m (6.53 ft) | -14.67 m (-48.13 ft) | 14.15 m (46.41 ft) |
| **Pine River** | **CSI GBX-12R** | 28.28 m (92.77 ft) | 3.29 m (10.81 ft) | 0.04 m (0.14 ft) | 1.30 m (4.26 ft) | -28.25 m (-92.67 ft) | 3.30 m (10.82 ft) |
| **Wisconsin Point** | **CSI GBX-12R** | 4.35 m (14.26 ft) | 2.64 m (8.86 ft) | -0.11 m (-0.35 ft) | 4.39 m (14.41 ft) | -0.41 m (-1.34 ft) | 2.54 m (8.33 ft) |
| **No Correction** | **Garmin GPS 76** | 2.06 m (6.74 ft) | 1.17 m (3.82 ft) | -0.04 m (-0.13 ft) | 1.75 m (5.75 ft) | -0.45 m (-1.48 ft) | 1.30 m (4.27 ft) |
| **WAAS** | **Garmin GPS 76** | 1.36 m (4.47 ft) | 1.19 m (3.89 ft) | 0.40 m (1.31 ft) | 1.40 m (4.60 ft) | 0.07 m (0.22 ft) | 1.57 m (5.14 ft) |

Table 4.18 Accuracies of GPS receivers at 60 MPH

From Table 4.18, an abnormally large lateral mean error and standard deviation (σ) was found again for the Garmin GPS 76 receiver when WAAS was used as the correction source. Similar to the event shown in Figure 4.37, the Garmin GPS receiver “jumped” 15 meters to the right for 18 seconds this time (Figure 4.39). Examination of the raw GPS data also found that the Garmin GPS receiver stopped outputting solutions for 16 seconds before the “jump” happened. With two similar events of a GPS jump at different speeds, it would seem appropriate to exclude position data from being applied to road user charges for few minutes after a GPS receiver stops computing solutions. An inexpensive inertial measurement sensor can be used to detect inaccurate jumps in the data from the GPS receiver should they occur.

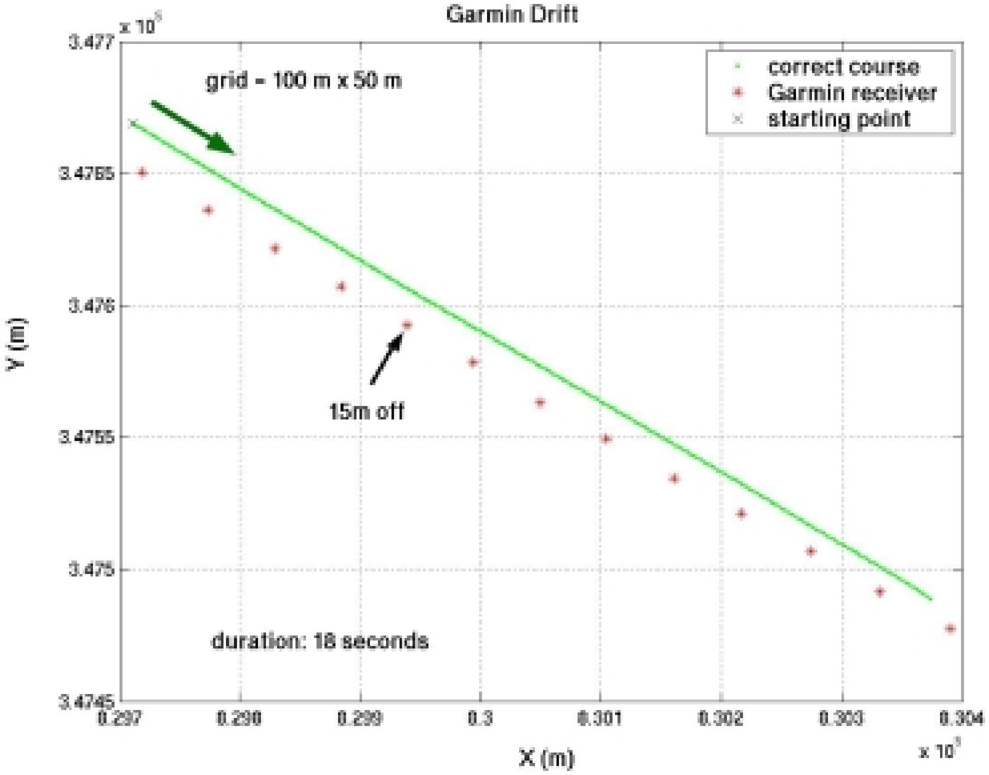


Figure 4.39 Abnormal jump of the Garmin GPS 76 receiver at 60 MPH

After removing the drift problem data on the Garmin GPS 76 receiver, the new results are presented in Table 4.19.

| **Correction Source** | **Receiver** | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|---|
| **WAAS** | **Garmin GPS 76** | 1.30 m<br>(4.25 ft) | 0.64 m<br>(2.10 ft) | 0.33 m<br>(1.07 ft) | 0.92 m<br>(3.01 ft) | -0.01 m<br>(-0.03 ft) | 1.13 m<br>(3.71 ft) |

Table 4.19 Accuracy of the Garmin GPS 76 receiver without drift at 60 MPH

### 4.3.5 Summary and Discussion of the DGPS Evaluation at Different Speeds

In this section, two receivers using different types of correction signals other than the NDGPS service were included in the evaluation. The NavCom SF-2050M receiver uses correction signal from a global satellite-based DGPS service. The Garmin GPS 76 receiver uses FAA's WAAS service to improve its position accuracy. These two GPS receivers together with two NDGPS receivers, the Trimble AgGPS 132 and the CSI GBX-12R, were tested at 15, 25, 40, and 60 MPH. Their positional, lateral, and longitudinal accuracies at each speed tested are presented in

Tables 4.14 ~ 4.19. The comparison of performance for each GPS receiver for all speeds are shown in Figures 4.40 ~ 4.47.

From the results, we found that the NavCom SF-2050M receiver had the best performance overall. However, the NavCom receiver is also the most expensive one among all. Its $6,000 price tag for each unit plus the subscription fee will make it prohibitive to be used in road user charging applications. Also, unless lane level discrimination is required, the accuracy of less than 50 cm (1.6 ft) for the NavCom SF-2050M receiver is also “overkill” for charging road users.

The performance of the Garmin GPS 76 receiver should not go unnoticed. With WAAS correction, the $200 Garmin receiver has a mean positional accuracy at around 1.5 m (4.9 ft), which is better than the performance of the $850 CSI GBX-12R receiver. More importantly, its performance is consistent at all speeds, which makes it a good candidate for road user charging applications.

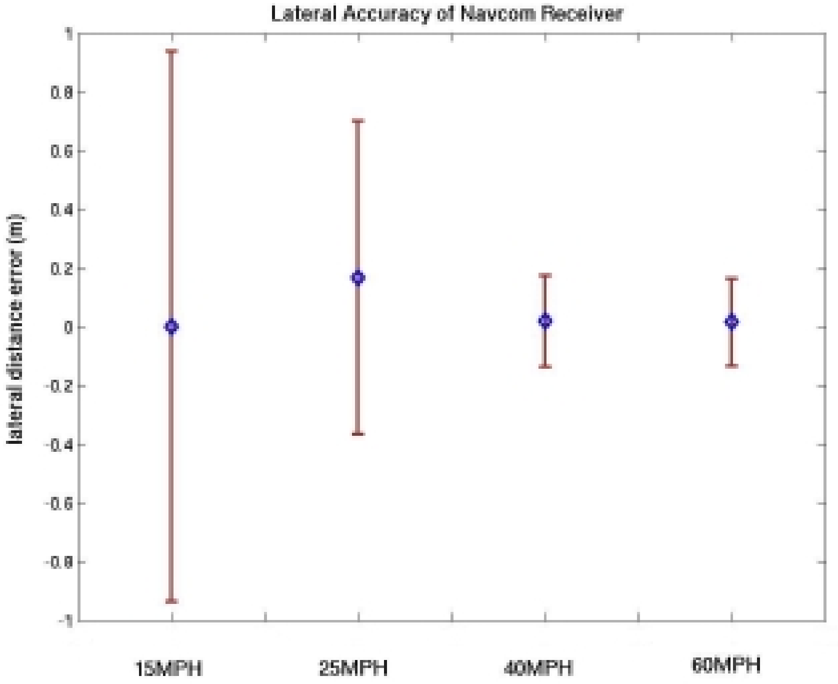


Figure 4.40 Lateral Accuracy of the NavCom Receiver for all measured speeds

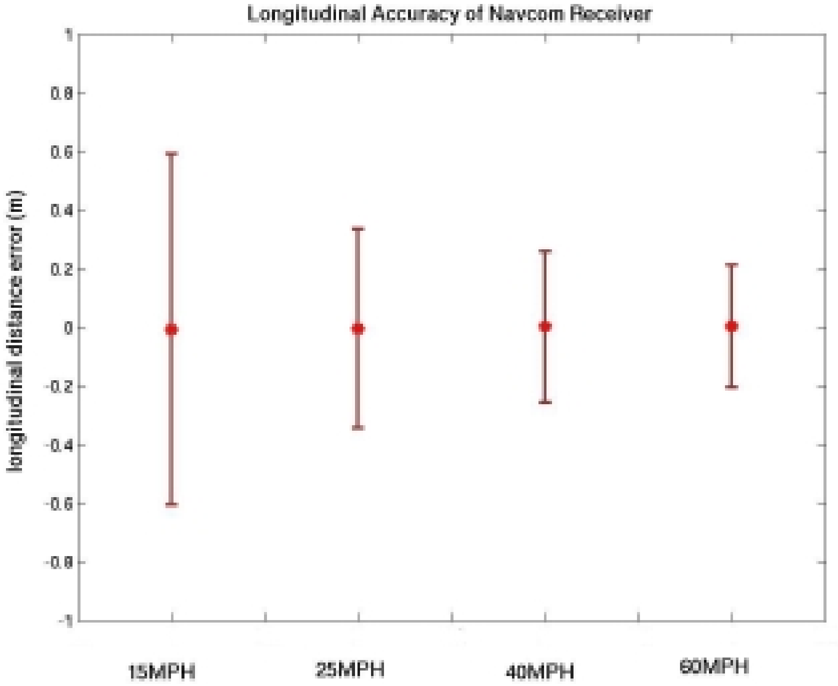


Figure 4.41 Longitudinal Accuracy of the NavCom Receiver for all measured speeds

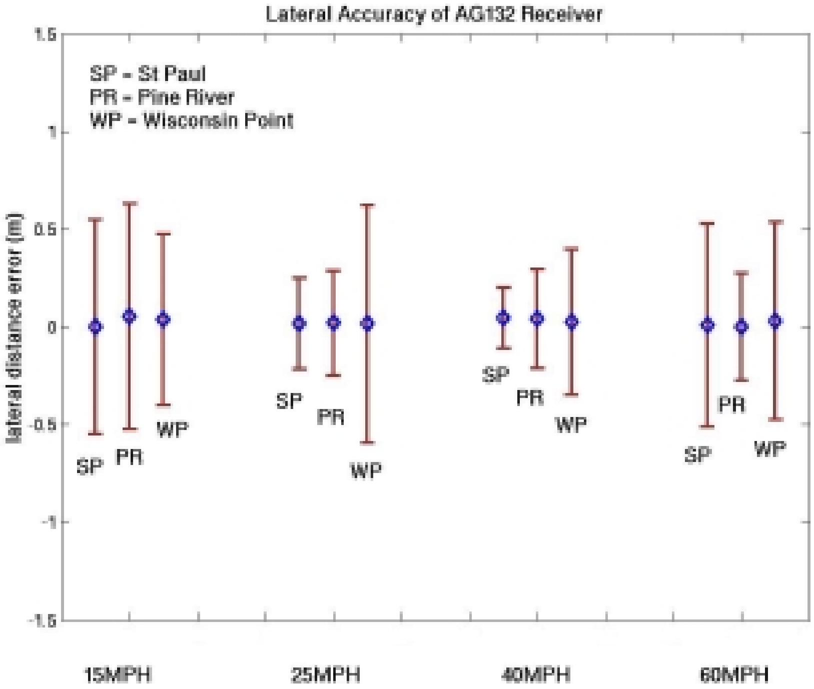


Figure 4.42 Lateral Accuracy of the Trimble AgGPS 132 receiver for all measured speeds

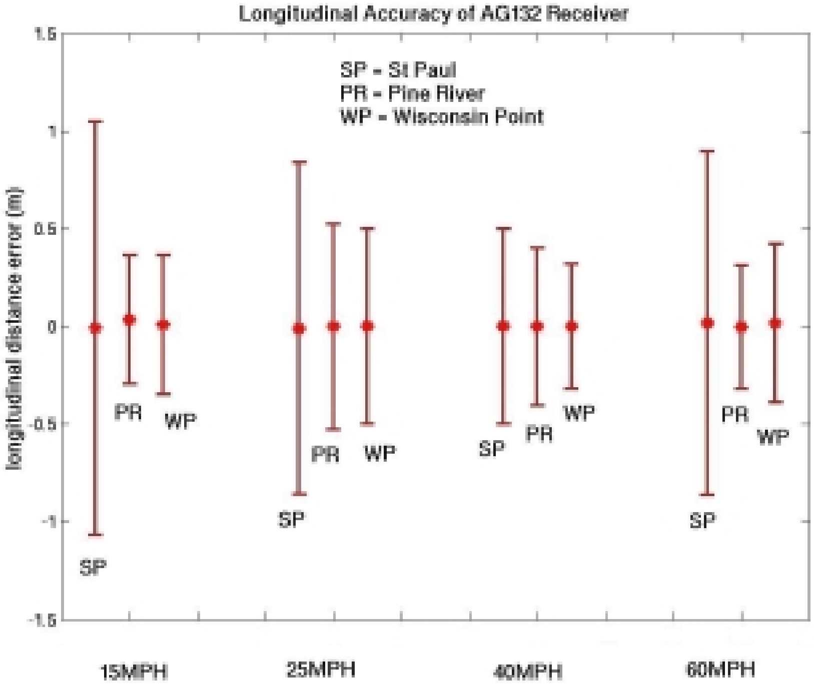


Figure 4.43 Longitudinal Accuracy of the Trimble AgGPS 132 receiver for all measured speeds

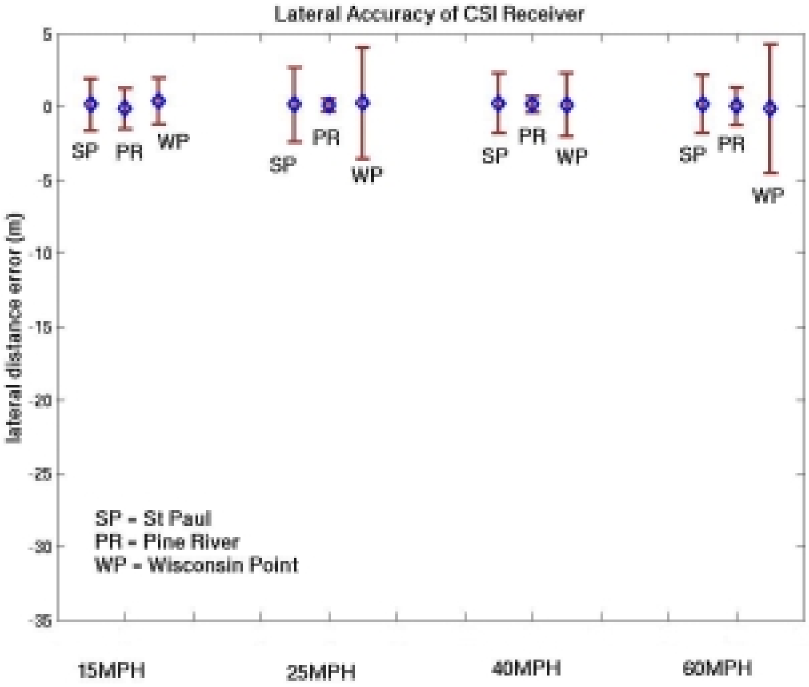


Figure 4.44 Lateral Accuracy of the CSI GBX-12R receiver for all measured speeds

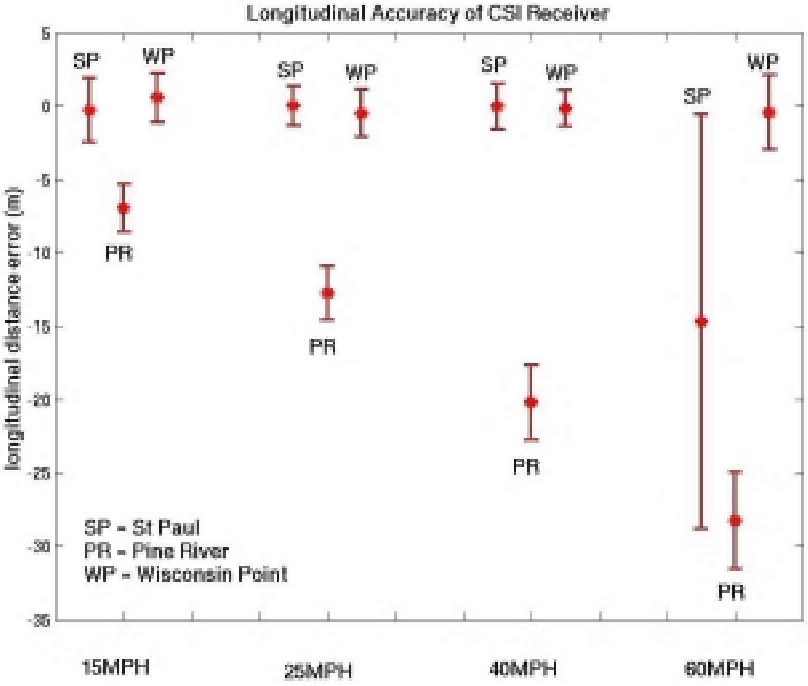


Figure 4.45 Longitudinal Accuracy of the CSI GBX-12R receiver for all measured speeds

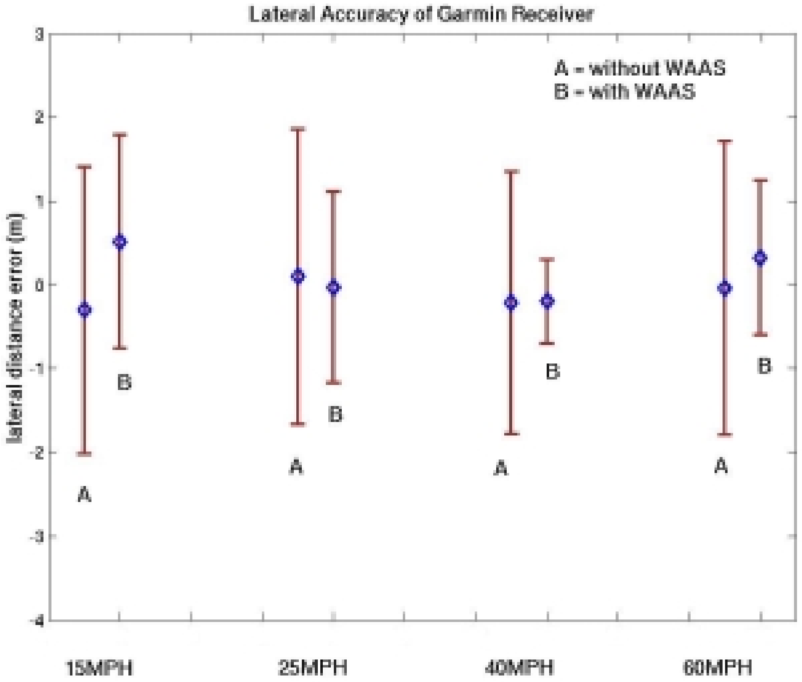


Figure 4.46 Lateral Accuracy of the Garmin GPS 76 receiver for all measured speeds

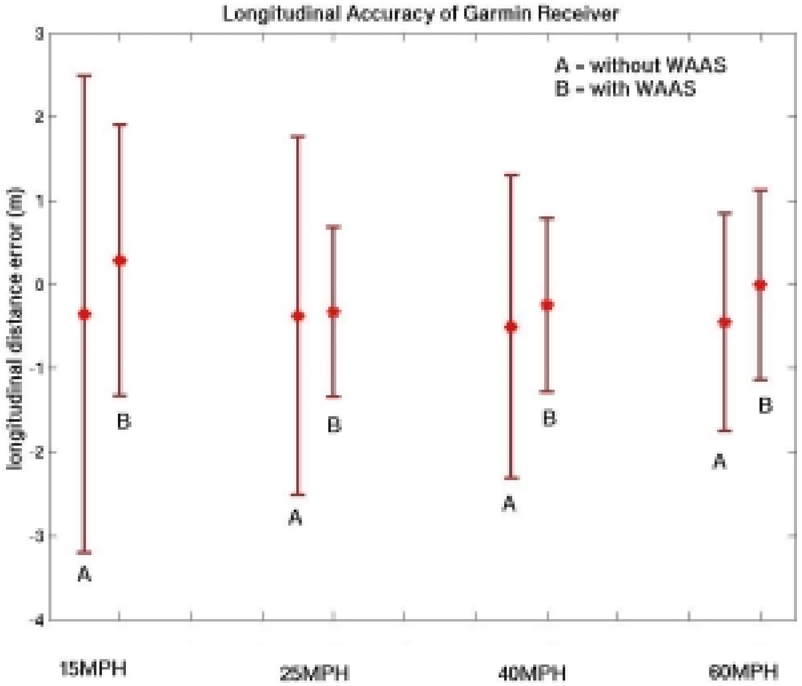


Figure 4.47 Longitudinal Accuracy of the Garmin GPS 76 receiver for all measured speeds

One interesting note that from examining Figures 4.41, 4.43, 4.45, and 4.47, it is found that the longitudinal accuracy of the NavCom and the Trimble AgGPS 132 receivers is almost constant for all speeds and is not a function of the vehicle speed. Of course, the high data output rate (10 Hz) for both receivers is a contributing factor for maintaining low longitudinal errors. However, it might also due to that the software algorithm inside the receiver compensates for the longitudinal error based on the vehicle speed. In other words, a GPS receiver projects ahead according to the speed of the vehicle and thus computes more accurate position outputs.

## *4.4 Effect of Elevation on the Accuracies of DGPS Receivers*

The DGPS receivers used in road user charging applications need to work in different types of environments. Not only do they need to work in the urban and rural environments, they also need to work in open plains and mountainous regions. In a mountainous (or hilly) region where elevation of roads can change dramatically in a short distance, the bluff on one side of the road could block the view of the sky and GPS signals. Also, it is known that radio propagation can be difficult in a mountainous (or hilly) region. In this evaluation, experiments were performed to study if and how elevation changes affect the accuracies of DGPS receivers. The evaluation was conducted in the city of Duluth in northern Minnesota. The city is located on the shore of the Lake Superior and most of roads connecting the lakeshore to other part of the town have steep slopes and large elevation changes.

The DGPS receivers tested in this evaluation included the NavCom SF-2050M, the Trimble AgGPS 132, the CSI GBX-12R, the JRC DGPS 212, and the Garmin GPS 76 receiver. Figure 4.48 shows all five routes tested on a topographic map. These routes covered about 77 km (48 miles). All routes were driven multiple times in both directions. However, because of problems associated with radio propagation in the area, only 54 km (34 miles or 70%) of the Trimble MS-750 data had the quality of “RTK fix”. This varied from experiment to experiment. By using the same data analysis procedure, the Trimble MS-750 data with “RTK fix” and the corresponding data segments from other DGPS receivers were extracted for data analysis. The change of elevation on the routes was ranged from 62 m (203 ft) to 211 m (692 ft). This DGPS evaluation in Duluth was conducted in February 2003.

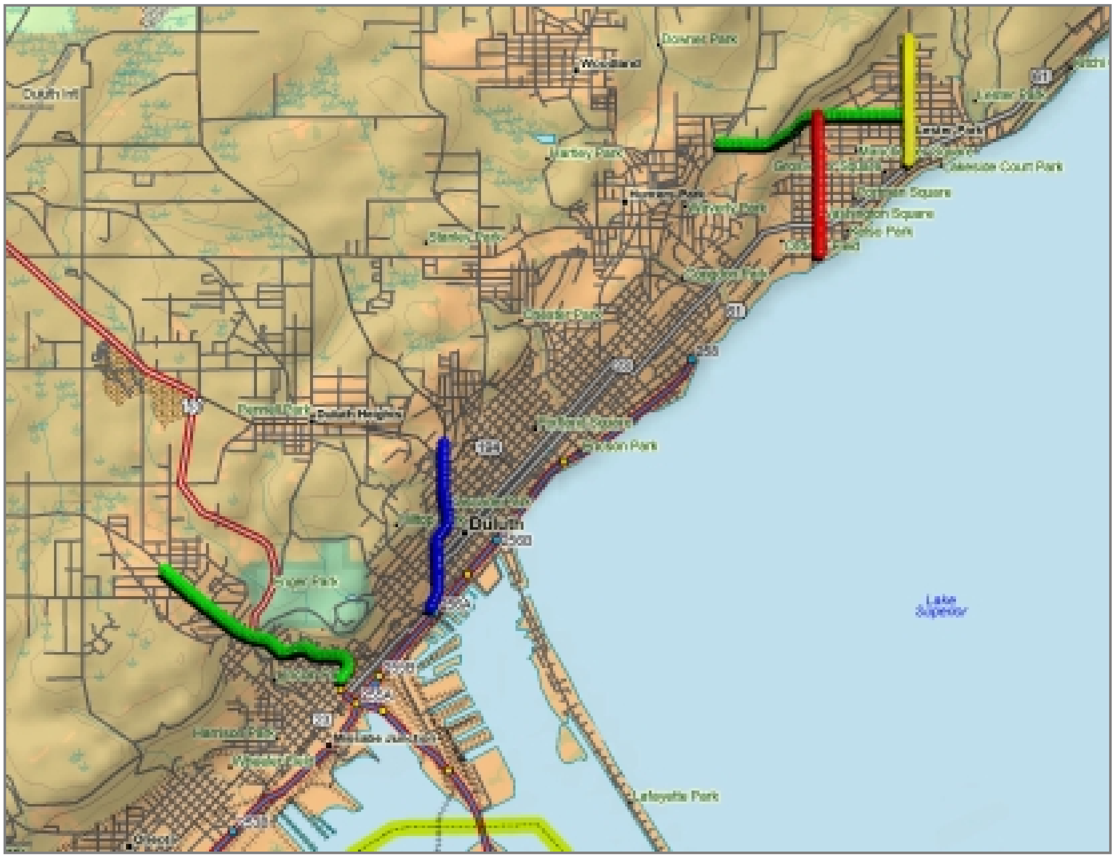


Figure 4.48 Test routes for DGPS evaluation in Duluth.

### 4.4.1 Results of the DGPS Evaluation on Duluth Route I

Duluth Route I ran along 43rd Ave in northeast Duluth from Glenwood Street to the junction of London Road. The total mileage for this route was 6 km (4.7 miles) and the mileage for “RTK fix” data was 2.4 km (1.5 miles or 40%). The average travel speed on this route was 8.7 m/sec (19 MPH). The difference in elevation on this route was 62 m (203 ft) from the lowest point to the highest point.

Figure 4.49 shows the route on a topographic map and the results are presented in Table 4.20 and Figures 2.50 ~ 2.51.

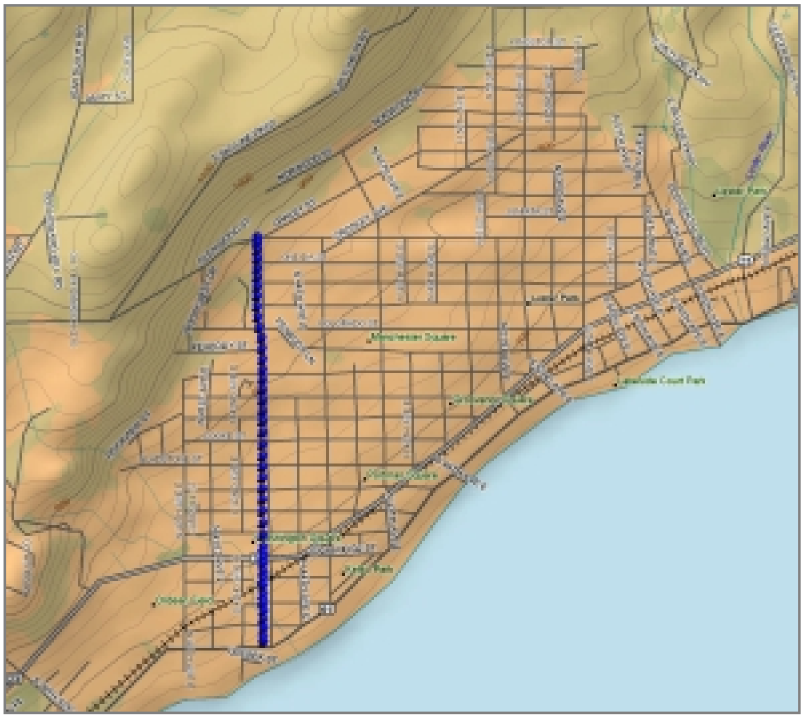


Figure 4.49 Duluth Route I

| Correction Source | Receiver | Positional mean error | σ | Lateral mean error | σ | Longitudinal mean error | σ |
|---|---|---|---|---|---|---|---|
| **Satellite** | **NavCom SF-2050M** | 0.80 m (2.62 ft) | 0.15 m (0.48 ft) | 0.26 m (0.84 ft) | 0.12 m (0.38 ft) | -0.30 m (-0.99 ft) | 0.29 m (0.94 ft) |
| **St Paul** | **Trimble AgGPS132** | 0.17 m (0.55 ft) | 0.09 m (0.29 ft) | 0.35 m (1.14 ft) | 0.03 m (0.11 ft) | 0.16 m (0.53 ft) | 0.09 m (0.31 ft) |
| **Pine River** | **Trimble AgGPS132** | 0.37 m (1.20 ft) | 0.03 m (0.08 ft) | 0.01 m (0.03 ft) | 0.03 m (0.10 ft) | 0.05 m (0.16 ft) | 0.08 m (0.26 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | N/A | | | | | |
| **St Paul** | **CSI GBX-12R** | 2.74 m (8.98 ft) | 0.72 m (2.35 ft) | 0.77 m (2.54 ft) | 0.54 m (1.78 ft) | 2.39 m (7.84 ft) | 0.97 m (3.19 ft) |
| **Pine River** | **CSI GBX-12R** | 2.08 m (6.82 ft) | 0.40 m (1.31 ft) | 0.08 m (0.26 ft) | 0.47 m (1.54 ft) | 1.99 m (6.53 ft) | 0.45 m (1.48 ft) |
| **Wisconsin Point** | **CSI GBX-12R** | N/A | | | | | |
| **No Correction** | **Garmin GPS 76** | 4.53 m (14.87 ft) | 2.10 m (6.90 ft) | 0.04 m (0.14 ft) | 0.63 m (2.05 ft) | 4.45 m (14.58 ft) | 2.08 m (6.83 ft) |
| **WAAS** | **Garmin GPS 76** | N/A | | | | | |

Table 4.20 Results of the DGPS Evaluation on Duluth Route I. Fields with “N/A” indicate not available due to problems obtaining a “RTK fix” on the Trimble MS 750 during the data collecting run. (average speed is 9 m/sec (20 MPH))

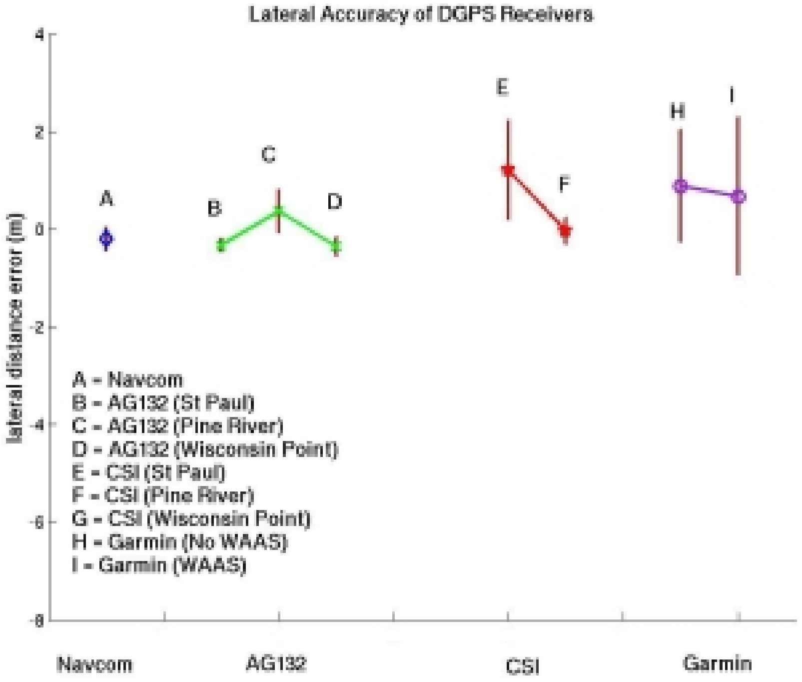


Figure 4.50 Lateral Accuracies of DGPS Receivers on Duluth Route I

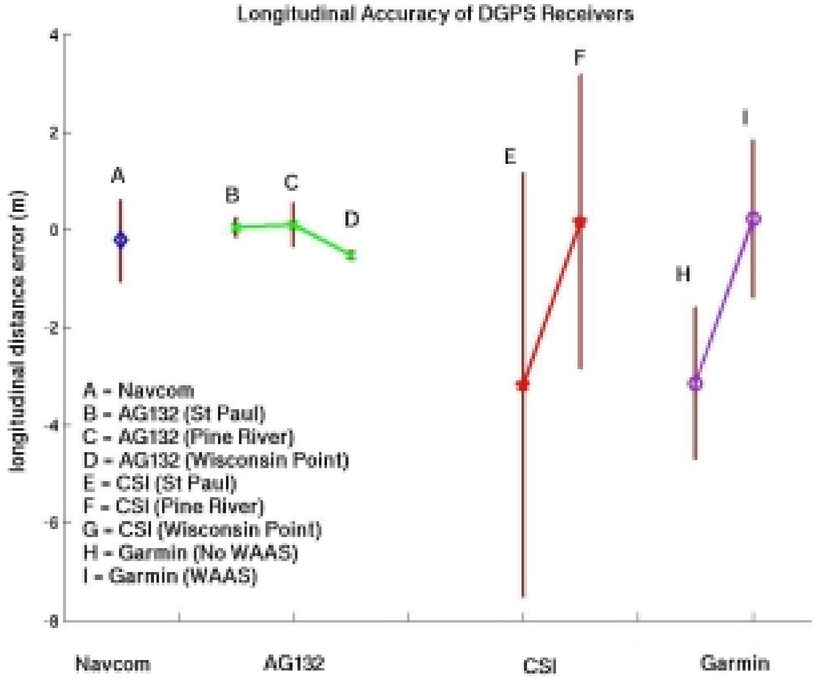


Figure 4.51 Longitudinal Accuracies of DGPS Receivers on Duluth Route I

Please note that due to radio propagation problems, the “gold-standard” reference (“RTK fix”) could not be obtained when data was collected on some experimental runs. Therefore, these experimental scenarios were excluded from data analysis and no results are presented. In Duluth Route I, experimental scenarios without results include the Trimble AgGPS 132 receiver using the Wisconsin Point reference station, the CSI receiver using the Wisconsin Point reference station and the Garmin GPS 76 receiver using the WAAS correction.

### 4.4.2 Results of the DGPS Evaluation on Duluth Route II

Duluth Route II ran along 52nd Ave in northeast Duluth from Woodlawn Street to the junction of Superior Street. The total mileage for this route was 13.6 km (8.4 miles) and the mileage for “RTK fix” data was 7.6 km (4.7 miles or 56%). The average travel speed on this route was 8.6 m/sec (19 MPH). The difference in elevation on this route was 62 m (203 ft) from the lowest point to the highest point.

Figure 4.52 shows the route on a topographic map and the results are presented in Table 4.21 and Figures 2.53 ~ 2.54. In this evaluation, the CSI GBX-12R receiver was not able to lock on to the St Paul reference station at the time when experiments were performed. Therefore, this scenario was excluded from the data analysis. The St Paul reference station is 327 km (203 miles) from Duluth. The experiments in Duluth were conducted in the winter. The experiments in the Twin Cities were conducted in the summer. It seemed that during the winter, there were more problems picking up signals from distant NDGPS reference stations.

Figure 4.52 Duluth Route II

| Correction Source | Receiver | Positional mean error | σ | Lateral mean error | σ | Longitudinal mean error | σ |
|---|---|---|---|---|---|---|---|
| **Satellite** | **NavCom SF-2050M** | 0.55 m (1.79 ft) | 0.76 m (2.49 ft) | -0.20 m (-0.65 ft) | 0.24 m (0.79 ft) | -0.22 m (-0.72 ft) | 0.84 m (2.77 ft) |
| **St Paul** | **Trimble AgGPS132** | 0.70 m (2.31 ft) | 0.14 m (0.46 ft) | -0.33 m (-1.08 ft) | 0.12 m (0.38 ft) | 0.05 m (0.15 ft) | 0.17 m (0.57 ft) |
| **Pine River** | **Trimble AgGPS132** | 0.45 m (1.47 ft) | 0.41 m (1.35 ft) | 0.37 m (1.21 ft) | 0.42 m (1.38 ft) | 0.10 m (0.31 ft) | 0.43 m (1.41 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | 0.88 m (2.89 ft) | 0.18 m (0.60 ft) | -0.35 m (-1.15 ft) | 0.17 m (0.56 ft) | -0.53 m (-1.72 ft) | 0.09 m (0.29 ft) |
| **St Paul** | **CSI GBX-12R** | N/A | | | | | |
| **Pine River** | **CSI GBX-12R** | 4.39 m (14.41 ft) | 3.56 m (11.67 ft) | 1.21 m (3.95 ft) | 1.00 m (3.27 ft) | -3.18 m (-10.43 ft) | 4.33 m (14.20 ft) |
| **Wisconsin Point** | **CSI GBX-12R** | 2.55 m (8.36 ft) | 1.60 m (5.25 ft) | -0.03 m (-0.11 ft) | 0.27 m (0.87 ft) | 0.16 m (0.51 ft) | 3.00 m (9.83 ft) |
| **No Correction** | **Garmin GPS 76** | 3.42 m (11.21 ft) | 1.37 m (4.50 ft) | 0.89 m (2.91 ft) | 1.13 m (3.72 ft) | -3.14 m (-10.31 ft) | 1.54 m (5.07 ft) |
| **WAAS** | **Garmin GPS 76** | 2.10 m (6.88 ft) | 0.86 m (2.81 ft) | 0.67 m (2.21 ft) | 1.60 m (5.24 ft) | 0.22 m (0.72 ft) | 1.60 m (5.23 ft) |

Table 4.21 Results of the DGPS Evaluation on Duluth Route II at an average speed of 9 m/sec (20 MPH)

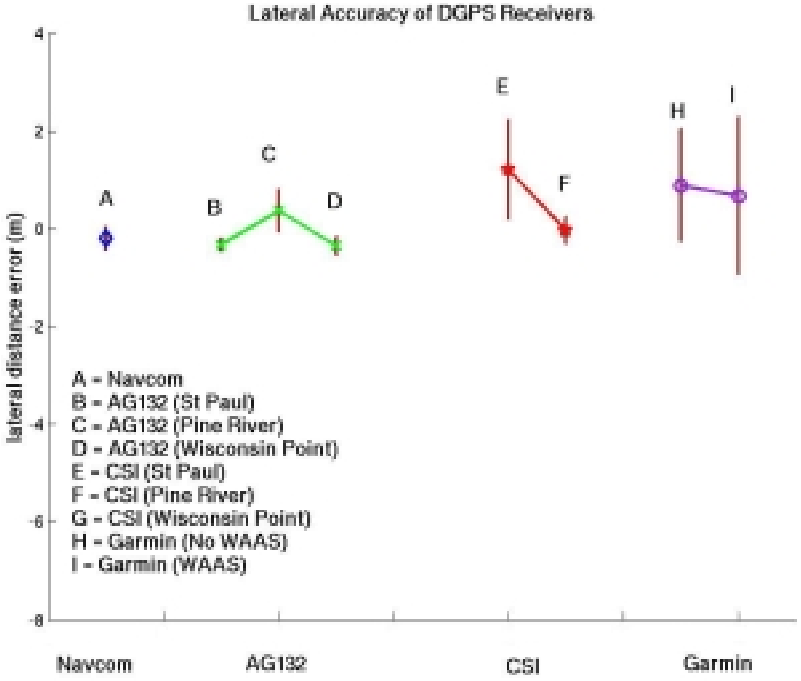


Figure 4.53 Lateral Accuracies of DGPS Receivers on Duluth Route II

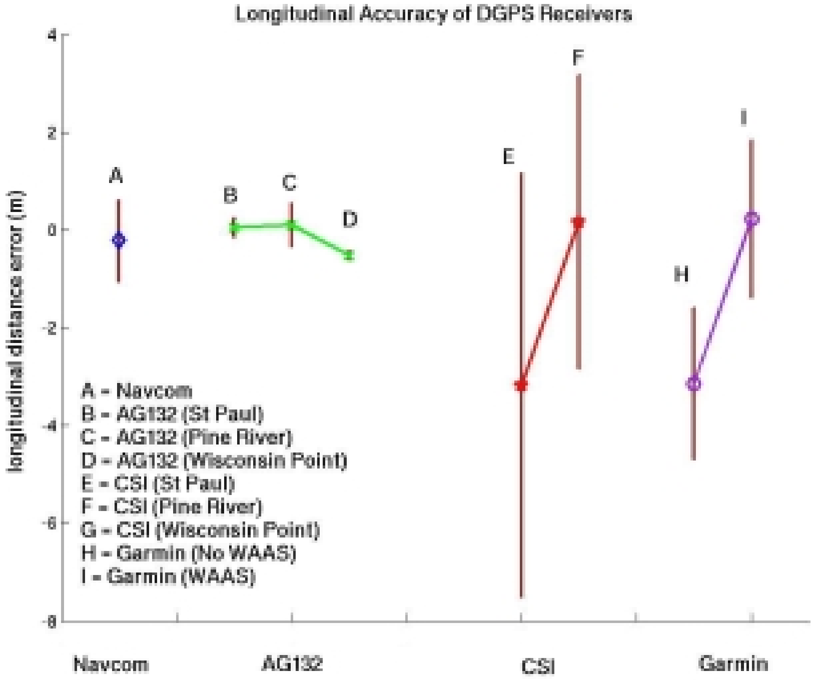


Figure 4.54 Longitudinal Accuracies of DGPS Receivers on Duluth Route II

### 4.4.3 Results of the DGPS Evaluation on Duluth Route III

Duluth Route III ran along Glenwood Street in northeast Duluth from Jean Duluth Road to the junction of 52nd Ave. The total mileage for this route was 13 km (8 miles) and the mileage for “RTK fix” data was 8.5 km (5.3 miles or 66%). The average travel speed on this route was 12 m/sec (27 MPH). The difference in elevation on this route was 106 m (346 ft) from the lowest point to the highest point.

Figure 4.55 shows the route on a topographic map and the results are presented in Table 4.22 and Figures 2.56 ~ 2.57. In this evaluation, the CSI GBX-12R receiver was not able to lock on to the St Paul reference station at the time the experiments were performed. Also, due to radio propagation problems, the “gold-standard” (“RTK fix”) reference could not be obtained for evaluation of the Garmin GPS 76 receiver using WAAS correction. Therefore, these scenarios were excluded from the data analysis.

Figure 4.55 Duluth Route III

| **Correction Source** | **Receiver** | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|---|
| **Satellite** | **NavCom SF-2050M** | 0.44 m (1.46 ft) | 0.23 m (0.74 ft) | -0.03 m (-0.11 ft) | 0.23 m (0.74 ft) | -0.13 m (-0.44 ft) | 0.14 m (0.47 ft) |
| **St Paul** | **Trimble AgGPS132** | 0.32 m (1.04 ft) | 0.13 m (0.44 ft) | 0.33 m (1.07 ft) | 0.23 m (0.76 ft) | 0.23 m (0.75 ft) | 0.11 m (0.37 ft) |
| **Pine River** | **Trimble AgGPS132** | 0.20 m (0.65 ft) | 0.09 m (0.29 ft) | 0.34 m (1.13 ft) | 0.16 m (0.53 ft) | -0.01 m (-0.03 ft) | 0.14 m (0.47 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | 1.11 m (3.65 ft) | 0.17 m (0.55 ft) | -0.65 m (-2.14 ft) | 0.36 m (1.17 ft) | -0.29 m (-0.95 ft) | 0.19 m (0.62 ft) |
| **St Paul** | **CSI GBX-12R** | N/A | | | | | |
| **Pine River** | **CSI GBX-12R** | 1.32 m (4.32 ft) | 0.75 m (2.47 ft) | -1.41 m (-4.64 ft) | 0.83 m (2.72 ft) | 0.19 m (0.62 ft) | 0.48 m (1.58 ft) |
| **Wisconsin Point** | **CSI GBX-12R** | 13.63 m (44.70 ft) | 3.62 m (11.89 ft) | 3.11 m (10.21 ft) | 1.80 m (5.91 ft) | -13.07 m (-42.87 ft) | 3.66 m (12.01 ft) |
| **No Correction** | **Garmin GPS 76** | 2.98 m (9.78 ft) | 1.67 m (5.49 ft) | -0.99 m (-3.25 ft) | 2.80 m (9.20 ft) | -0.25 m (-0.81 ft) | 0.89 m (2.91 ft) |
| **WAAS** | **Garmin GPS 76** | N/A | | | | | |

Table 4.22 Results of the DGPS Evaluation on Duluth Route III at an average speed of 12 m/sec (27 MPH)

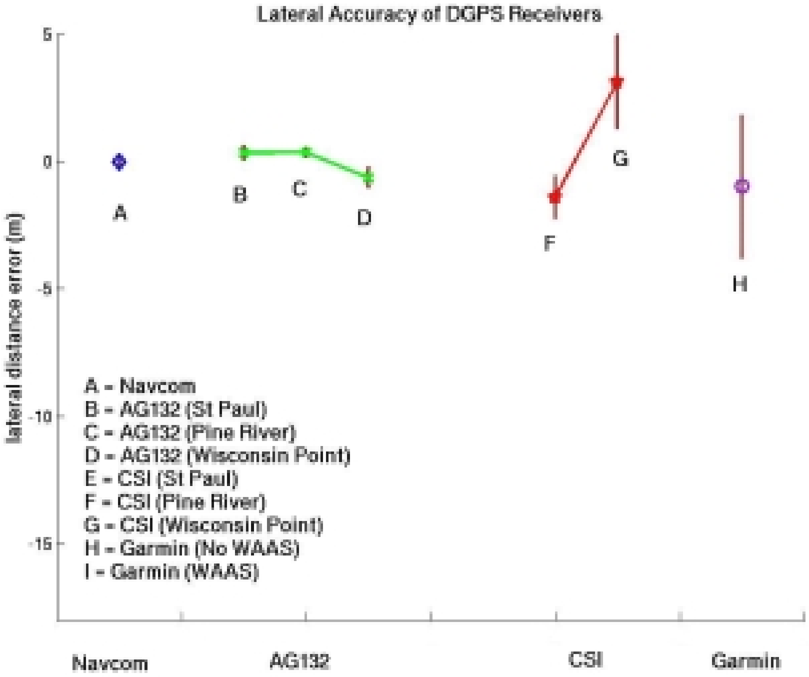


Figure 4.56 Lateral Accuracies of DGPS Receivers on Duluth Route III

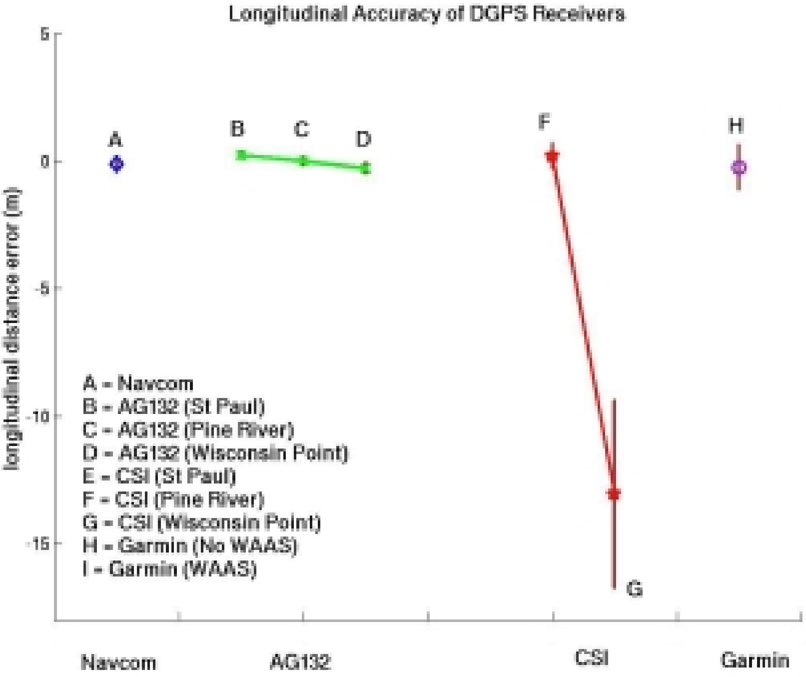


Figure 4.57 Longitudinal Accuracies of DGPS Receivers on Duluth Route III

### 4.4.4 Results of the DGPS Evaluation on Duluth Route IV

Duluth Route IV ran along Mesaba Ave in downtown Duluth from Central Entrance to the junction of Interstate highway I-35. The total mileage for this route was 22 km (13 miles) and the mileage for “RTK fix” data was 15 km (9.5 miles or 71%). The average travel speed on this route was 12 m/sec (27 MPH). The difference in elevation on this route was 142 m (467 ft) from the lowest point to the highest point.

Figure 4.58 shows the route on a topographic map and the results are presented in Table 4.23 and Figures 2.59 ~ 2.60. In this evaluation, the CSI GBX-12R receiver was not able to lock on to the St Paul reference station at the time when experiments were performed. Therefore, this scenario was not included in the data analysis.

Figure 4.58 Duluth Route IV

| **Correction Source** | **Receiver** | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|---|
| **Satellite** | **NavCom SF-2050M** | 1.05 m (3.43 ft) | 0.49 m (1.60 ft) | 0.17 m (0.55 ft) | 0.73 m (2.38 ft) | -0.10 m (-0.33 ft) | 0.66 m (2.17 ft) |
| **St Paul** | **Trimble AgGPS132** | 0.55 m (1.80 ft) | 0.29 m (0.94 ft) | 0.01 m (0.03 ft) | 0.44 m (1.43 ft) | -0.21 m (-0.70 ft) | 0.15 m (0.48 ft) |
| **Pine River** | **Trimble AgGPS132** | 0.47 m (1.56 ft) | 0.32 m (1.04 ft) | 0.12 m (0.41 ft) | 0.25 m (0.83 ft) | 0.33 m (1.07 ft) | 0.32 m (1.04 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | 0.41 m (1.33 ft) | 0.25 m (0.82 ft) | 0.08 m (0.28 ft) | 0.26 m (0.84 ft) | 0.15 m (0.50 ft) | 0.25 m (0.83 ft) |
| **St Paul** | **CSI GBX-12R** | N/A | | | | | |
| **Pine River** | **CSI GBX-12R** | 1.90 m (6.24 ft) | 1.51 m (4.97 ft) | 0.62 m (2.03 ft) | 0.91 m (2.99 ft) | -1.18 m (-3.86 ft) | 1.71 m (5.62 ft) |
| **Wisconsin Point** | **CSI GBX-12R** | 8.57 m (28.11 ft) | 5.06 m (16.58 ft) | -0.12 m (-0.39 ft) | 1.32 m (4.34 ft) | -7.29 m (-23.93 ft) | 6.64 m (21.78 ft) |
| **No Correction** | **Garmin GPS 76** | 2.81 m (9.22 ft) | 1.72 m (5.63 ft) | 0.14 m (0.47 ft) | 1.29 m (4.22 ft) | 0.54 m (1.79 ft) | 2.93 m (9.60 ft) |
| **WAAS** | **Garmin GPS 76** | 1.18 m (3.86 ft) | 0.40 m (1.32 ft) | 0.63 m (2.07 ft) | 0.44 m (1.45 ft) | 0.79 m (2.61 ft) | 0.85 m (2.79 ft) |

Table 4.23 Results of the DGPS Evaluation on Duluth Route IV at an average speed of 12 m/sec (27 MPH)

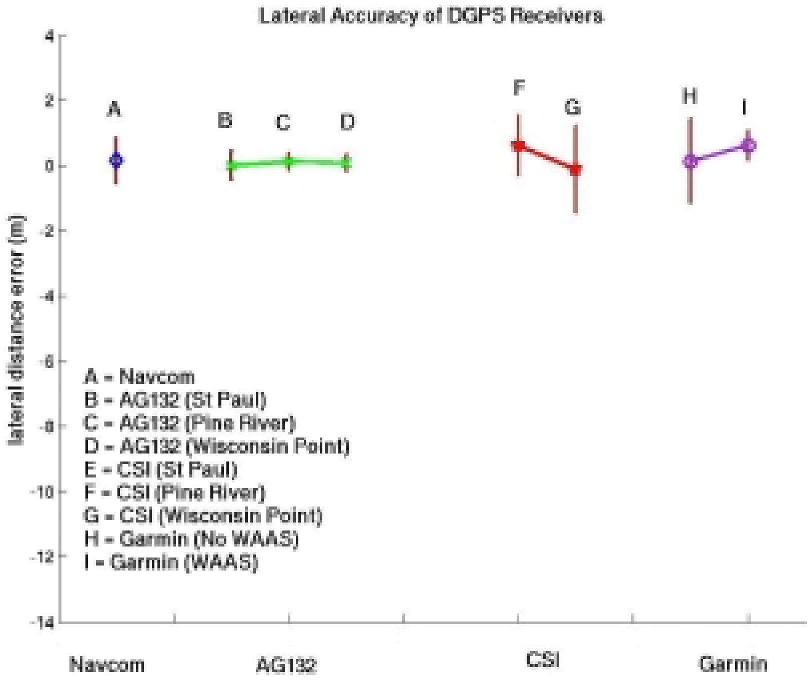


Figure 4.59 Lateral Accuracies of DGPS Receivers on Duluth Route IV

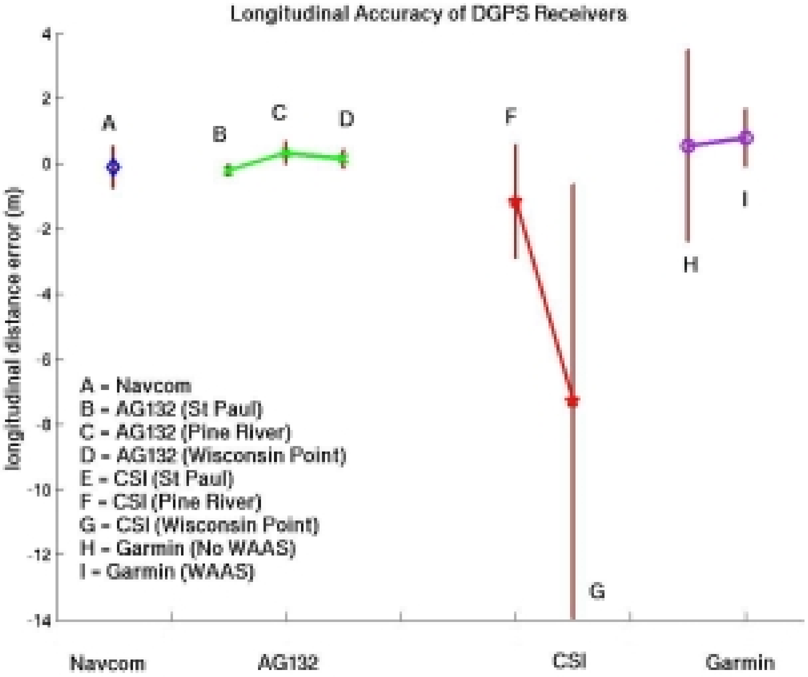


Figure 4.60 Longitudinal Accuracies of DGPS Receivers on Duluth Route IV

### 4.4.5 Results of the DGPS Evaluation on Duluth Route V

Duluth Route V ran along Piedment Ave in southwest Duluth from Chambersburg Ave to the junction of Interstate highway I-35. The total mileage for this route was 22 km (14 miles) and the mileage for “RTK fix” data was 20 km (13 miles or 89%). The average travel speed on this route was 11 m/sec (24 MPH). The difference in elevation on this route was 211 m (691 ft) from the lowest point to the highest point.

Figure 4.61 shows the route on a topographic map and the results are presented in Table 4.24 and Figures 2.62 ~ 2.63. In this evaluation, the CSI GBX-12R receiver was not able to lock on to the St Paul reference station at the time when experiments were performed. Also, due to radio propagation problems, the “gold-standard” (“RTK fix”) reference could not be obtained for evaluation of the Garmin GPS 76 receiver with no correction for the GPS. Therefore, these scenarios were not included in the data analysis.

Figure 4.61 Duluth Route V

| **Correction Source** | **Receiver** | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|---|
| **Satellite** | **NavCom SF-2050M** | 0.83 m (2.73 ft) | 0.78 m (2.55 ft) | 0.08 m (0.27 ft) | 0.77 m (2.54 ft) | -0.20 m (-0.64 ft) | 0.63 m (2.07 ft) |
| **St Paul** | **Trimble AgGPS132** | 0.28 m (0.92 ft) | 0.25 m (0.81 ft) | 0.30 m (1.00 ft) | 0.26 m (0.86 ft) | -0.17 m (-0.56 ft) | 0.19 m (0.64 ft) |
| **Pine River** | **Trimble AgGPS132** | 0.20 m (0.67 ft) | 0.13 m (0.41 ft) | 0.38 m (1.25 ft) | 0.15 m (0.50 ft) | -0.04 m (-0.14 ft) | 0.18 m (0.58 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | 0.37 m (1.23 ft) | 0.13 m (0.44 ft) | 0.02 m (0.05 ft) | 0.16 m (0.52 ft) | -0.03 m (-0.09 ft) | 0.13 m (0.42 ft) |
| **St Paul** | **CSI GBX-12R** | N/A | | | | | |
| **Pine River** | **CSI GBX-12R** | 1.73 m (5.68 ft) | 0.66 m (2.16 ft) | -0.11 m (-0.35 ft) | 0.95 m (3.12 ft) | -1.40 m (-4.59 ft) | 0.74 m (2.43 ft) |
| **Wisconsin Point** | **CSI GBX-12R** | 2.36 m (7.74 ft) | 0.50 m (1.64 ft) | 1.92 m (6.29 ft) | 0.64 m (2.11 ft) | -0.29 m (-0.96 ft) | 0.78 m (2.55 ft) |
| **No Correction** | **Garmin GPS 76** | N/A | | | | | |
| **WAAS** | **Garmin GPS 76** | 0.73 m (2.41 ft) | 0.35 m (1.13 ft) | 0.33 m (1.09 ft) | 0.38 m (1.24 ft) | 0.13 m (0.43 ft) | 0.58 m (1.89 ft) |

Table 4.24 Results of the DGPS Evaluation on Duluth Route V at an average speed of 11 m/sec (25 MPH)

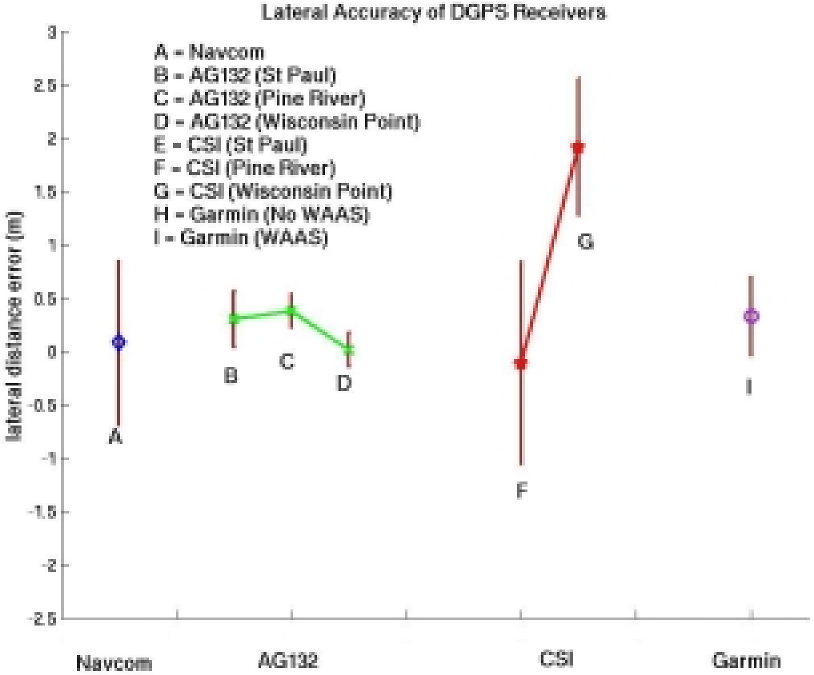


Figure 4.62 Lateral Accuracies of DGPS Receivers on Duluth Route V

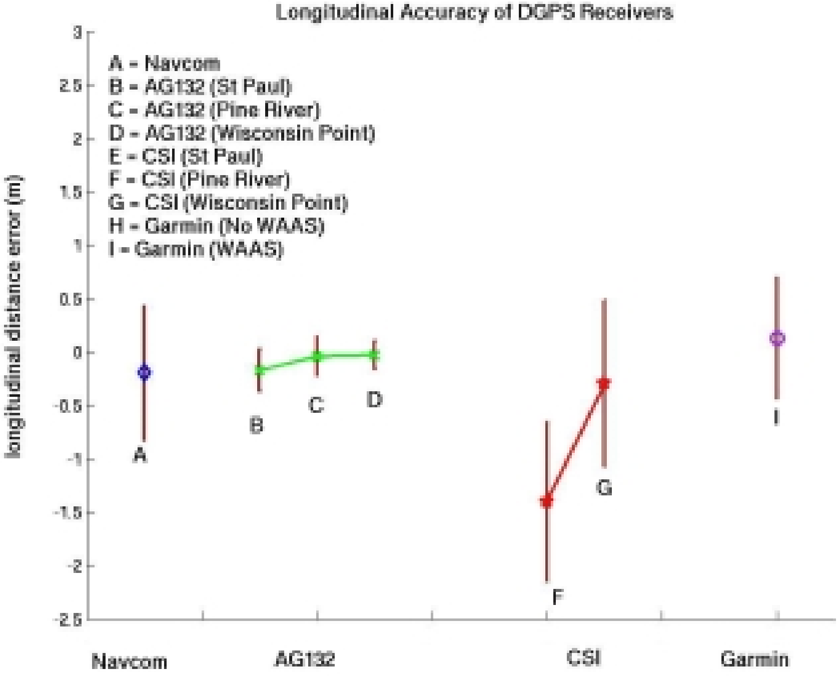


Figure 4.63 Longitudinal Accuracies of DGPS Receivers on Duluth Route V

### 4.4.6 Summary and Discussion of the DGPS Evaluation in Duluth

The following summarizes the results presented in Sections 4.4.1 ~ 4.4.5:

- The results found for the DGPS evaluation in Duluth, Minnesota were consistent with the results found for other DGPS evaluations. The accuracies of the DGPS receiver did not degrade in an environment where the elevation of roads changes dramatically in a short distance. The overall accuracies for all the DGPS receivers tested are shown in Table 4.25. The comparison of lateral and longitudinal accuracies of all DGPS receivers evaluated in Duluth are shown in Figures 2.64 ~ 2.65.
- It is interesting to note that the Wisconsin Point reference station is the nearest NDGPS base station in the Duluth area. The distance from the city of Duluth to the Wisconsin Point reference station is about 14 km (or 9 miles). However, both the Trimble AgGPS 132 and the CSI GBX-12R receivers had the worst accuracies using the Wisconsin Point reference station. Thus, it is very likely that the range rate correction in the NDGPS service has a detrimental effect on the GPS receivers. The closer a GPS receiver is to the base station, the more effect the range rate correction would have on the location solutions.
- No GPS drift of any kind was recorded for any GPS receiver in this evaluation.

| **Correction Source** | **Receiver** | **Positional mean error** | **σ** | **Lateral mean error** | **σ** | **Longitudinal mean error** | **σ** |
|---|---|---|---|---|---|---|---|
| **Satellite** | **NavCom SF-2050M** | 0.81 m<br>(2.62 ft) | 0.66 m<br>(2.15 ft) | 0.06 m<br>(0.20 ft) | 0.64 m<br>(2.09 ft) | -0.17 m<br>(-0.56 ft) | 0.63 m<br>(2.08 ft) |
| **St Paul** | **Trimble AgGPS132** | 0.38 m<br>(1.26 ft) | 0.27 m<br>(0.90 ft) | 0.17 m<br>(0.57 ft) | 0.36 m<br>(1.18 ft) | -0.05 m<br>(-0.15 ft) | 0.24 m<br>(0.78 ft) |
| **Pine River** | **Trimble AgGPS132** | 0.34 m<br>(1.13 ft) | 0.31 m<br>(1.01 m) | 0.30 m<br>(0.99 ft) | 0.30 m<br>(0.99 ft) | 0.09 m<br>(0.29 ft) | 0.33 m<br>(1.09 ft) |
| **Wisconsin Point** | **Trimble AgGPS132** | 0.59 m<br>(1.94 ft) | 0.36 m<br>(1.20 ft) | -0.14 m<br>(-0.44 ft) | 0.39 m<br>(1.28 ft) | -0.06 m<br>(-0.19 ft) | 0.30 m<br>(0.97 ft) |
| **St Paul** | **CSI GBX-12R** | 2.74 m<br>(8.98 ft) | 0.72 m<br>(2.35 ft) | 0.77 m<br>(2.54 ft) | 0.54 m<br>(1.78 ft) | 2.39 m<br>(7.84 ft) | 0.97 m<br>(3.19 ft) |
| **Pine River** | **CSI GBX-12R** | 2.55 m<br>(8.36 ft) | 2.47 m<br>(8.11 ft) | 0.30 m<br>(0.99 ft) | 1.24 m<br>(4.07 ft) | -1.58 m<br>(-5.17 ft) | 2.88 m<br>(9.43 ft) |
| **Wisconsin Point** | **CSI GBX-12R** | 7.21 m<br>(23.65 ft) | 5.62 m<br>(18.43 ft) | 1.16 m<br>(3.82 ft) | 1.80 m<br>(5.92 ft) | -5.72 m<br>(-18.75 ft) | 6.75 m<br>(22.15 ft) |
| **No Correction** | **Garmin GPS 76** | 3.15 m<br>(10.35 ft) | 1.77 m<br>(5.82 ft) | -0.07 m<br>(-0.24 ft) | 1.93 m<br>(6.33 ft) | 0.08 m<br>(0.28 ft) | 2.95 m<br>(9.68 ft) |
| **WAAS** | **Garmin GPS 76** | 1.42 m<br>(4.67 ft) | 0.90 m<br>(2.94 ft) | 0.54 m<br>(1.76 ft) | 1.13 m<br>(3.69 ft) | 0.28 m<br>(0.92 ft) | 1.20 m<br>(3.94 ft) |

Table 4.25 Summary of the results of the DGPS Evaluation in Duluth, Minnesota

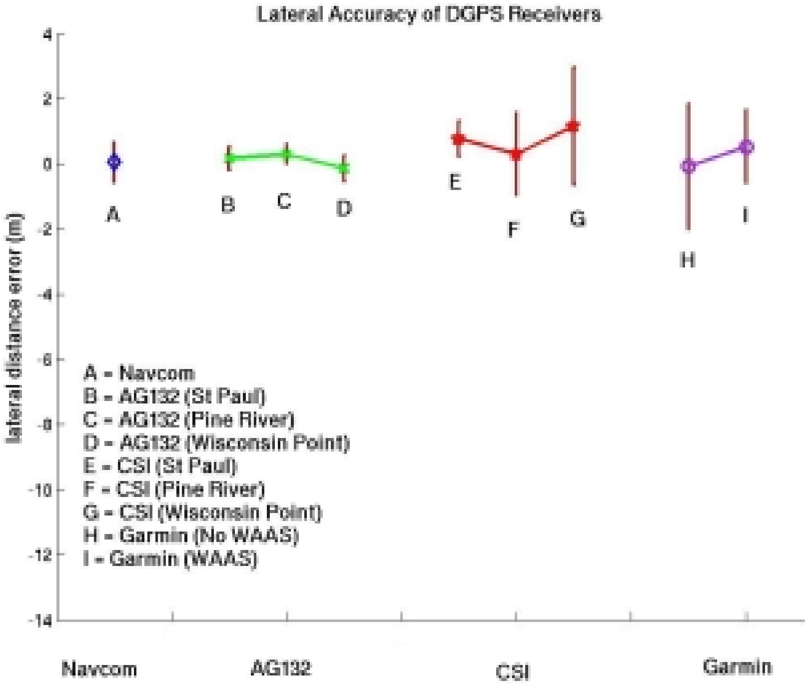


Figure 4.64 Comparison of lateral accuracies of GPS receivers evaluated in Duluth, MN

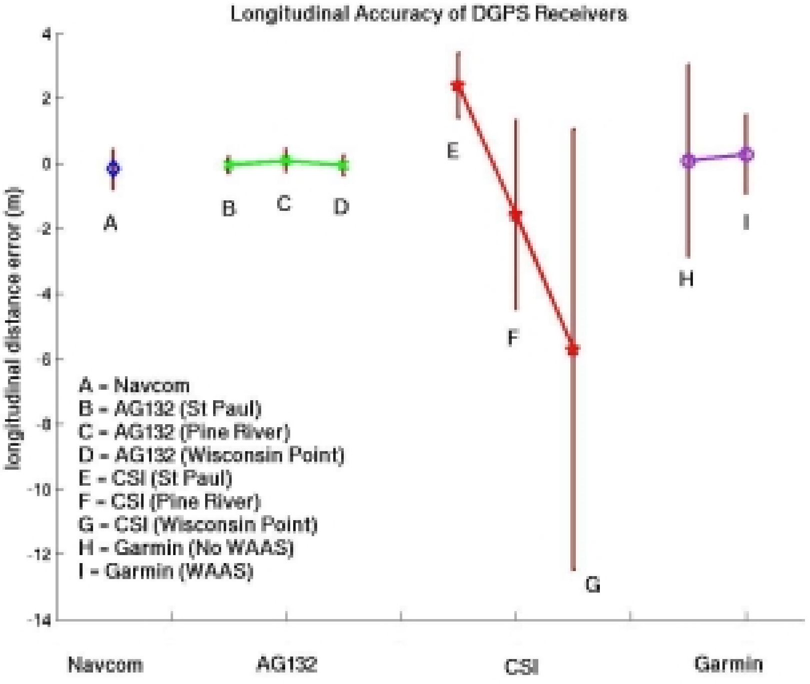


Figure 4.65 Comparison of longitudinal accuracies of GPS receivers evaluated in Duluth, MN

### *4.5 GPS Coverage in a Downtown Environment*

Downtown is an environment of obstructions. With tall buildings, parking ramps, and skyways, only small portions of the sky are in view. This is known as the urban canyon phenomenon, which causes problems for GPS receivers to acquire satellites. The challenge of obtaining a GPS fix in a downtown environment is further compounded by multipath effects. Multipath effects are defined as the refraction or reflection of the satellite signal by electronic or physical interference. The reflection of the signal distorts the time variable in the location equation yielding incorrect solutions. In addition to the direct path from the satellite to the GPS antenna, the GPS signals also arrive at the receiver after one or more reflections from the buildings or structures. The multipath might have three undesired effects for GPS receivers. First, the reflected signal may destructively interfere with the direct signal and fade the composite signal power. Second, the reflected signal might have approximately the same power as the direct signal and distort the GPS measurements. Last but probably most importantly is that the reflected signal might be stronger than the direct signal and cause the receiver to assume that the reflected signal is the direct signal.

Since road user charge applications need to work in different environments, it is important to study the GPS coverage in a downtown environment. As the largest downtown in Minnesota, downtown Minneapolis (Figure 4.66) was selected to test for GPS coverage. The testing area was bounded by Washington Avenue South, 10th Street South, Hennepin Avenue, and Portland Avenue. This area is home to over 80 office buildings and has about 70 connected skyways between buildings. It includes most of the tall buildings, parking ramps, and skyways in the downtown Minneapolis area. Results of the experiments are shown in Figure 4.67. Testing routes are labeled with text boxes in the figure.

Figure 4.66 Downtown Minneapolis, Minnesota.

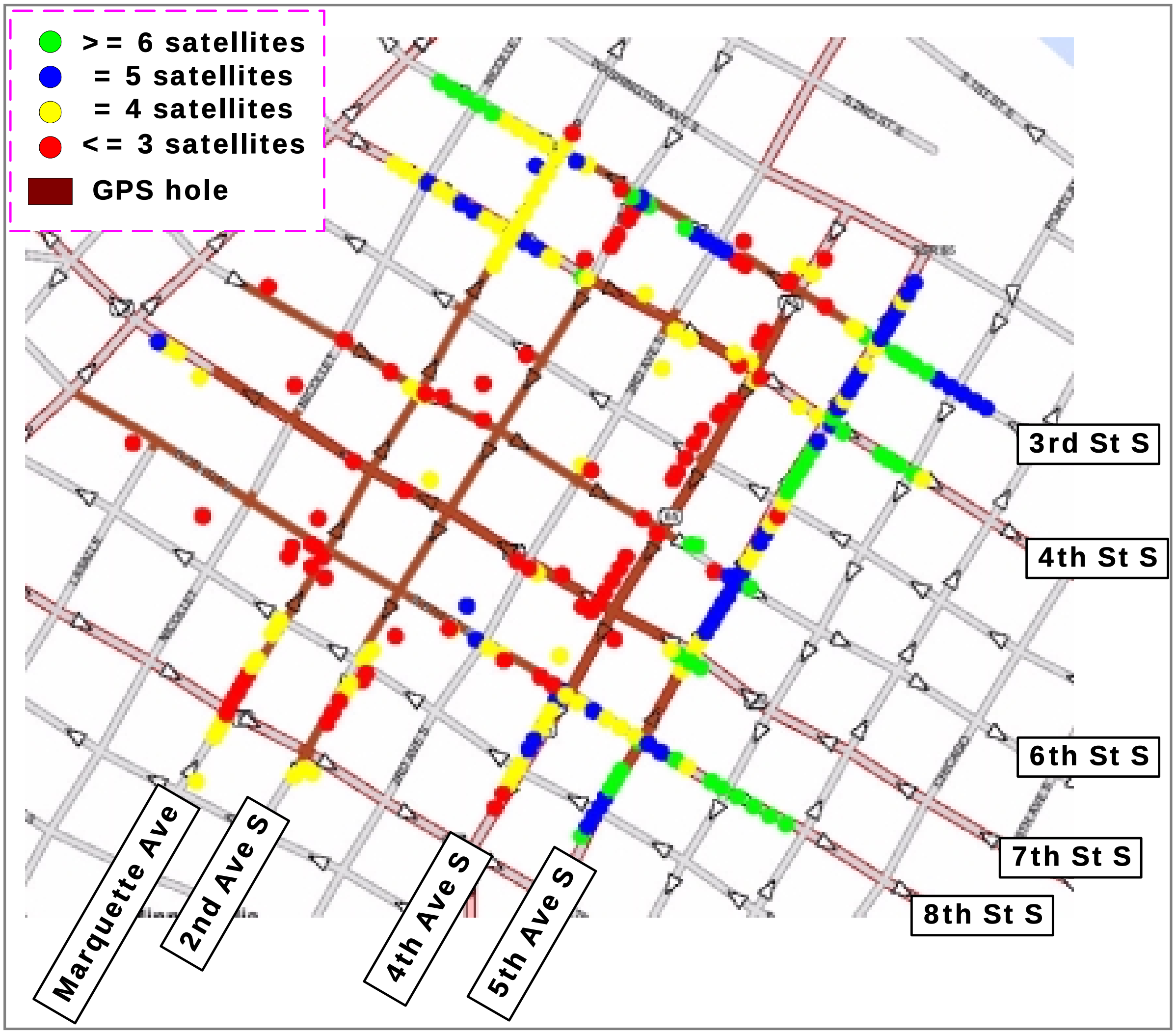


Figure 4.67 GPS coverage in downtown Minneapolis on a street atlas

By examining the results drawn in the figure, it is found that the GPS coverage was good on 5th Avenue South where buildings are generally not taller than 4 stories above the ground and with several parking lots (i.e., open space) along the street. As the vehicle entered the core downtown area where the urban canyon phenomenon and multipath effects are the worst, the GPS coverage was just not good enough for any GPS receiver to function properly. As one can see from the figure, there is basically a large GPS “hole” inside the block bounded by 3rd Street South, 8th Street South, Nicollet Mall and 4th Ave South. Inside this block, the GPS receiver either acquired less than 4 satellites or received no signal. Even though a GPS receiver was still able to compute position solutions based on a limited number of satellites available, the results were erroneous as shown on the figure. Please note that the digital map used in Figure 4.67 is a commercial street atlas whose accuracy is unknown. The street atlas is used to illustrate the problems of GPS coverage in the downtown area and is not used to evaluate the accuracies of the GPS solutions. Figure 4.68 shows the same GPS coverage for downtown Minneapolis displayed on a digital map provided by the City of Minneapolis. This map is accurate to less than 10 m (33 ft). From examining the figure, one can see that the GPS position outputs could be off by as much as half a block. Therefore, one should not trust the outputs from a GPS receiver when the number of satellites in view is less than 4.

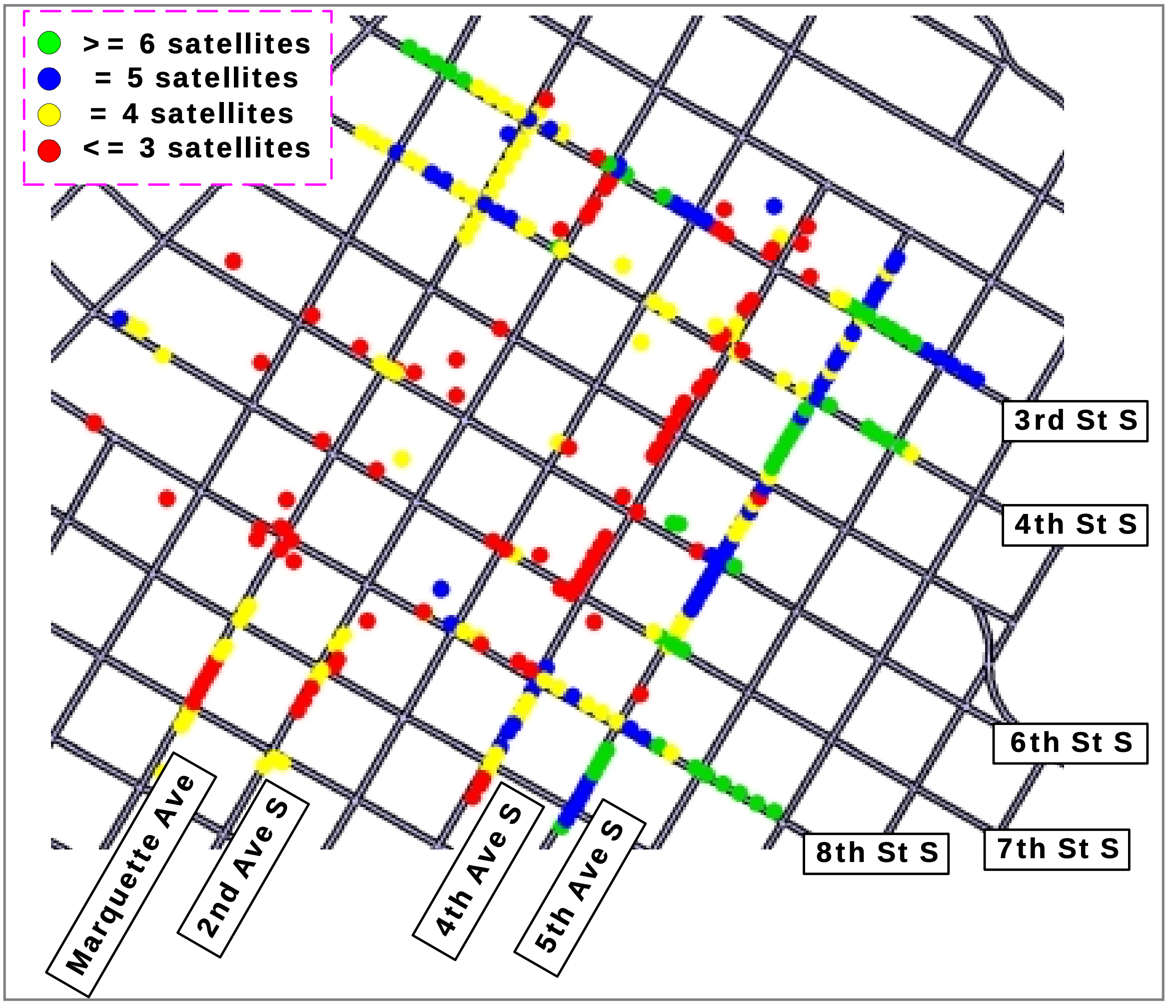


Figure 4.68 GPS coverage in downtown Minneapolis on the city map

From the experiments, one can conclude that it is unlikely that a GPS receiver can track a vehicle continuously in a downtown environment where the urban canyon phenomenon and multipath effects can adversely affect the functionality of a GPS receiver. Fortunately, since most roads in downtown are municipal streets and belong to the same jurisdiction, road user charges still can be applied with the help of secondary sensors (e.g., an odometer like one used in taxicabs) to track the mileage traveled inside the downtown area. A special road user charge rule might be needed for charging vehicles traveling in the downtown area. More research is required to work out the details in both road user charge policies and technologies to enable such charging.

It is still possible to use GPS to determine when one enters and leaves such an area and then use odometer to measure the VMT in that area. However, it does lose the ability to identify travel on for example a county road that passes through the downtown area, but that is not likely to be much of a problem.

# Chapter 5
# Conclusions and Recommendations

This chapter summarizes the GPS portion of the project and makes suggestions for future work.

## *5.1 Conclusions*

This study recommends the minimum required accuracy for the GPS based on the road separation distance associated with a specified requirement to distinguish roads running in close proximity from each other. A mathematical representation of the desired accuracy of GPS was presented and the equation can also be used to determine the minimum road separation distance if the accuracy specification of a GPS receiver is known.

A systematic approach for evaluating GPS receivers was also developed and a number of GPS receivers were evaluated using various differential correction signals. The following summarizes the results for the GPS technology evaluation:

- The NavCom SF-2050M receiver has the highest overall accuracy among all GPS receivers tested. This is a dual-frequency GPS receiver that can pick up proprietary global DGPS correction signals. It is able to distinguish between two roads with a separation of 1.2 m (4 ft) at a confidence level of 99.73%. However, the present (year 2003) cost of $6,000 for each unit is high for road user charging applications in the near term. Besides, in order to maintain the highest accuracy that this GPS receiver can provide, each unit also needs to pay $850 for an annual DGPS service subscription.
- The Trimble AgGPS 132 receiver has the highest accuracy among DGPS receivers that utilize publicly available correction signals. This is a single-frequency receiver designed to use the NDGPS correction signals. The receiver is capable of distinguishing two roads that are only separated by 1.8 m (6 ft) at 99.73%. Although the cost of $5,000 for each unit is high for road user charge applications, the price is expected to drop significantly if large quantities of such receivers are used in road user charging applications nationwide. Less expensive versions of this receiver exists. This particular unit was selected for evaluation since it can also be used with L-band satellite correction signals (e.g., OmniSTAR).
- The Garmin GPS 76 receiver has the best price/performance ratio among all GPS receivers tested. At $200, this receiver can distinguish two adjacent roads with a separation of 6.1m (20 ft) at 99.73%. This is a single-frequency receiver that can pick up the WAAS correction signals. At such an accuracy level, the Garmin GPS 76 receiver is a good candidate for most of the road user charging applications that do not require lane-level road pricing.
- The accuracies of the NDGPS receivers are relatively insensitive to baseline distance or changes of base stations. In general, an NDGPS receiver can obtain the highest possible accuracy by using the nearest base station, and in most cases, the NDGPS receiver still can maintain the same level of accuracy by using reference stations that are farther away.

Occasionally, the accuracy of the receiver is better with a reference station using a longer baseline. However, the result is not consistent enough to make any statistical conclusion other than its accuracy is independent of the baseline.

- On rare occasions, a GPS receiver would drift out of its normal course for few seconds and then converge back. This might be due to an insufficient number of satellites in view or other factors (e.g., the satellite constellation geometry). This problem can be corrected by using an inexpensive inertial measurement sensor.
- The accuracies of GPS receivers are not affected by vehicle speeds. Results have shown that the accuracy of a GPS receiver does not degrade if the vehicle travels faster. This is consistent for all receivers and across the range of speeds tested.
- The accuracies of GPS receivers are not affected by a change of elevation. Results have shown that the accuracy of a GPS receiver does not degrade when a vehicle travels in hilly terrain as long as the GPS receiver has a sufficient number of satellites in view to compute position solutions.
- The GPS coverage in a downtown environment is spotty. This is especially true in areas where tall buildings on both sides of the streets create an urban canyon. Urban canyons present serious multipath problems that are difficult to overcome. It is very difficult for a GPS receiver to function properly in a downtown environment. Secondary sensors (e.g., odometers) can be used to track mileage traveled in such downtown areas. The GPS receiver can be used to determine entry and exit from a downtown area designated boundary.

In this study, the “RTK fix” data from the Trimble MS-750 receiver was used as the “gold-standard” to evaluate other lower accuracy DGPS receivers. It should be noted that in order for a Trimble MS-750 receiver to obtain data with the quality of “RTK fix”, it needs to have an unobstructed view of the sky as well as good transmission of correction signals. Even though testing routes were carefully selected to highlight the problems associated with distinguishing between roads that were parallel and adjacent to each other, the data included in the analysis actually represented the “best” of the “worst” case scenarios for road user charging applications. Thus, higher standards are recommended for specifying and/or selecting a GPS receiver for a road user charge application. In other words, the accuracy numbers of GPS receivers for a confidence level of 99.97% ($3\sigma$) or higher should be used for road user charging purposes in stead of the accuracy numbers for a confidence level of 95% ($2\sigma$) or lower.

## *5.2 Recommendations*

1. As mentioned earlier, road user charging applications not only can be used to raise revenues for road infrastructure but can also be used to manage demand. One way to achieve both purposes is to open High-Occupancy Vehicle (HOV) lanes on interstate highways for tolling (“High-Occupancy Toll” or HOT) during rush hours. Studies have shown that HOV lanes are not operating at their full potential over the entire morning and afternoon peak hours [I-18]. However, other regular lanes are generally very congested during the same period of time. By opening HOV lanes for HOT, motorists have an

option to pay for premium service when they need to avoid delays in order to be on time for business or personal appointments. A GPS/digital map combination would allow the implementation of HOT lanes with an easy opt-in/opt-out approach and would not require any physical infrastructure. This would also free up demand on regular lanes so that traffic can move more smoothly. The implementation of a HOT lane demonstration project would put all theories into test. Invaluable lessons will be learned from the demonstration project to set the foundation for a large-scale road user charging field operational test.

2. The public and political acceptance of the road user charging schemes is the key toward the success of the program. Approaches beyond simple mileage-based charges would likely need to be phased in gradually in order to give motorists time to adjust. A field operational test together with intensive government outreach activities are a good starting point and could answer questions on acceptance and effectiveness of the program. The field operational test would also provide a test-bed to experiment with real-life road pricing situations. The knowledge gained from the field operational test would be able to support road pricing policy development and provide guidance on effective implementation and exploitation of the road user charging concepts.

3. One of the side-benefits of a GPS based road user charging system is that the GPS receivers on vehicles can provide data to a central server that aggregate the results into congestion measures. This same procedure can also be used to set the variable congestion based rate structure in real-time value pricing applications and provide traffic data for transportation system management, incident detection and traveler information.

The digital map analysis described in Part II clearly shows that existing digital road maps are not adequate for most of the road user charging applications. This is because that they are not designed for charging road usage and thus may lead to inaccurate and unfair charges. New high accuracy next generation digital maps are already being used for safety applications. They can also be used for general road user charging systems or even for HOT lane pricing. Such next generation digital maps have already been developed by the University of Minnesota and are discussed in next section.

## *5.3 Next Generation Digital Maps*

Recall from Section 1.4 that the maximum allowable position error for a road user charging application is equal to half of the road separation distance (Equation 1.6). If the required minimum road separation distance for a road user charge application is 6 m (20 ft), then the digital map used for this application needs to possess a positional accuracy of 3 m (10 ft) or less. If lane-level road pricing was required (e.g., “High-Occupancy Toll” or HOT), then a digital map with less than 0.3 m (1 ft) of accuracy is needed.

To achieve such a high accuracy, we need to take advantage of newly available next generation digital maps. These high-accuracy digital maps are based on the geospatial database system developed for implementing lane departure warning systems that are one form of driver-assistive technology. These technologies seek to increase driver safety in difficult driving conditions through the use of vehicle-guidance and collision-avoidance technologies [I-19][I-20][I-21].

This geospatial database contains all the relevant fixed landscape elements local to the road, including lane boundaries, lane centers, road shoulders, guardrails, dividers, and signs, as well as attributes such as intersections, speed regulations, etc. The accuracy of this database is 20 cm or better. Furthermore, this geospatial database is designed for real-time access by a moving vehicle, which requires minimal latency. Since the database is designed for real-time (30 to 40 msec response) applications, it is compact and thus does not require significant storage capacity. For a database that contains only lane centers and lane boundaries where each is represented by one data point every 5 meters, the size of the database is about 10.5 KB per lane kilometer. Figure 5.1 shows the level of details that this geospatial database can achieve.

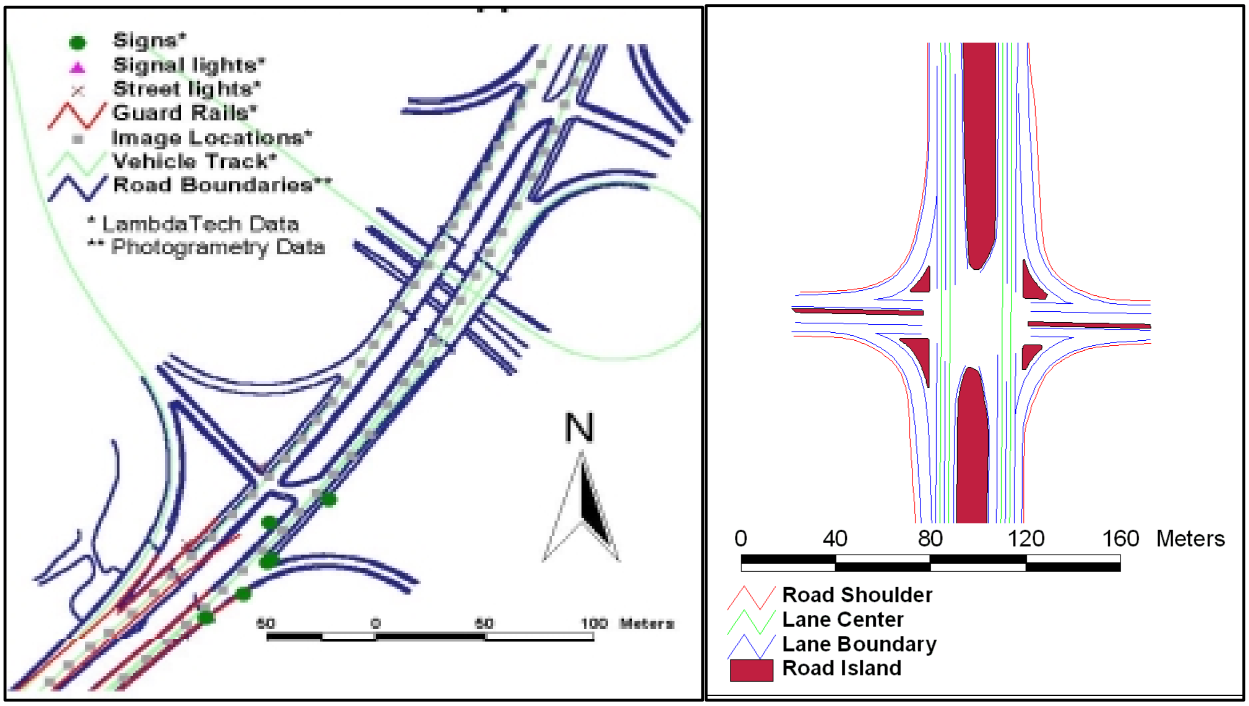


Figure 5.1 Level of details that can be achieved in a high-accuracy digital map database.

Please note that since the structure of the database is flexible, the level of details can be modified for road user charging applications. In addition, attributes pertinent to road user charging applications can be embedded into the database on top of the road network. For a road segment, the attributes may include jurisdiction, road type, road name, pricing structure, and congestion pricing detail.

It is also important to note that this database has been successfully tested and validated during the past several years and was used in the driver assistive system under test for the IVI Specialty Vehicle Field Operational Test funded by U.S. DOT [I-22]. It has also been used for the Lane Assist Technology evaluation funded by the U.S. DOT for potential use in Bus Rapid Transit

(BRT) systems. [I-21]. Figure 5.2 shows lane boundaries from the database superimposed on the actual painted lane boundaries to demonstrate its accuracy.

Figure 5.2 Yellow lane boundaries and white center line from the database are superimposed over actual lane markings as a demonstration of accuracy. The short horizontal bars are superimposed for calibration and evaluation purposes and are not typically used.

The creation of a digital map database consists of two key components: the collection of data used to create the database, and the processing of that data into useful geospatial information. Data can be collected in a number of ways, including photogrammetry, lane striping operations, and specifically designed mapping vehicles. Each of these techniques is explained below:

1. In areas where photogrammetry data of sufficient accuracy is available, the data files representing the roadway can be directly converted into the vehicle specific format in the database.
2. For lane striping operations, a paint-striping machine equipped with DGPS and additional sensors can be used to determine the location of the paint nozzles as they apply paint to the road. By tracking the nozzles as the vehicle moves, the lane boundaries can be digitized.
3. In areas where the road geometries are simple and where intersection density is low, driving roads in a GPS equipped vehicle and recording lane centers can serve as the basis

for the geospatial database. Known road geometry and design guidelines are fused with centerline information to create a high accuracy representation of the road and its surroundings.

4. For areas with complex or highly variable road geometry, vehicles equipped with DGPS and image capture and processing equipment can be used to locate existing lane boundaries. With this technique, a camera looking down at the pavement captures images of the roadway. Once an image is captured, image processing algorithms are used to determine the location of the skip lines in the image in real-time.

After data has been collected, the next step is to process the raw data and place it into the geospatial database. This process involves a number of steps, including data reduction, data smoothing, and the optimization of the representation of the data in the database. One major task of this optimization is to properly balance database density and the level of details contained in the database.

In the IVI Specialty Vehicle Field Operational Test, the database was used both to determine where the vehicle is located within the lane and used as a comparison against the predicted vehicle trajectory to estimate whether a lane departure event is likely in the immediate future [I-22]. With an accuracy of 20 cm or better, the database not only can be used to issue warnings should a lane departure event be imminent but also can be used in lane-level road pricing applications. Combining this database together with sub-meter accuracy GPS receivers, HOT lane pricing can become a reality without the installation of significant new infrastructure. Such a system would be able to identify a vehicle entering or leaving a designated lane and allow the driver to choose either to opt-in or op-out as he/she travels.

For road user charging applications that do not require lane-level pricing, a simplified version of the database with less accuracy can readily be implemented. Since the accuracy requirement is not as strict as the lane-level pricing applications, such a digital map database can be created in a shorter period of time. It is known from the GPS analysis that the current GPS technology is sufficiently accurate enough for road user charging applications. With this improved digital map database and already proven GPS technology, the implementation of a road user charging system with good lateral resolution becomes viable.

In conclusion, the next generation of digital map database is far more accurate than the digital maps currently available from the public or private sectors and is flexible enough to be adopted for different types of road user charging applications. Given that these digital map databases of higher accuracies have not yet entered the mainstream, a broad based field operational test is recommended to evaluate a road user charging system that would take advantage of this new technology.

# PART II

# Digital Map Component

# Chapter 6
# Research Tasks for GIS Subsystem

This portion of the report is primarily concerned with the evaluation of the ability of digital road map databases to determine whether they meet the requirements of a road user charge system.

## *6.1 Objectives*

The objective of this project is to develop a GIS subsystem to evaluate the ability of digital road map databases to meet the requirements of the road user charge system and recommend next steps. We begin by examining the content and quality requirements for digital GIS road maps and ensure their correctness and completeness. The content requirements for road user charges include economic attributes (e.g. administrative zones, congestion zones), geographic locations (freeway - mile point, state plain coordinate, latitude - longitude), route attributes (name, type, time restriction), route segment attributes (road segment length, direction, type, restrictions), etc. We also examine road map quality metrics (e.g., confidence, reliability, accuracy, coverage, currency, costs) developed for other applications within Intelligent Transportation Systems (ITS) including in-car navigation devices, commercial vehicle tracking, etc. This project aims at developing techniques for digital road map evaluation and trying to define a new digital map accuracy measurement based on spatial computation techniques.

## *6.2 Framework of GIS Subsystem*

Our methodology for the GIS subsystem can be divided into several parts. The first core activity was to acquire a digital map for evaluation. The second important activity was to select the test routes which represent the most difficult test case samples for the evaluation. Then we needed to collect GPS field data to be used as gold standard for testing the digital maps. Finally we proposed an approach for the analysis and visualize the results. Figure 6.1 illustrates the framework of our approach for evaluating digital map accuracy.

Six core activities are involved in this framework.

- **Acquire digital road maps:** Survey and research on the characteristics of current available digital road maps
- **Select test routes:** Propose a co-location approach to find line string co-location pattern for GPS field data collection
- **Gather gold standard data for the test routes:** Drive vehicle on test routes to collect GPS field data, using high accurate GPS receiver
- **Assess positional accuracy for the test routes:** Propose a buffer-based line string digital road map accuracy measurement for large road networks

- **Analyze result statistically:** Present the computed result statistically and analyze the performance of related algorithms
- **Visualize raw data and result:** Display digital road map, overlay GPS field data on it, and show the computed result visually

Among the six core activities, digital map survey, test routes site selection and map accuracy analysis are major activities in GIS subsystem. We will discuss them in Chapter 7, Chapter 8 and Chapter 9 separately. In the following subsections we briefly discuss all these six activities.

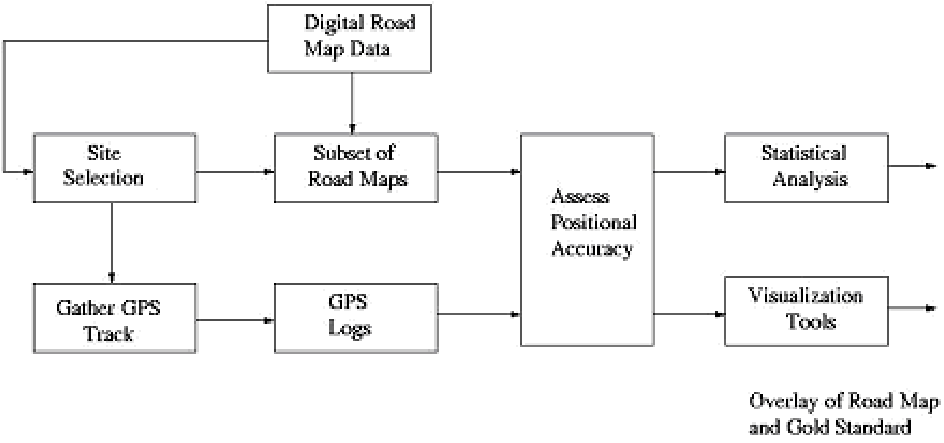


Figure 6.1 Framework for Evaluating Digital Map Accuracy

## 6.2.1 Digital Map Data Acquisition

### Commercial Digital Road Map Vendor Justification

In this report, we will evaluate a roadmap dataset covering the Twin Cities metropolitan area in Minneapolis-St. Paul area from a commercial source, which will be called vendor X. The report will not name the source for multiple reasons. Roadmap accuracy results depend on a number of factors including the recency of datasets, test sites, accuracy measure etc. It is necessary to compare these procedural details in order to interpret the results on roadmap accuracy. This research team did not have access to the data quality professionals at vendor X to compare the procedural details. Reduction in budget for the project made it difficult to acquire the most recent versions of the roadmap data from the commercial source. Test sites used in our study focus on areas where roads are close to each other instead of sampling the entire dataset. In addition, this study uses a novel buffer based accuracy measure that is different from commonly used point based accuracy measure from National Map Accuracy Standard. To minimize the risk of mis-interpretation of the results, this report will not name the commercial source.

### Digital Map Data Acquisition

We surveyed and evaluated the current available digital road maps that are commonly used in current GIS applications. We evaluated Navtech from Navtech Inc. [II-1], map X from vendor X, Mn/DOT basemap from Minnesota Department of Transportation [II-2], and TIGER map from the US Department of Commerce Census Bureau [II-3]. Considering the requirements of the road use charging system application, the road data availability, i.e., data can be used in our evaluation software, and the claim of data accuracy, we chose one commercial digital map and one public digital map for evaluation.

## 6.2.2 Field Test Site Selection

As noted earlier, we needed to evaluate different digital map accuracy performance under various conditions. We cared more about the worst-case condition because map accuracy in the worst-case condition actually determines the usability of the road user charging system. That means we had to guarantee that the system would work well even under bad conditions. For example, we wanted the system to work well in urban areas within which there is a dense road network.

### 6.2.2.1 Digital Map Data in the Twin Cities Area

For the rural area data collection, we used the Twin Cities digital data from Mn/DOT as our data warehouse. Specifically we used data from seven counties around the cities of St. Paul and Minneapolis, namely Ramsey County, Hennepin County, Washington County, Dakota County, Scott County, Carver County and Anoka County. We also acquired a Minneapolis city map for the evaluation of Minneapolis city map accuracy in Minneapolis downtown area. As a sample area in which elevation changes are significant and which represent a small urban area, we used the City of Duluth digital data that is part of the Mn/DOT basemap. In our GIS subsystem, centerline road representation within these areas is good for the purpose of digital road map evaluation.

### 6.2.2.2 Field Route Selection

We first performed a baseline evaluation of the GIS subsystem. From this evaluation we would like to know the routes and locations for which the errors are supposed to be greater than for other areas. Intuitively, if two routes are very close to each other, it is hard to be distinguished. Mapmakers must locate the roads “far” apart from each other for them to be distinguished. We needed a method to identify roads located close to each other which have likely been mapped inaccurately previously. In spatial data mining, there is a spatial association rule called the co-location rule [II-7] to locate the nearby roads patterns called co-location patterns. We developed a co-location miner for line string (CoMineLS) to look for the routes with co-location patterns and proposed five test routes for the field data collection.

### 6.2.3 GPS Track Data Gathering

Based on our field test route selection module output, we proposed five test routes in the Twin Cities metropolitan area. On a vehicle we installed GPS receivers to collect the GPS field data. Please refer to Section 3.5 for more information about GPS track data gathering.

### 6.2.4 Positional Accuracy Assessment

No digital road map is perfect. Digital road map databases always contain some errors related to accuracy. For our application, we mostly cared about positional accuracy. We proposed a buffer based line string digital map accuracy measure for digital road map positional accuracy analysis. After we conducted field tests to collect reliable high accurate GPS signal, we used them as gold standard and selected corresponding digital road map data for these field test routes. Then a buffer had been generated around the reliable GPS data and the intersections of this buffer and the selected road map data from digital road map dataset had been computed. Finally, the line string map accuracy ratio had been calculated.

### 6.2.5 Statistical Analysis

We proposed five test routes for field test data collection and digital map accuracy analysis. In road user charge systems, road type is an important parameter to calculate the charging fee. Thus in statistical analysis, we summarized the total intersected road length and the total road length by road types and calculated the line string co-location ratio and map accuracy ratio for different road types.

### 6.2.6 Raw Data and Result Visualization

We developed a GIS/GPS integration software to display the road map and overlay the GPS signals on the underlying digital road map. This software can load different types of digital road maps and leave open interfaces for other module installations. It can also be used to generate the statistical analysis results and visualize the results. It is a powerful tool for our spatial framework.

## *6.3 Scope*

The dataset of a digital map is so large that it is impossible to analyze every road segment for a given digital map. We had to choose representative samples for different kinds of roads. For practical feasibility, we categorized the whole dataset into metropolitan areas, rural areas and hilly areas and decided to focus most of our effort on roads in the Twin Cities area, an area of typical of a general flat urban terrain. For our representative sample of a hilly area, we chose to evaluate the Mn/DOT basemap of an area in Duluth, MN, which is a representative of significant hilly terrain.

Digital map data quality analysis involves description in five areas: lineage, positional accuracy, attribute accuracy, logical consistency and completeness. However, only positional accuracy can be formalized and analyzed within a specific formal model. The other four aspects, such as attribute accuracy, are very difficult to formally model. Thus, in this study, we only analyze the positional accuracy of our digital maps.

## *6.4 Outline*

The remainder of this report is organized as follows. Chapter 7 briefly introduces current major digital maps and compares the assessment approaches used with our proposed approach. We then discuss the site selection problem, using co-location patterns in core Twin Cities metropolitan area in Chapter 8. In Chapter 9, we present the map accuracy results and the result analysis.

# Chapter 7
# Digital Road Map Survey

In an automatic road user charge system, there are many factors that affect the correctness of the system. Correctness means the system charges the road user only for his or her actual use of the road. In this chapter, we introduce the digital map accuracy standard, survey current digital road maps, and discuss the approaches and methods used in digital road map accuracy analysis.

## *7.1 Digital Map Accuracy Standard and Digital Road Maps*

In this section, we introduce a digital road map accuracy standard and our survey of the available digital maps, compare the characteristics of these digital maps, and explain how we chose the digital maps. We introduce different digital maps, namely Mn/DOT basemap, Map X, Navtech, and TIGER. After comparing their different properties, we explain the underlying reasons for choosing the digital maps that we did.

### 7.1.1 Digital Road Map Accuracy Standard

The GIS subsystem we were designing is primarily concerned with the evaluation of the ability of digital road map databases to meet the requirements of a road user charge system. Thus the first step for the requirement analysis is to understand the digital road map accuracy requirement. An inaccurate map is not very useful, especially in an automatic road user charge system whose reliability highly depends on the underlying digital road map accuracy. A poor toll charging system might charge more for one road user and charge less for another similar road user, which will make the system useless.

National map accuracy standards have varied during different historical periods for different requirements. Over time, our understanding of road map accuracy has developed and become more precise. From the beginning, standard makers focused on positional accuracy. However, there are other sources of errors. Names and symbols of features and classification of roads all can cause errors. Reduced scales of map introduce even more errors. For example, in congested areas, large buildings may be plotted to scale and the smaller buildings may have to be omitted. At a map scale, it may not be possible to show each of several closely spaced linear features in its correct position. In such cases, one feature is positioned in its true location and others, such as parallel roads or rivers, are placed in nearby location in order for users to distinguish them. This introduces errors related to scale.

Although these different kinds of error sources exist, most major digital map vendors claim their digital map accuracies conform to National Map Accuracy Standard (NMAS). We introduce this standard briefly in the following.

## National Map Accuracy Standard (NMAS)

The NMAS standard was adopted in 1947 and provided the first version of accuracy standards for published maps [II-4]. This standard mainly focused on positional accuracy and proposed horizontal accuracy and vertical accuracy standards. It mainly defines the threshold for 90% of the tested points.

- 90% of the tested points have errors < threshold.
    - Threshold = 1/30 inch for scale > 1:24,000. This is equivalent to a threshold of 66.6 ft (20.3m).
    - Threshold = 1/50 inch for scale < 1:24,000. This is equivalent to a threshold of threshold of 40 ft (12.2m).

## 7.1.2 Survey of Digital Maps

For this study, we chose navigable digital road maps from both the private sector and the public sector.
In this section, we introduce four digital maps; two released by different commercial companies such as Navtech [II-1] and vendor X and two from state and federal government departments [II-2, II-3]. These digital maps differ in their characteristics and claimed accuracy. Our purpose is to research their characteristics and choose possible candidates for our later evaluation.

### 7.1.2.1 Mn/DOT Basemap

The Mn/DOT basemap [II-2] is a digital map dataset developed at a scale of 1:24000. Road network, which represents road centerlines within the state, is a layer of the State of Minnesota basemap 2001, which consists of a number of individual data layers or themes digitized from a USGS 7.5-minute quadrangles paper map so it cannot be assumed to exceed National Map Accuracy Standards for 1:24,000 scale map (+/- 40 ft (12.2m)). The dataset includes information about transportation features (roads, railroads and navigable waters), as well as boundary information (State, County, and Municipal Boundaries, Mn/DOT District Boundaries, Civil, and Congressional Townships, State Forests and Parks, Military Reservations, Indian Reservation Lands, National Forests and Parks), and stream and lake locations.

The Mn/DOT basemap is stored in a Shapefile format that can be downloaded from a web page http://rocky.dot.state.mn.us/basemap. The attribute table that explains the data-tuple or geocoding of the digital map is also available online. Metadata to help users understand the dataset for this Mn/DOT basemap can be downloaded on line.

#### 7.1.2.2 Map X

Map X data are collected from many sources. Some road data are verified by driving on actual roads.

Claims by map X are as follows: the urban areas in map X digital map that have been enhanced have an absolute accuracy of 40 ft (12.2 m) and a relative accuracy of 16 ft (4.9 m). All other areas have an absolute accuracy of 160 ft (48.8 m) and relative accuracy of 18.3 m (60 ft). Map X digital maps meet National Map Accuracy Standards (NMAS) for an absolute accuracy of 40 or 160 ft (12.2 or 48.8m), respectively. That means 90% well-defined points in Vendor X digital map lie within this accuracy.

#### 7.1.2.3 Navtech

Navtech’s commercial digital map [II-1] has the biggest market share in the US. It claims 97% accuracy (accuracy =100% - percent error). In its definition, the percent error is linear combination of 13 components that include segment existence, name, direction, speed, ownership (public/private), address range, prohibited maneuver etc. Navtech does not separate out positional accuracy when defining accuracy.

The definitions for sampling in Navtech are as follows:

- Metropolitan areas (MA): city and suburbs (US)
- Primary Sampling Units (PSU) = USGS 7.5 minute quadrangles (US)
- Cells - PSUs have 25 cells (5 by 5 grid)
- Subcells - A cell has 4 subcells (2 by 2 grid)
- Samples: Random cells from 6 PSUs per MA (150-200 segments)
- Pick all roads in class 1, 2 and 3 (arterial)
- Pick roads in class 4 (non-arterial) from a random subcell

#### 7.1.2.4 TIGER

The US Department of Commerce Census Bureau's Topologically Integrated Geographic Encoding and Referencing (TIGER) digital map [II-3] is another source of public digital maps. The source materials used in developing the TIGER database are principally based on: 1:100,000 US Geological Survey (USGS) topographic maps that were scanned by USGS for the Census Bureau (although there are many other data sources that were used). The positional accuracy varies with the source materials used, but at best meets the established NMAS (approximately +/- 166 ft (50.6 m)) where 1:100,000-scale maps from the USGS are the source. The Census Bureau cannot specify the accuracy of features from other map sources. Thus, the level of positional accuracy in the TIGER files is not suitable for high-precision measurement applications such as engineering problems, property transfers, or other uses that might require highly accurate measurements of the earth's surface.

### 7.1.2.5 Choice of Digital Map to Be Evaluated

Based on the above information, we chose two maps, the map X and the Mn/DOT basemap, for our analysis of digital map accuracy.

We selected the vendor commercial digital map for analysis. Unlike the other maps, the map X has a positional accuracy claim that has been publicized. Although Navtech also claims the accuracy for its digital map, its accuracy claim considers percent error based on the combination of 13 components. The positional accuracy is not specified separately. The map accuracy analysis in our project mainly focuses on positional accuracy. Thus we used map X instead of the Navtech map, since no comparison was possible with Navtech result.

For public sector digital maps, we considered TIGER and Mn/DOT basemap. The TIGER map comes from many sources (although much of it comes from the USGS map). It gets data from the 1:100,000 scale USGS map, so it cannot be used in applications that require highly accurate data. The Mn/DOT basemap is digitized from a USGS 1:24,000 scale paper map. It should have almost the same data accuracy as the USGS paper map and thus 90% of well-defined points on the map should lie within 40 ft (12.2 m) of their true positions. The Mn/DOT basemap has our needed level of accuracy; therefore we chose it for evaluation.

### 7.1.2.6 Comparison Of Different Digital Map Assessment and Our Approach

In the previous section, we briefly introduced four different digital maps that are representatives of current commercial and public digital map sources. Below we compare their characteristics with our proposed approach, focusing on positional error and map assessment approach.

Table 7.1 summarizes the features of these approaches. As can be seen, the accuracy measures of the existing digital maps are all point-based. The biggest drawback of point-based approach is that it cannot scale to large road network system in that these approaches using the point-to-point comparison are too slow and limited. They use limited number of reference points and compare these predefined reference points to limited number of field data points. There are three problems in evaluating digital roadmap. First, the road network system is actually a line segment dataset instead of point dataset. The approach of using line segment as basic evaluating data object is the natural extension to the feature of road networks. In our framework, a line segment based evaluation approach has been proposed. Second, in point based approach, data points are collected for fixed reference points. Thus it is very hard to take large number of sampling reference points. However, road network consists of millions number of road segments. The more sampling points have been collected, the more accurate the digital map analysis is. Finally, limited sampling approach and limited sampling points impose huge limit on the scalability of these approaches.

| Evaluation Tool | Gold Standard | Accuracy Measure | Map Data | Positional Error |
|---|---|---|---|---|
| **Authors' Approach** | GPS | Buffer Based | Mn/DOT Basemap, | **Test routes in Mn/DOT basemap 90th percentile for limited access highway is 50 ft (18.3 m).** |
| Vendor X | Land Survey | Point Based | Vendor X File | Conform to NMAS (90th percentile error 12.2-51m) |
| Navtech | Land Survey | Point Based | Navtech File (Urban Area, Other Area) | 97% Accuracy (includes attribute errors; no positional accuracy specified) |
| TIGER | GPS | Point Based | TIGER File | 90th percentile error = 360.8 to 1312 ft (110m to 400m) |

Table 7.1 Comparison of Digital Map Assessment and our Approach

In the following chapters, we will discuss our proposed approach in more detail.

# Chapter 8
# Field Test Site Selection

It is difficult for GPS to distinguish patterns of roads located close together in large road networks. Close road patterns in large road networks are hard to be distinguished by GPS when error exists in the underlying digital road map. For a road user charge system to work correctly and fairly, the system must be able to distinguish not only the roads far away from each other but also the roads very close to each other. We formalize the "close road" pattern as a co-location pattern. A high co-location pattern means that two or more types of roads are too close to be distinguished by GPS in face of errors in a digital road map. Our co-location discovery approach can be used to find the co-location patterns in digital road maps. These discovered co-location patterns were used to select the field test sites.

In this chapter, we developed a line string co-location miner to find co-location patterns by road types in a dense road networks (e.g. Twin Cities metropolitan area) and selected the test routes according to the co-location miner output.

## *8.1 Co-location Miner and the Proposed Five Test Routes*

### 8.1.1 Association Rules and the Co-location Rule Problem

Association rule finding [II-8, II-9, II-10] is an important data mining technique which has helped retailers interested in finding items frequently bought together to make store arrangements, plan catalogs, and promote products together. The co-location rule [II-7] is a special case of the association rule problem. It is developed to handle spatial binary point datasets that reside in underlying continuous spatial context.

### 8.1.2 Our Proposed Co-location Miner For Line Strings (CoMineLS)

In road networks, the most concern is about the closeness of a set of line segments belonging to one road type to the set of line segments belonging to other road types. We extended point-based co-location approach to support the line string co-location pattern discovery in road networks. We developed a co-location mining method that is based on buffer computation to identify close road-pairs in a road map. This method is a special case of the co-location mining approach because it only finds close road pairs and handles the line strings in road networks.

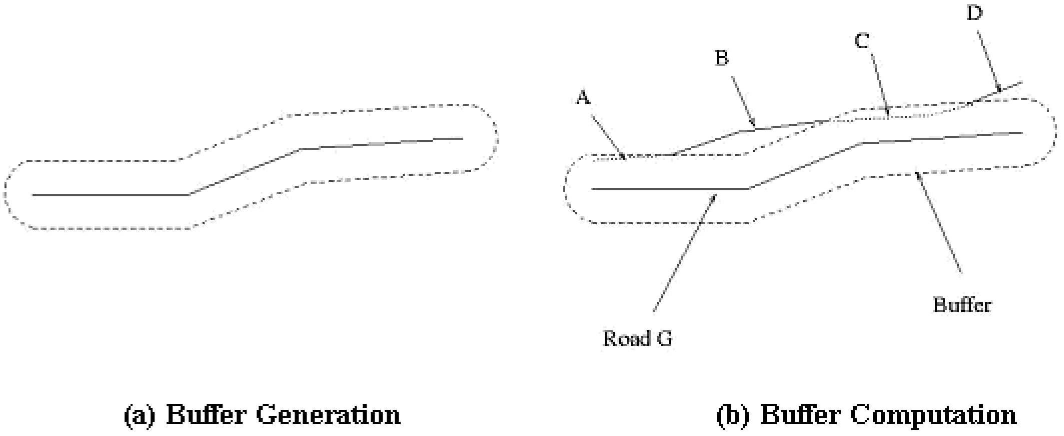
We first introduce buffer computation. Then we define a new interest measure (e.g. co-location ratio) to show the closeness of two line segment sets. Finally we design Co-location Miner for Line Strings (CoMineLS) algorithm.

### 8.1.2.1 **Definition of Buffer Computation**

Buffering is an important analysis technique that is used to constrain the space around individual land features. It combines spatial data query techniques and cartographic modeling. It is generally used for defining all of the spaces within a certain distance of a type of feature, or a subset of features that are selected according to an attribute value. Points, lines and polygons can be buffered, as well as raster pixels or groups of pixels. Conceptually, the buffer operator is a generic GIS tool. Lines can be buffered to one side or the other as well as equal distances (right, left, and full buffers) on both sides of the line, while polygons can have an inside buffer or an outside buffer in addition to buffers on both sides of the polygon boundary.

Figure 8.1 (a) shows a buffer created around a geospatial object polyline. The solid line is the polyline used to create the buffer. The dashed line is the created buffer around this polyline. Figure 8.1 (b) shows how we can use this buffer operation to calculate the co-location ratio. In line string co-location ratio calculation, the digital map dataset has been divided into two sub-datasets. One is for the specified or analyzed road type that includes road segments A, B, C, and D in Figure 8.1(b). The other is for other road types that include road segments G in Figure 8.1 (b). A buffer is generated around the segments belonging to other road types, e.g., road G in Figure 8.1 (b). The ratio of the road length of a specified road type that falls into the buffer to the total length of the specified road type has been calculated as a line string co-location ratio.

It is important to emphasize that a buffer is a two-sided term, i.e., when we discuss a buffer of +/- 40 ft (12.2m), it means that the error of that road type is +/- 40 ft (12.2m).



**(a) Buffer Generation** **(b) Buffer Computation**

Figure 8.1 Illustration of Buffer Computation

### 8.1.2.2 **Line String Co-location Ratio**

The line string co-location ratio is defined to capture the closeness of a line segment dataset to another line segment dataset with a specified buffer size. It is the portion of road belonging to road type A that is co-located with road type B with the specified buffer size.

The line string co-location ratio is defined as follows.

- **line string co-location ratio (Road-Type, Buffer-Size)** = (Length of road of Road-Type within Buffer of all other types of roads) / (Total length of road of Road-Type)

(We will use the term "co-location ratio" for "line string co-location ratio" in the late part of the report.)

#### 8.1.2.3 **Problem Definition of Co-location Mining for Line Strings**

We gave the formal problem definition of the co-location mining for line strings.

**Given:**

- A digital dataset of a roadmap
- A buffer size
- A road type

**Find:**

- Close road-pairs and co-location ratio for different road types in a roadmap satisfying a given buffer size.

**Objective:**

- **Completeness**: An algorithm is complete if it finds all close road-pairs in a roadmap with one road segment falling into the buffer generated around another road segment with a user specified buffer size.
- **Correctness**: An algorithm is correct if it finds all road pairs with one road segment falling into the buffer generated around another road segment with user specified buffer size.
- **Computational efficiency**: The I/O and CPU costs to identify close road-pairs should be acceptable.

#### 8.1.2.4 **Co-location Miner for Line Strings (CoMineLS) Algorithm**

There are two steps involved in CoMineLS:

- Coarse Filter Search
- Fine Filter Search

In CoMineLS, digital map dataset is partitioned into two sub datasets. One dataset, S1, belongs to the specified road type. The other dataset, S2, which is used to generate buffers belongs to other road types. A quad tree index is generated on buffers generated around line segments in dataset S2. A coarse filter is used to search the Minimum Bounding Box (MBB) of a given line segment based on the quad tree index. After the bounding box is found, a brute force search is used to compute the intersection of the give line segment with all buffers in the bounding box one by one in a refinement step. Then we calculate the length of intersected line segments and total length of line segments for specified road type. Finally, the co-location ratio is calculated and output.

### 8.1.3 Co-location Patterns for Basemap Data in the Core Twin Cities Metropolitan Area

We input the Mn/DOT basemap data into our CoMineLS program to find the co-location patterns in the Twin Cities metropolitan area. Figure 8.2 shows the co-location pattern in a core Twin Cities metropolitan area with buffer size of 30 ft (9.1 m). Clustered dark line segments indicate the many road segments that are co-located closely. After carefully studying co-location patterns, we found that most co-location patterns are around highway segments. In other words, around highway routes, we might have more errors than other areas because the routes are too close to be distinguished by map maker or other map making tools. Thus we selected our test routes around the highway areas in which the co-location patterns are concentrated.

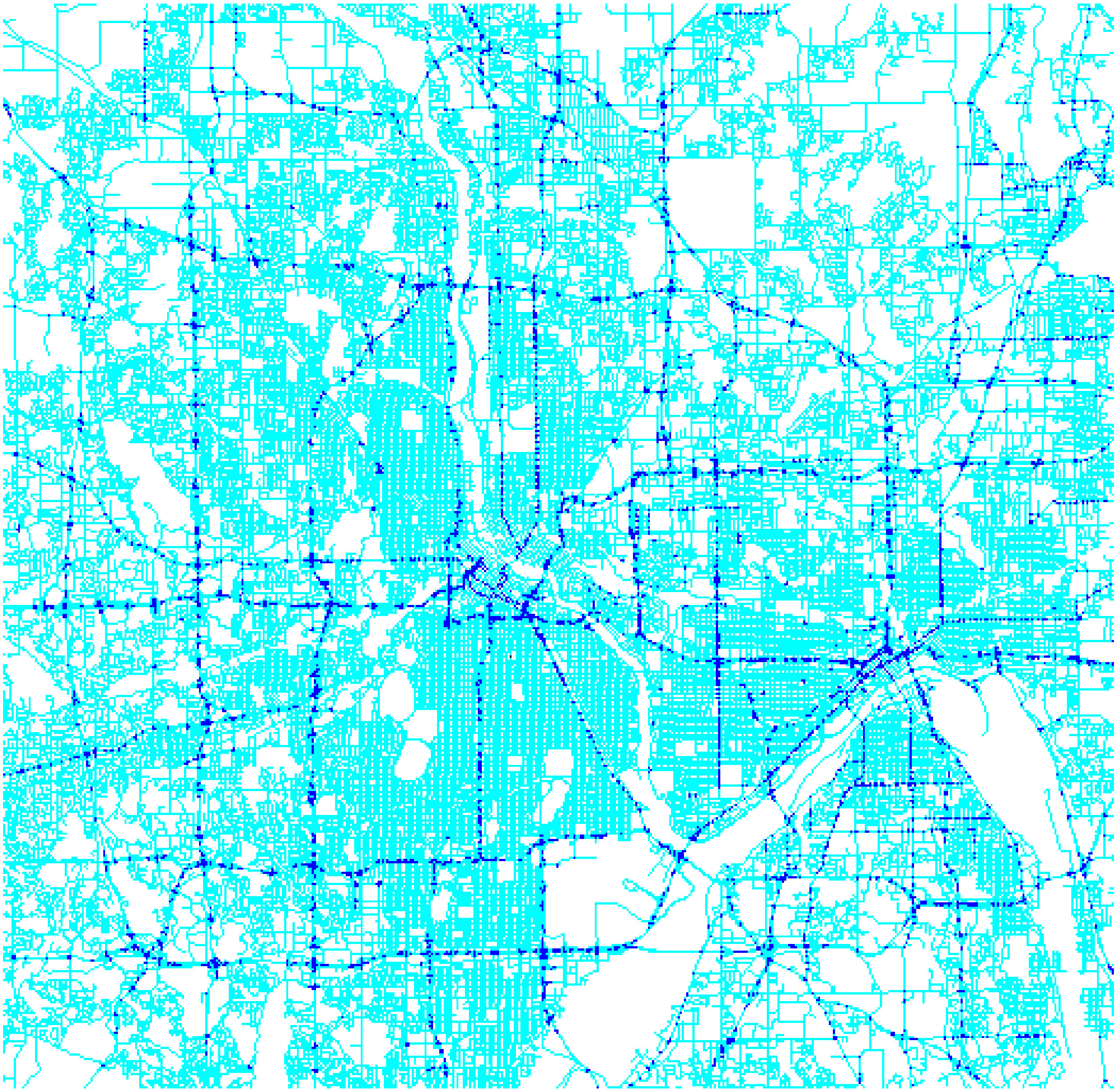


Figure 8.2 Co-location Patterns For Basemap Data in the core Twin Cities Metropolitan area

### 8.1.4 Five Proposed Routes

We proposed five field test routes to collect GPS data. These five routes covered most of the area with many co-located road segments in the core Twin Cities metropolitan area.
Figure 8.3 illustrates our proposed field test route 1. (Please refer to Appendix B for other four proposed test routes)

We selected the roads with many co-location patterns to the west of Minneapolis, e.g. US169(south) ⇒ I394(east) ⇒ 100(south) ⇒ 62(east) ⇒ I35W(north). Along each highway, there are two or more roads that are close. Thus we can conduct field road tests to collect GPS data to assess the GPS receiver's quality and determine the errors in the digital road map.

When we carried out the field test for these five test routes, we collected GPS data not only from the highway route illustrated above, but also collected data on the local routes along these highway routes. This way, we covered all road types in the core Twin Cities metropolitan area.

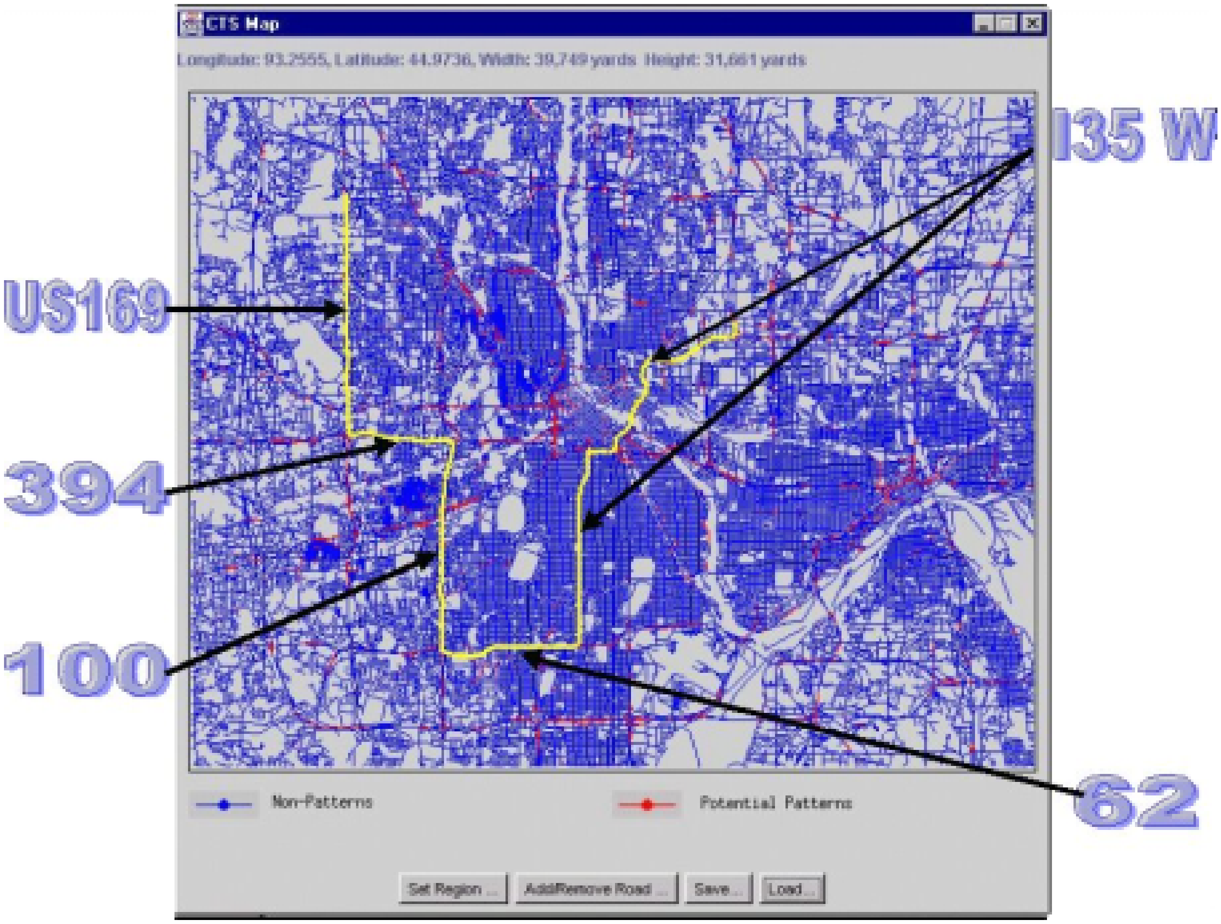

Longitude: 93.2555, Latitude: 44.9736, Width: 39,749 yards Height: 31,661 yards

Figure 8.3 Selected Test Route1

## *8.2 Co-location Pattern Statistics for Digital Maps*

We calculated the co-location ratio for each road type in the Twin Cities metropolitan with vendor X map and Mn/DOT basemap.

The co-location ratio of different road types for the vendor X digital map is shown in Figure 8.4 in which the Xtype means map X road type (refer to appendix A for the definition of the road types). The ratio is computed with buffer size 20, 30, 40, 50, 60 and 100 ft (6.1, 9.1, 12.2, 15.2, 18.3 and 30.5 m), using the definition of the line string co-location ratio introduced in Section 8.1.2. As can be seen, the co-location ratio goes up as the buffer size is increased. Vendor X road type 1 (Interstate highway, US highway or other limited access highway) and type 9 (low speed ramp) have bigger co-location ratios than the other road types.

Table 8.1 illustrates the total road length of the map X analyzed by map X road types, and co-location ratio for 50 ft and 100 ft (15.2 and 30.5 m). (CR means Co-location Ratio and CL means co-location Length (in miles), which is the length of road of specified road type within buffer of all other types of roads).

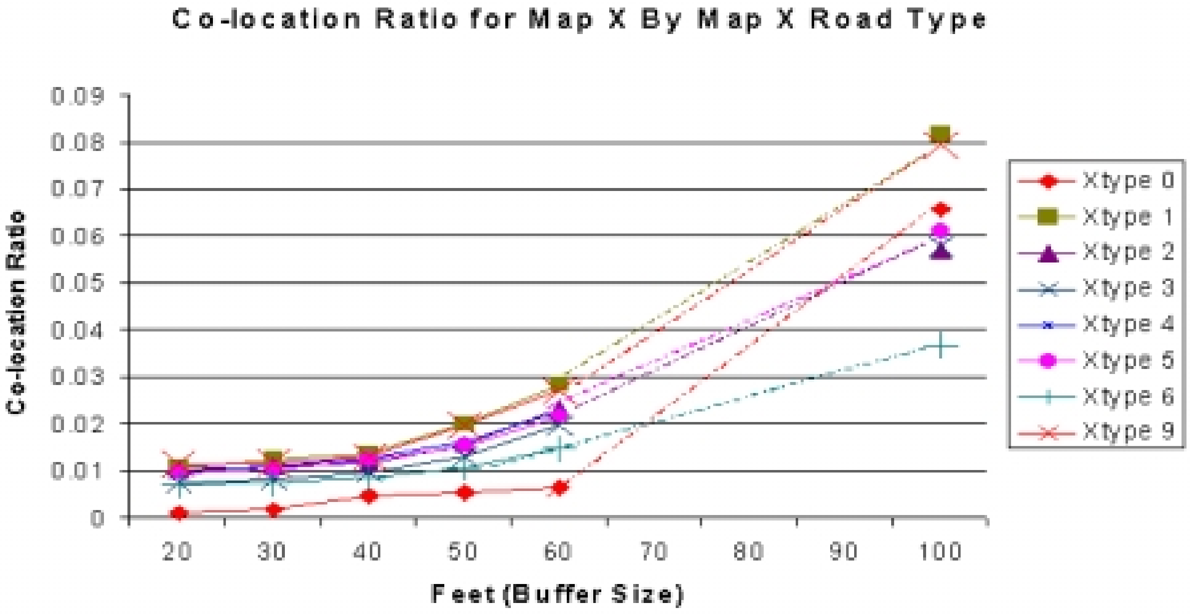


Figure 8.4 Co-location Ratio for Different Road Types in Map X

| Xtype | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 9 |
|---|---|---|---|---|---|---|---|---|
| length (miles) | **26.6** | **546.9** | **575.0** | **1980.2** | **2059.7** | **10456.4** | **1318.6** | **203.1** |
| 50 ft CR (%) | 0.55 | 1.99 | 1.6 | 1.3 | 1.6 | 1.5 | 1.1 | 1.98 |
| 50 ft CL (miles) | **0.2** | **11.2** | **9.2** | **25.7** | **33.0** | **156.9** | **14.5** | **4.0** |
| 100 ft CR (%) | 6.6 | 8.2 | 5.7 | 5.8 | 6.0 | 6.1 | 3.7 | 7.9 |
| 100 ft CL (miles) | **1.8** | **44.9** | **32.8** | **114.9** | **123.6** | **637.8** | **48.8** | **16.0** |

Table 8.1 Road Length and Co-location Result with Buffer Size 50 and 100 ft (15.2 and 30.5 m) in Map X

Figure 8.5 illustrates the co-location distance distribution for the road type 1 (Interstate highway, US highway or other limited access highway) in the map X. The co-location ratio with buffer size of 100 ft (30.5 m) for map X road type 1 (Interstate, US hwy or other limited access state hwy) is about 8%. In other words, 8% of the road length of road type 1 falls into the buffer generated around other road types with buffer size of 100 ft (30.5 m).

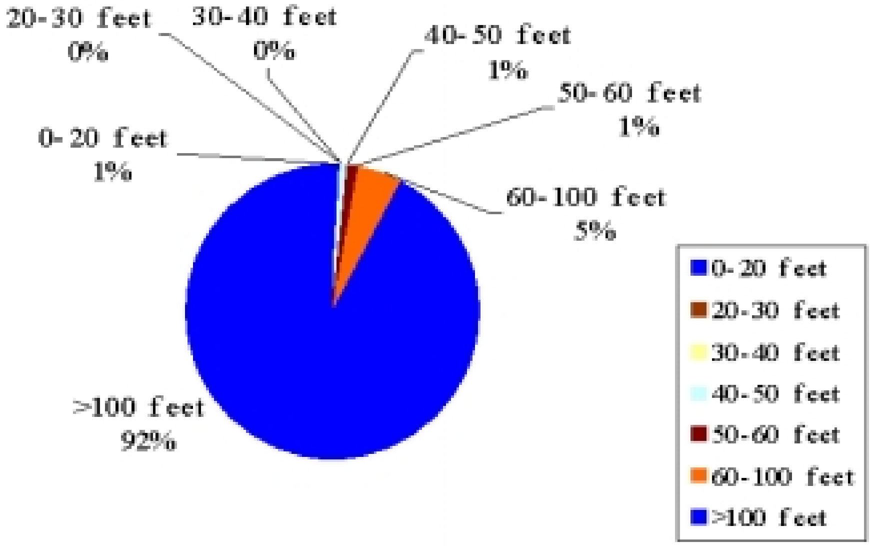


Figure 8.5 Co-location Distance Distribution for map X Road Type 1

Figure 8.6 shows the co-location ratio of different basemap road types that are called Btypes for the Mn/DOT basemap (Please refer to Appendix A for road type definitions). The ratio is also computed with buffer size 20, 30, 40, 50, 60 and 100 ft (6.1, 9.1, 12.2, 15.2, 18.3 and 30.5 m), using the definition of line string co-location ratio introduced in previous sub section. As can be seen, Basemap road type 22 (connector) and type 1 (Interstate highway) have higher co-location ratios. When the buffer size is 100 ft (30.5 m), they are about 32% and 20% respectively. The co-location ratio goes up as the buffer size is increased. The basemap type 2 and 3 have 100 ft (30.5 m) co-location ratios of about 11%. When the buffer size is 50 ft (15.2 m), basemap road type 1 (Interstates Highway) has a co-location ratio of about 5%.

This Figure shows how the co-location patterns are affected by the buffer sizes. The co-location ratio increases as the buffer sizes increase. Another apparent characteristic is that the co-location ratio for road type 21 is greater than for others. In the Mn/DOT basemap definition, road type 21 is state game preserve road. This means that the state game preserve roads are very close to some other kind of roads in the Mn/DOT digital map.

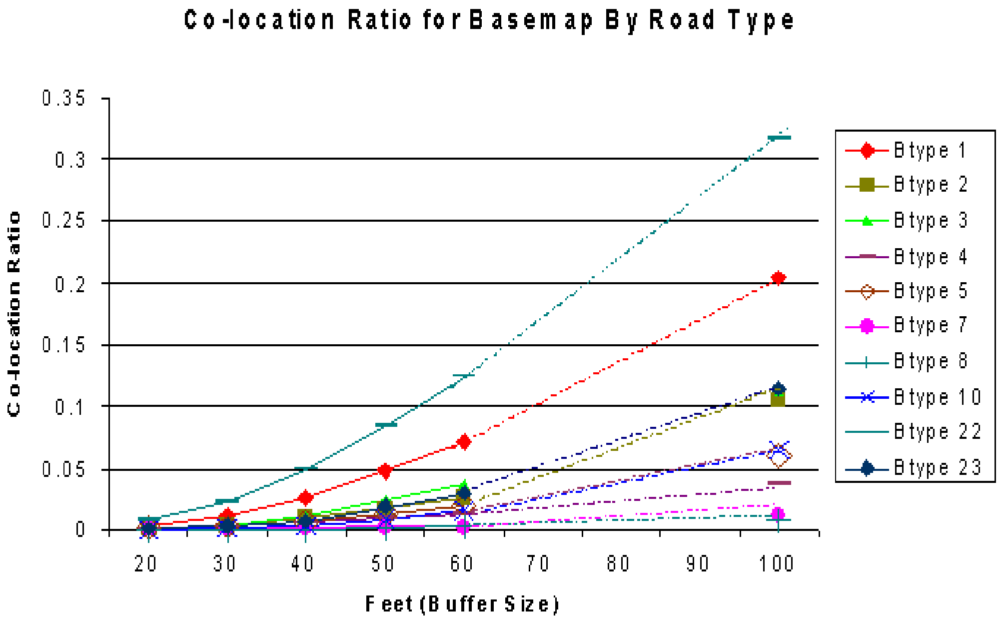


Figure 8.6 Co-location Ratio for Different Road Types in Mn/DOT Basemap

Table 8.2 illustrates the total road length of the basemap analyzed by basemap road types and co-location ratio for 50 ft and 100 ft (15.2 and 30.5 m). (CR means Co-location Ratio and CL means co-location Length (in miles)). The road length of basemap type 22 is 517 miles (832 km) and the road length of basemap type 1 is 458 miles (737 km). They are relatively short segments compared to the dominant types (e.g., the road length of basemap type 10, Municipal Streets, is 12,054 miles (19359 km)).

| Type | 1 | 2 | 3 | 4 | 5 | 7 | 8 | 10 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|
| Length (miles) | **457.5** | **450.5** | **1063.2** | **3409.2** | **2566.7** | **1087.5** | **2815.0** | **12053.9** | **517.3** | **20.0** |
| 50 ft CR (%) | 4.8 | 1.7 | 2.4 | 0.9 | 1.3 | 0.18 | 0.12 | 0.83 | 0.84 | 0.84 |
| 50 ft CL (miles) | **22.0** | **7.7** | **25.5** | **30.7** | **33.4** | **2.0** | **3.4** | **100.0** | **4.4** | **0.02** |
| 100 ft CR (%) | 20.4 | 10.5 | 11.2 | 3.7 | 6.0 | 1.1 | 0.9 | 6.6 | 31.8 | 11.4 |
| 100 ft CL (miles) | **93.3** | **47.3** | **119.1** | **126.1** | **154.0** | **12.0** | **25.3** | **795.6** | **164.5** | **2.3** |

Table 8.2 Road Length and Co-location Result with Buffer Size 50 and 100 ft (15.2 and 30.5 m) in Basemap

Figure 8.7 displays the co-location distance distribution for the basemap road type 1 (Interstate highway). The co-location ratio for 100 ft (30.5 m) for road type 1 (Interstate) is about 20%. In other words, 20% of the road length of road type 1 falls into the buffer generated around other road types with buffer size 100 ft (30.5 m).

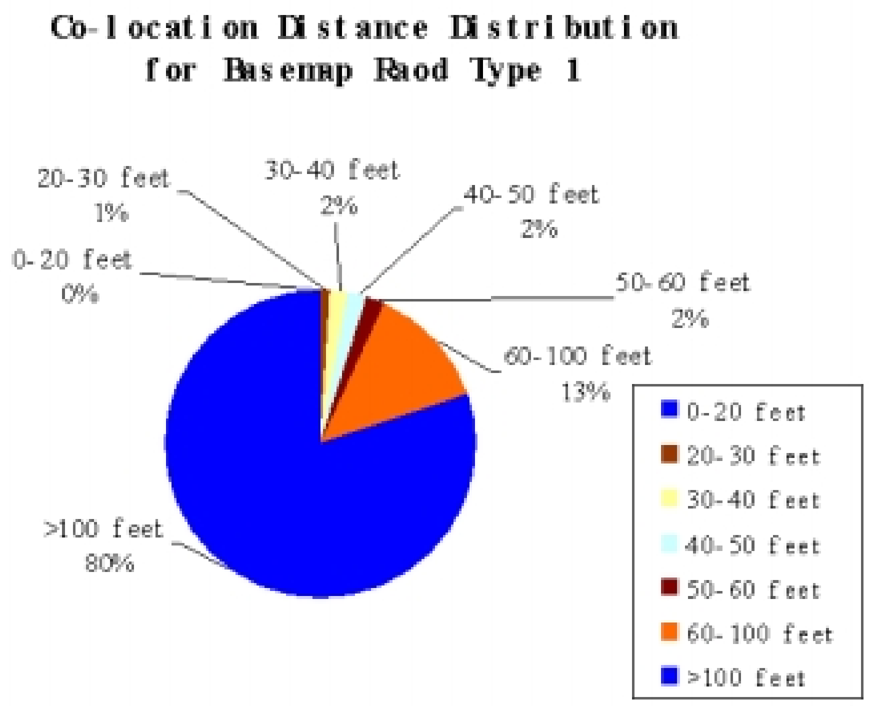


Figure 8.7 Co-location Distance Distribution for Basemap Road Type 1

Figure 8.8 shows the co-location distance distribution for the basemap road type 2 (US highway). The co-location ratio for 100 ft (30.5 m) for road type 2 (US highway) is about 11%. In other words, 11% of road length of road type 2 falls into the buffer generated around other road types with buffer size 100 ft (30.5 m).

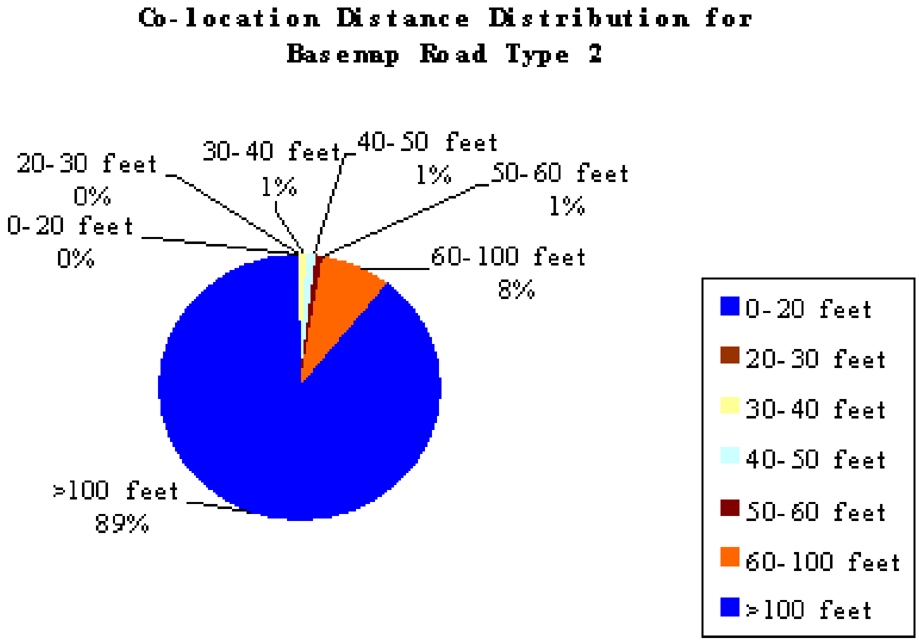


Figure 8.8 Co-location Distance Distribution for Basemap Road Type 2

Figure 8.9 illustrates the co-location distance distribution for the basemap road type 3 (MN highway). The co-location ratio for 100 ft (30.5 m) for basemap road type 3 (MN highway) is about 11%. In other words, 11% road length of road type 3 falls into the buffer generated around other road types with buffer size 100 ft (30.5 m).

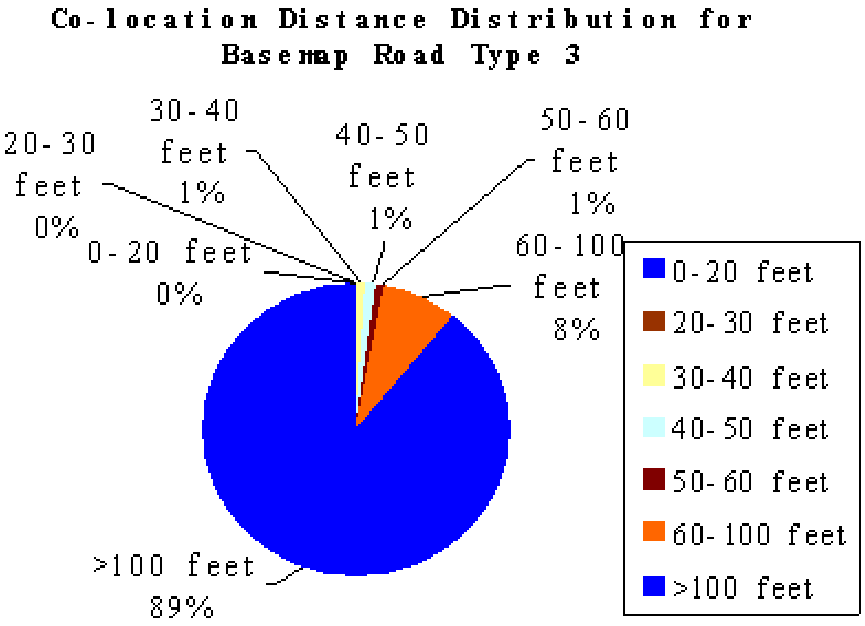


Figure 8.9 Co-location Distance Distribution for Basemap Road Type 3

Basemap road type 1 (Interstate hwy) has more roads co-located with other basemap road types within 100 ft (30.5 m) (20%) than basemap road type 2 (US Trunk hwy) (11%) and road type 3 (MN highway) (11%).

From the discussion above, we found a relatively large part of the metro area highways have higher co-location (with other roads) than was believed (20 % for basemap road type 1, 11% for basemap road type 2, and 11% for basemap road type 3), which will very much affect the understanding of final map accuracy results. For example, if we found that there was a 20% co-location ratio for road type x at 50 ft (15.2 m), and we found that 80% of road type x was within +/- 50 ft (15.2 m) from its true position, then this is “bad” news about road type x for the road user charging system, especially if road type x is the type of road that we need to charge for. We cannot have 20% of the roads misclassified. Thus the co-location ratios for different road types are very important for our field test route selection.

# Chapter 9
# Digital Map Accuracy Evaluation

In this chapter, we analyze the quality, especially the positional accuracy, of some given digital maps. First we discuss the data quality of digital maps. Then we give the definition and format of GPS road track information. Third, we analyze the formats of the different digital maps, commercial digital map from vendor X and the Mn/DOT basemap. Finally, we analyze the positional accuracy of these digital maps, using buffer analysis method in the Arc/Info software package.

## *9.1 Data Quality of Digital Maps*

Data quality refers to the relative accuracy and precision of a particular GIS database. These facts are often documented in a data quality report as a part of metadata. The data of digital maps is a type of geospatial data. The purpose of a geospatial data quality report is to provide detailed information for a user to evaluate the fitness of geospatial data for a particular use. To provide a data quality report based on a geospatial data standard, a digital data producer must include the most rigorous and quantitative information available on the components of data quality. Data quality is a part of the geospatial metadata defined by the Federal Geographic Data committee (FGDC) [II-6].

### 9.1.1 Metadata Standard

The metadata standard documents the content, quality, condition, and other characteristics of data so that geospatial digital data users can evaluate the fitness of the data for their particular purpose. There are three major uses of metadata [II-11]:

- To help organize and maintain an organization's internal investment in spatial data
- To provide information about an organization's data holdings to data catalogues, clearinghouses, and brokerages
- To provide information to process and interpret data received through a transfer from an external source

This standard provides a common set of terminology and definitions for the documentation of spatial data, which include identification information, data quality information, spatial data organization information, spatial reference information, entity and attribute information, distribution information and metadata reference information.

### 9.1.2 Data Quality Information

The part of spatial metadata that is related to data quality provides an assessment of the quality of spatial dataset. Historically, positional accuracy has been considered as the main issue in map accuracy. With the development of spatial data understanding, more and more map accuracy standards have been proposed. Here we focus on the important standard related to spatial data, the Spatial Data Transfer Standard [II-12].

**Spatial Data Transfer Standard (SDTS):** SDTS is a standard that defines a non-proprietary format for packaging vector or raster spatial data with attributes, metadata, a data quality report and usually a data dictionary. SDTS is primarily intended to be used for spatial data product distribution and archiving. The format and structure of a SDTS file set are designed to enable blind transfer of information between different hardware/software environments without loss of contextual information [II-12]. The Data Quality Report of SDTS consists of five portions that are covering lineage, positional accuracy, attribute accuracy, logical consistency, and completeness.

The quality report can be issued as a paper document or encoded on computer-compatible media in the form prescribed by this Standard. Since the quality report will function in the assessment of fitness for use, it shall be obtainable separately from the actual data. The digital data transmission may contain a quality report, in whole or in part, but, as a minimum, it must contain a reference to the quality report and how to obtain it.

## *9.2 Format of Digital Maps*

We planed to evaluate two digital maps, the commercially available map X and the publicly available Mn/DOT basemap. The map X allows us to extract road positional information, and the Mn/DOT map can be readily downloaded. Both maps are widely used. In this section, we introduce the format of these two digital maps in order to help readers understand the analysis procedure in the later sections.

### 9.2.1 Format of a Commercial Map

The commercial map we evaluated is the vendor X digital map. We accessed text data files on seven Minnesota counties, namely, Hennepin, Ramsey, Anoka, Washington, Dakota, Carver and Scott. The types of information found for the seven counties in six data files include map data, adjacent information, node records, edges, road information, and road names. The primary data source is seven county data map files containing eight attributes. The attributes for counties include start node id, ending node id, road id, edge class id, longitude of start node, latitude of start node, longitude of end node, and latitude of end node. There are 158087 tuples in this map data file. The data format of all the map files is ANSII text with tab separation. For our evaluation, we need the coordinate information that is in file 7.map. A sample tuple in 7.map is in Table 9.1.

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| 62746978 | 62752372 | 0 | 5 | 93.280937 | 45.205612 | 93.286171 | 45.208675 |

Table 9.1 Example of vendor X Digital Map Data

See Table 9.2 for explanation of each field.

For the purpose of evaluation, we needed to find the corresponding road for a known road name and GPS track, so we needed another file ROADNAMES to map the road name to the road ID. This way, for every road segment, we can readily find the road that this segment belongs to. The format of RAODNAMES file is very simple. The first data field is the road ID and the second data field is the road name.

| Field | Meaning |
|---|---|
| 1 | Endpoint 1 ID |
| 2 | Endpoint 2 ID |
| 3 | Road ID, road means what the segment belongs to |
| 4 | Road type ID |
| 5 | Endpoint 1 longitude |
| 6 | Endpoint 1 latitude |
| 7 | Endpoint 2 longitude |
| 8 | Endpoint 2 latitude |

Table 9.2 Meaning of vendor X Data File 7.map Format

### 9.2.2 Format of the Mn/DOT Basemap

The Mn/DOT basemap can be downloaded from the web page http://rocky.dot.state.mn.us/basemap. We evaluated the map accuracy for the same seven counties. The basemap is stored in a shapefile format that can be read and displayed by Arc/View, Arc/Info and other GIS tools. The shapefile format in most counties is a polyline with measurements that cannot be read by Arc/Info version 7, which is the version we have access to. Therefore we used the Arc/View script program to extract the data, and then read the transformed shapefile and processed it. The attribute fields that we can use for evaluation are described in an attribute table that is available from the basemap web page.

## *9.3 Map Accuracy Analysis*

In this section, we discuss the procedure we followed to evaluate the map accuracy. Basically, we used Arc/Info buffer computation to calculate the ratio of road length that falls into the buffer created around gold standard road data. Because the buffer computation is very time-consuming, this analysis is also very time-consuming. Finally, we also analyzed the accuracy based on a road classification method.

### 9.3.1 Introduction to Buffer Computation and Accuracy Measurement

We used the same buffer computation introduced in Section 8.1.2.1 and illustrated in Figure 8.1. However, the meanings of road segments are different in Figure 8.1 (b). In Figure 8.1 (b), when computing the road map accuracy, road G is the gold standard data with the “correct” value. Road segments A, B, C, and D are the road segments to be evaluated. Our basic assumption is that the error for every point in one segment is uniformly distributed along the line segment. That is to say, from every point on the line, the possible error distance equals the buffer size. Therefore, if we want to evaluate whether some line segment has larger or smaller error distance than some given error distance, we just need to calculate what portion (by length) of a given segment falls into the buffer created around the road segment with the “correct” or “actual” value. To create the “correct” or “actual” value of a road segment, we drove down the road using a highly accurate DGPS, thereby developing a GPS track for that segment as our gold standard. We then could readily calculate the ratio of a road length falling into a buffer to the total length for a given line segment. This reflects our measure of digital map accuracy. Since this approach uses buffer computation generated around a line string (e.g. road G) and measures the accuracy of line strings (e.g. A, B, C, and D), it is a buffer based line string approach to measure digital map accuracy.

### 9.3.2 Our Approaches to Map Accuracy Analysis

We propose two different approaches to evaluate digital map accuracy. First, we use an approach based on a buffer operation to evaluate the positional accuracy of the given digital maps. Second, we use a classification approach to evaluate the map matching accuracy.

#### 9.3.2.1 **Definition of Accuracy**

Accuracy is the degree to which information on a map or in a digital database matches true or accepted values. Accuracy is an issue related to the data quality and the number of errors contained in a dataset or digital maps. In discussing a GIS database or digital road maps, we often consider horizontal and vertical accuracy with respect to geographic position, as well as attribute, conceptual, and logical accuracy. For a road user charge system, it is most important to evaluate the positional accuracy of the digital road map. The level of accuracy required for particular applications varies greatly. In the road user charge system, we require a highly accurate digital road map. In this discussion, we are assuming that the GPS reading taken while driving down a particular lane of a road has been appropriately offset to compensate its offset from the road centerline contained in a digital map.

Formally, the traditional positional accuracy of GIS road map database has two components.

- **Lateral Accuracy:** Perpendicular distance from the GPS reading to the center line of the road in the road map
- **Longitudinal Accuracy:** Horizontal distance from the GPS reading to the corresponding Geodetic point

Figure 9.1 illustrates the lateral accuracy and longitudinal accuracy.

In a road map evaluation system used for a road user charge system, lateral accuracy is more important than longitudinal accuracy since it is critical to distinguish one road from a nearby parallel road. Very often, such roads belong to a different jurisdiction and, as a result, to be categorized differently for charging purposes.

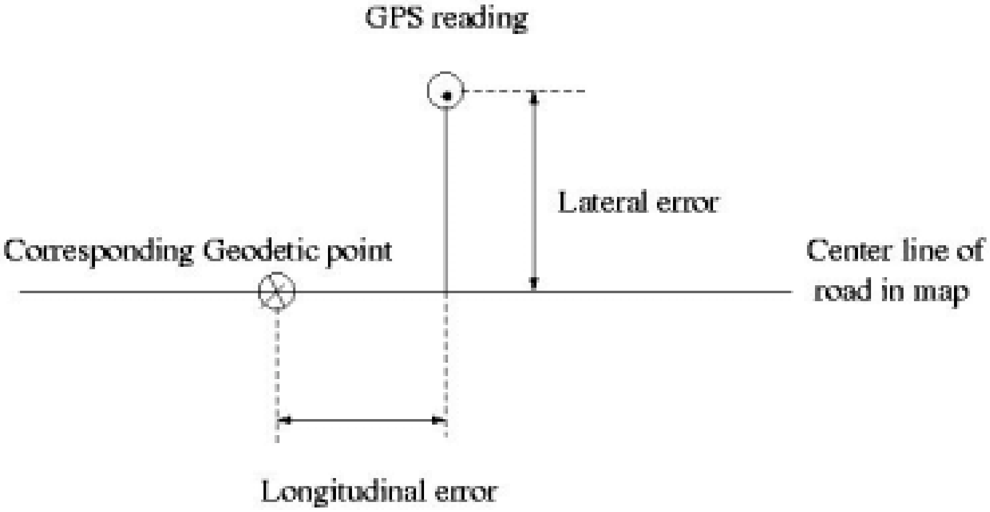


Figure 9.1 Lateral Accuracy and Longitudinal Accuracy

We can also categorize positional accuracy as either point-based or line-string based accuracy. In the point-based approach, we are given pairs of corresponding points on both the road map and the gold standard GPS track file. We then calculate the Root Mean Square (RMS) error between the pairs. Using this approach, we need to decide which point in the GPS track is the corresponding Geodetic point on the digital road map. Then either we need to stop the vehicle around the geodetic point to get a corresponding GPS point or we need to come up with some approximate approach to match a point on the GPS track to a geodetic point. This will introduce more errors. In the line-string based approach, we can use the buffer operation approach that was introduced in Section 9.3.1.

### 9.3.2.2 **Positional Accuracy Evaluation Based on Buffer Operation**

We still use Figure 8.1 (b) as an example to show our computation of positional accuracy. When using the buffer operation to evaluate digital map accuracy, we calculate the ratio $\frac{(len(A)+len(C))}{len(RoadG)}$ as the evaluated digital map accuracy for this road segment. The whole procedure is to add up all the GPS road segments (length L) and at the same time add up all the road segments (length Lb) from the digital map that fall into the buffer. The digital map accuracy then is measured by $\frac{Lb}{L}$. This value actually tells us to what extent the error of the digital map is within a specific error distance bound represented exactly by the buffer size. This buffer-based line string approach actually interpolates GPS readings between any GPS reading points and then evaluates the accuracy of the corresponding line strings or line segments in the digital road map.

### 9.3.2.3 **Accuracy Measurement Definition Based On Buffer Computation**

Using this buffer computation, a new accuracy measurement can be defined.

**Map accuracy ratio** (Gold-std, Buffer-size) =
(Length of Gold-standard road track where evaluated road from the map is within Buffer) /
(Total length of Gold-standard GPS road track)

Buffer size represents the range in which the results are considered accurate: the larger the buffer, the lower the accuracy. On the other hand, with a fixed buffer size, the greater the accuracy ratio value, the higher the accuracy. A greater accuracy ratio value meansthere are longer road segments falling into the buffer generated around the gold standard.

From another point of view, we define incremental error ratio to measure the map accuracy.

**Incremental error ratio** (Gold-std, Buffer-size) =
(Incremental error associated with widening the buffer) /
(Total length of Gold-standard GPS road track)

Incremental error ratio identifies the proportion that each road type contributes to the error.

When we use a GPS signal as the gold standard, we require that the data have higher accuracy. We define and use reliable test data as the GPS gold standard. We chose the RTK (Real Time Kinematic) Fix and RTK Float as “reliable” data. Note here that RTK Fix and RTK Float are the annotations for GPS data quality used in the Trimble MS 750 GPS receiver [II-13]. The error range of RTK Fix is +/- 0.07 ft (0.0 2 m) and the error range of RTK Float is +/- 1.64 ft (0.5 m). These data source are at least an order of magnitude more accurate than common digital maps.

It is very important to filter out only those portions of the GPS track files that meet this condition, as the GPS data collected when the RTK Fix or Float is not achieved is undefined.

**Reliable test data**: GPS road test data with quality RTK Fix or RTK Float

**Reliable test route length**: the route length of reliable test data

### 9.3.2.4 Experimental Design for the Buffer Based Approach

Figure 9.2 shows the experiment design for the accuracy analysis. First, a subset of digital road data in the Twin Cities area was extracted according to the line string co-location miner output as the selected test sites. Then GPS data for these selected test roads has been collected by driving vehicle on these roads. The GPS sampling interval is 0.1 second. In total, five main test routes have been selected in Twin Cities metro area. GPS data (RTK Fix and RTK Float) from Trimble MS 750 GPS receiver has been used as gold standard data. Then, a buffer has been generated around these GPS gold standard data with different buffer sizes. Finally, the ratio of road length for specified roads from digital map that falls into the generated buffer to the total length specified roads of has been calculated as the map accuracy ratio.

**Gold standard data:** We used a Trimble MS 750 GPS receiver to collect GPS road data for selected routes and then selected reliable GPS data whose data quality are RTK Fix and RTK Float as the gold standard. We also transformed the format of the GPS data into the Arc/Info required data structure for generating Arc/Info coverage.

**Map data:** We selected a subset of data from the digital map that corresponds to line segments in GPS gold standard data. The line segments from GPS gold standard data and the line segments from the digital map indicate the same road.

**Buffer size:** We selected different buffer sizes to evaluate the digital map accuracy. That means we assumed different error distances for roads and evaluated how much the length of the selected routes are within this assumed error distances. We expected the ratio to increase as the buffer size is increased.

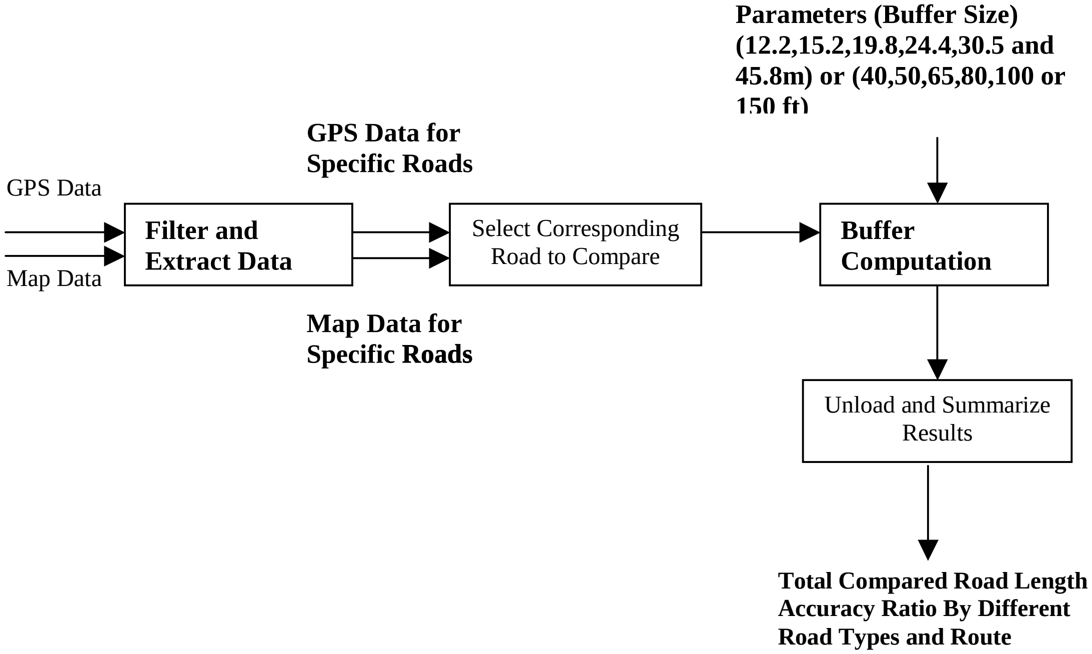


Figure 9.2 Flowchart for Experiment Design

### 9.3.2.5 Evaluation Results and Analysis

#### 9.3.2.5.1 Evaluation of the Map X and Basemap in the Twin Cities Metro Area

We evaluated the commercial digital map X and the Mn/DOT basemap. The results show that using the buffer based approach, the Mn/DOT basemap has a higher accuracy than the vendor X digital map.

Table 3 gives the reliable test road lengths when we considered map X. The data represents some test run drive of at least 1.6 km (1 mile) along all five routes.

In the table, all Interstate highways are map X road type 1. Most US highways and state highways are also map X road type 1. All other local roads belong to map X road types 2, 3, 4, or 5. ) Please refer to Appendix A for map X road type definitions.)

| Xtype | 1 | 2 | 3 | 4 | 5 | Total |
|---|---|---|---|---|---|---|
| km | 144.5 | 8.0 | 8.6 | 14.1 | 17.0 | 192.2 |
| mile | 90.3 | 5.0 | 5.4 | 8.8 | 10.6 | 120.1 |

Table 9.3 Collected GPS Data length Statistics for Map X

Figure 9.3 shows the map X accuracy results from the buffer based approach with buffer size 40, 50, 65, 80, 100, and 150 ft (12.2, 15.2, 19.8, 24.4, 30.5, and 45.7 m). As we expected, the ratio of the road length that falls into the buffer to the total length by road type goes up as the buffer size is increased. This demonstrates that our intuition about the buffer computation and road accuracy based on buffer computation is correct. Another characteristic of this plotted data chart is that the ratios for road types 2 (state highway) and 3 (arterial) are generally greater than others. By analysis, this is also reasonable. In real life, along most of major highways, there are often some local roads such as frontage roads. There are potential errors here because it is easy to mistake highway data for local data or vice versa. They both have higher accuracy. Road type 4 (Collector) and type 5 (Light duty) both have lower accuracy.

With a buffer size of 40 ft (12.2 m), the accuracy ratios for almost all routes are below or around 60%. When the buffer size is increased to 150 ft (45.7 m), the accuracy ratios are all greater than 80%. For map X road type 1 (limited access highway), 35% of map X road type 1 (limited access hwy) has a buffer size of less than 40 ft (12.2 m). Fifteen percent of map X road type 1 (limited access highway) has a buffer size between 40 to 50 ft (12.2 to 15.2 m).

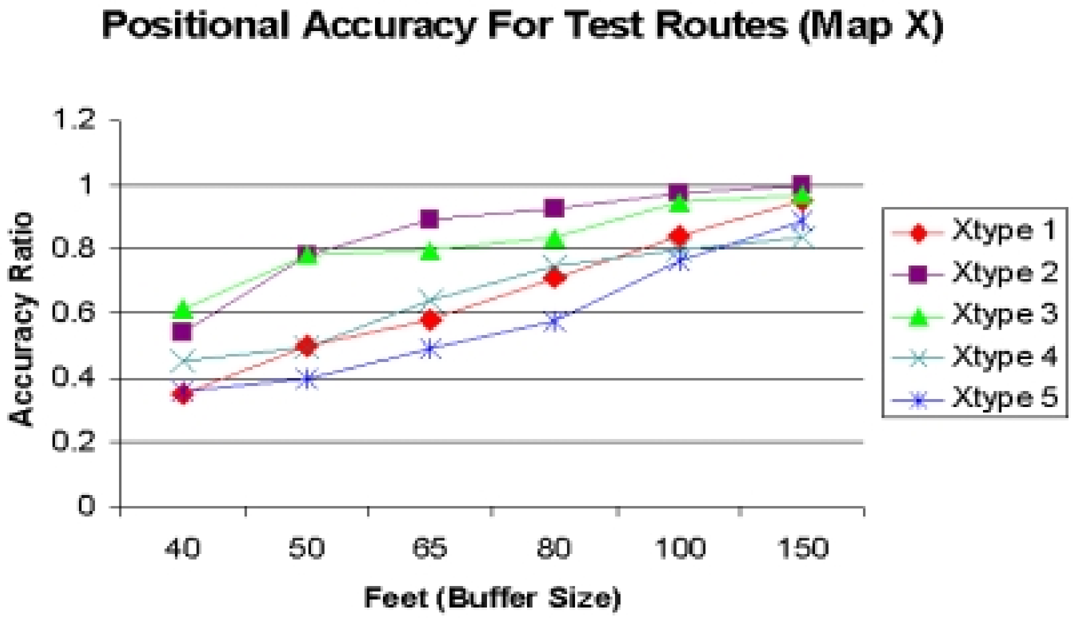


Figure 9.3 Map Accuracy for Vendor X Road Map by Road Types

Figure 9.4 shows the incremental error ratio for all map X road types. In Figure 9.5, the error distribution for map X road type 1 has been shown. 35% of Xtype 1 (limited access highway) incremental error ratio is within 40 ft (12.2 m) range. 15% of Xtype 1 (limited access hwy) incremental error ratio is between 40 to 50 ft (12.2 to 15.2 m) range.

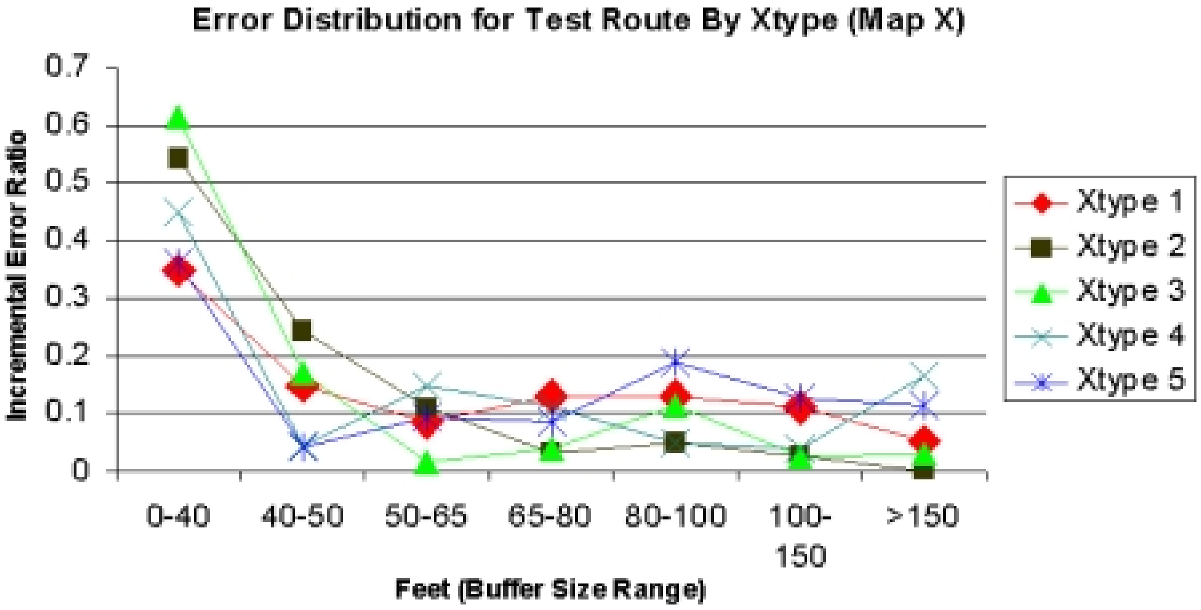


Figure 9.4 Error Distribution for Test Route by Map X Road Types

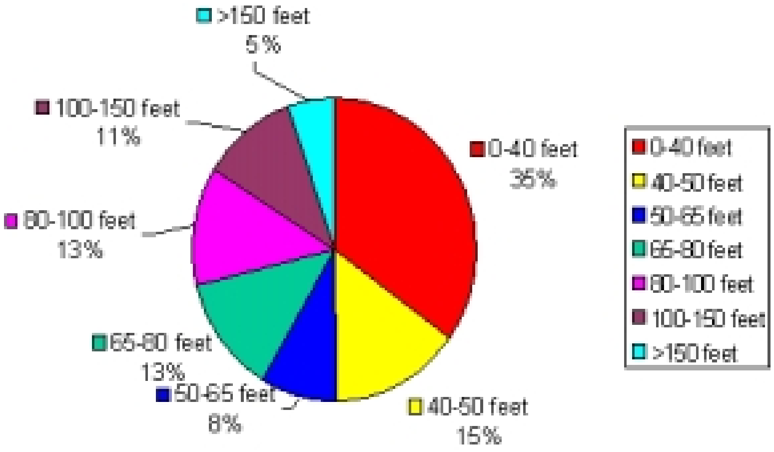


Figure 9.5 Error Distribution for Road XType 1

Figure 9.6 shows the overall error distribution for map X types, not differentiating the map X road types. 38% of incremental error ratio is within 40 ft (12.2 m) range. 14% of incremental error ratio is between 40 to 50 ft (12.2 to 15.2 m ) range. There is similar trend for the incremental error ratio between map X road type 1 and overall map X road types.

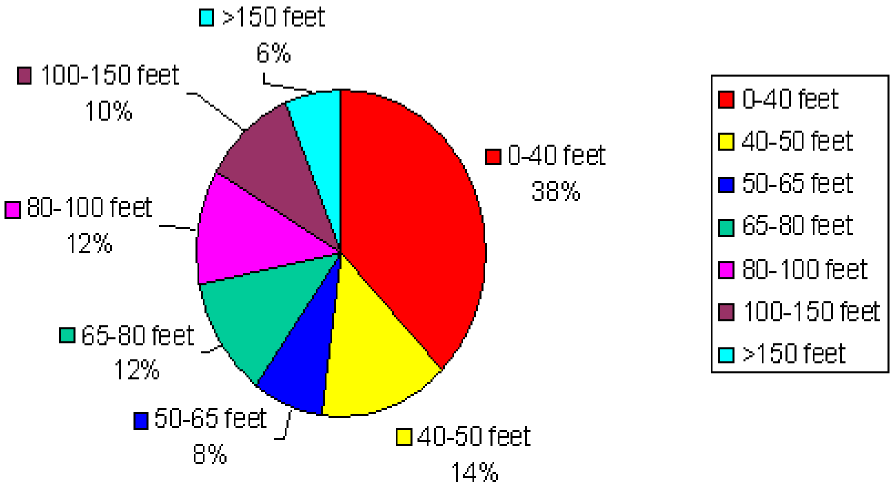


Figure 9.6 Error Distribution for Overall Map X Types

Table 9.4 gives the reliable test road lengths when we consider the Mn/DOT basemap and the estimation of GPS signal points. The data represents one test run drive of at least 1.6 km (1 mile) along all five routes.

| Type | 1 | 2 | 3 | 4 | 5 | 10 | Total |
|---|---|---|---|---|---|---|---|
| km | 103.2 | 24.8 | 46.2 | 16.1 | 13.0 | 21.0 | 225.8 |
| mile | 64.5 | 15.5 | 28.9 | 10.0 | 8.7 | 13.1 | 141.1 |

Table 9.4 Collected GPS Data length Statistics for Basemap

Tested basemap route types are defined by Mn/DOT. Some road type definitions that are used in our sampling and analysis are listed below. For more road type definitions, please refer to appendix A.

- 01 Interstate Trunk Highway
- 02 U.S. Trunk Highway
- 03 Minnesota Trunk Highway
- 04 County State-aid Highway
- 05 Municipal State-aid Street
- 10 Municipal Street

Figure 9.7 shows the Mn/DOT basemap accuracy results from the buffer based approach. Similar to the analysis of the map X, the ratio of the road length that falls into the buffer to the total length by road types goes up as the buffer size is also increased. This again demonstrates that our intuition about the buffer computation and road accuracy based on buffer computation is correct. A very apparent characteristic here is that road type 10, which represents municipal roads, has much lower accuracy. This means the roads in the city have significant errors.

We can also see that the accuracy of basemap becomes very good when the buffer size is greater than 65 ft (19.8 m). The accuracies for all road types are almost about 95% except basemap road type 10. The Mn/DOT basemap has a much higher accuracy than the map X, whose map accuracy for all road types is around 95% only when the buffer size is greater than 150 ft (45.7m).

Figure 9.8 shows the incremental error ratio for all basemap road types. 75%-85% of Btype 1,2 and 3 incremental error ratio is within 40 ft (12.2 m) range. 6%-11% of Btype 1,2 and 3 incremental error ratio is between 40 to 50 ft (12.2 to 15.2 m) range.

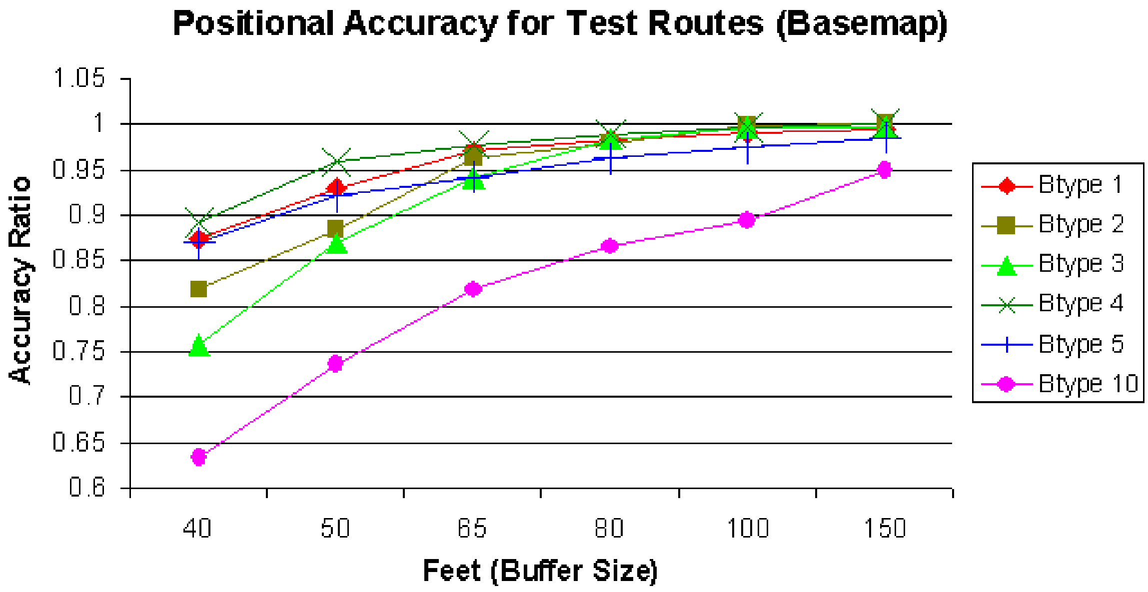


Figure 9.7 Map Accuracy for Basemap Road Map by Road Types in Twin Cities Metropolitan

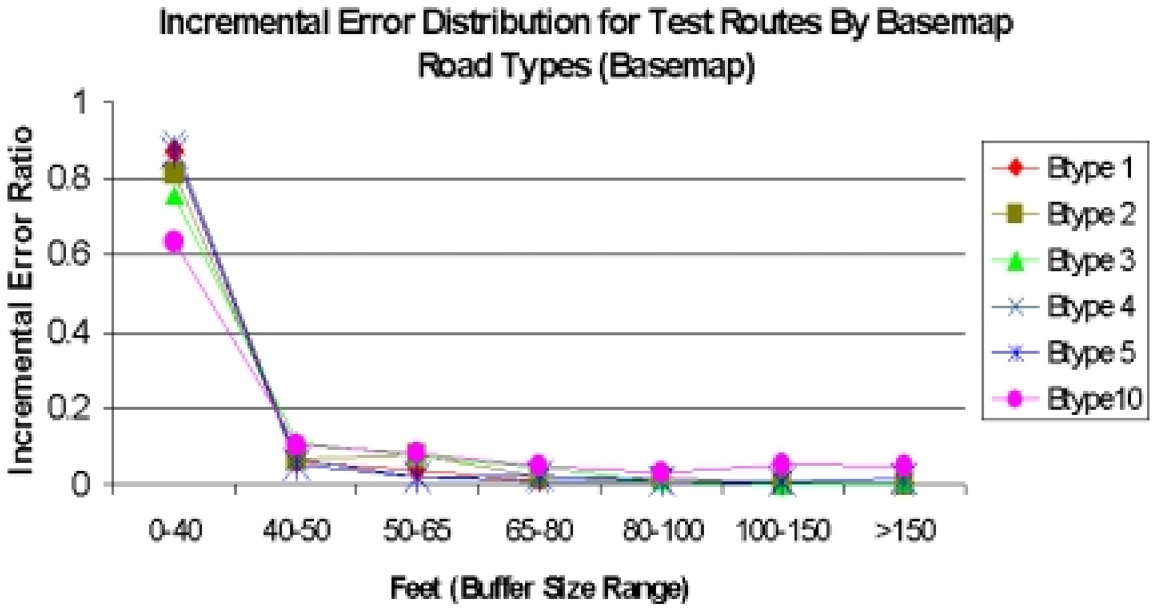


Figure 9.8 Error Distribution for Test Route by Basemap Road Type

In Figure 9.9, the error distribution for basemap road type 1 has been shown. 87% of Btype 1 (Interstate highway) incremental error ratio is within 40 ft (12.2 m) range. 6% of Btype 1 (Interstate highway) incremental error ratio is between 40 to 50 ft (12.2 to 15.2 m) range.

In Figure 9.10, the error distribution for basemap road type 2 has been shown. 81% of Btype 2 (US highway) incremental error ratio is within 40 ft (12.2 m) range. 7% of Btype 1 (US highway) incremental error ratio is between 40 to 50 ft (12.2 to 15.2 m) range.

In Figure 9.11, the error distribution for basemap road type 3 has been shown. 77% of Btype 3 (MN highway) incremental error ratio is within 40 ft (12.2 m) range.11% of Btype 1 (US highway) incremental error ratio is between 40 to 50 ft (12.2 to 15.2 m) range. Compared to Figure 3.9 and 3.10, Btype 3 (MN Highway) incremental error ratio result (77%) is worse than Btype 1 (87%) and Btype 2 (81%).

In Figure 9.12, the error distribution for overall basemap road types has been shown. 83% of overall basemap road types incremental error ratio is within 40 ft (12.2 m) range.7% of overall basemap road types incremental error ratio is between 40 to 50 ft (12.2 to 15.2 m) range.

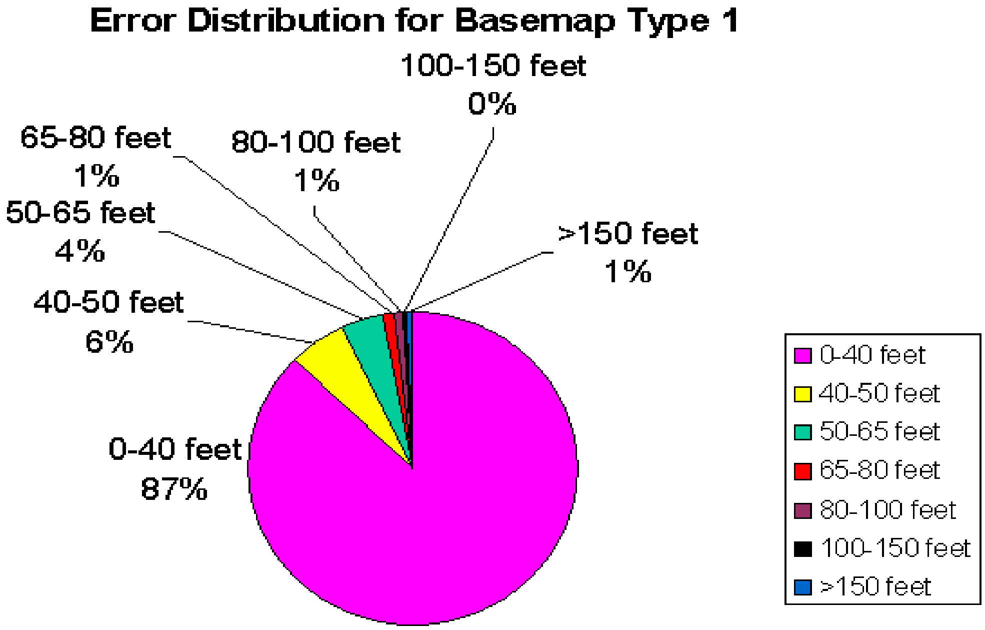


Figure 9.9 Error Distribution for Basemap Type 1

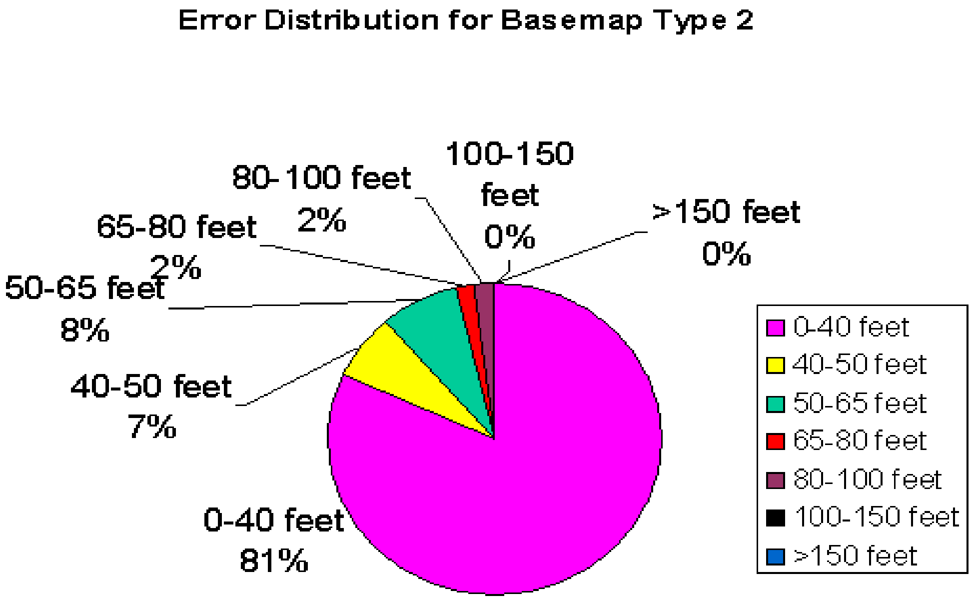


Figure 9.10 Error Distribution for Basemap Type 2

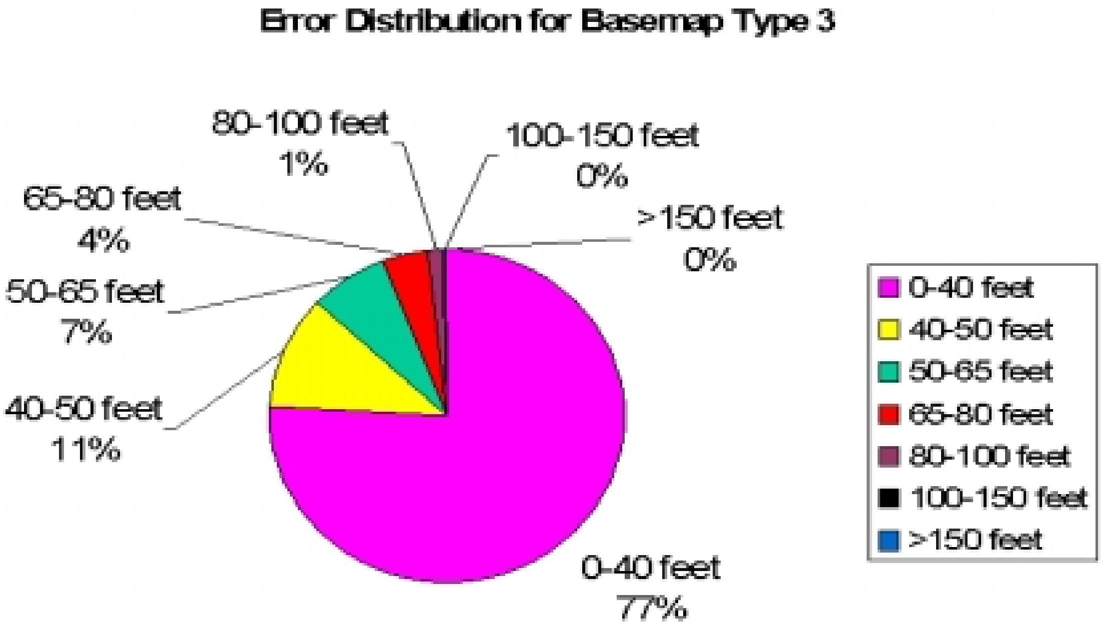


Figure 9.11 Error Distribution for Basemap Type 3

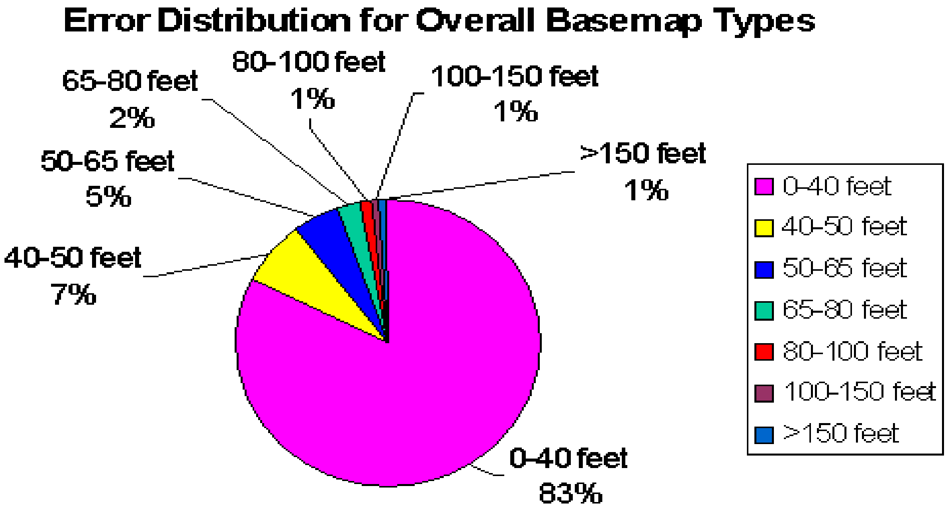


Figure 9.12 Error Distribution for Overall Basemap Types

### 9.3.2.5.2 Evaluation of Basemap in the Hills of Duluth

In order to evaluate digital map accuracy in areas where there are significant elevation changes, we evaluated five GPS field routes in the hilly area of Duluth to collect GPS gold standard track files. These five routes were intentionally picked because they have steep slopes from a higher elevation to a lower elevation. Test routes were selected on roads where the elevation changed dramatically.

By this choice, we hoped to find how elevation affects digital map accuracy.

In this area, we were able to get a more accurate GPS signal than the GPS signal we collected previously in Twin Cities area and the collected data is of very high quality in that most of the GPS data have a data quality RTK fix. Another approach that we used was to combine GPS data from many driving runs into one whole GPS track and use this as the gold standard data in our analysis. Thus it was possible to have more precise and complete data in this analysis than in our previous analysis.

Table 9.5 shows the summarized length of the collected GPS data used in the analysis. Since the total length of driven road is about 16.1 km (10 miles), it provides only weak support for our conclusion later.

Figure 9.13 illustrates the accuracy of the basemap in Duluth. Basemap road type 10 (municipal street) has 100% positional accuracy. But its length is just 0.02 miles. Compared to the positional accuracy in the Twin Cities metropolitan area, the positional accuracies for basemap road types 2, 3, and 5 are higher in Duluth (Rural area) than in the Twin Cities metropolitan area.

| Type | 2 | 3 | 4 | 5 | 10 | Total |
|---|---|---|---|---|---|---|
| km | 2.6 | 4.0 | 2.7 | 6.7 | 0.03 | 16.1 |
| mile | 1.6 | 2.5 | 1.7 | 4.2 | 0.02 | 10.02 |

Table 9.5 Collected GPS Data Length Statistics for Basemap in Duluth

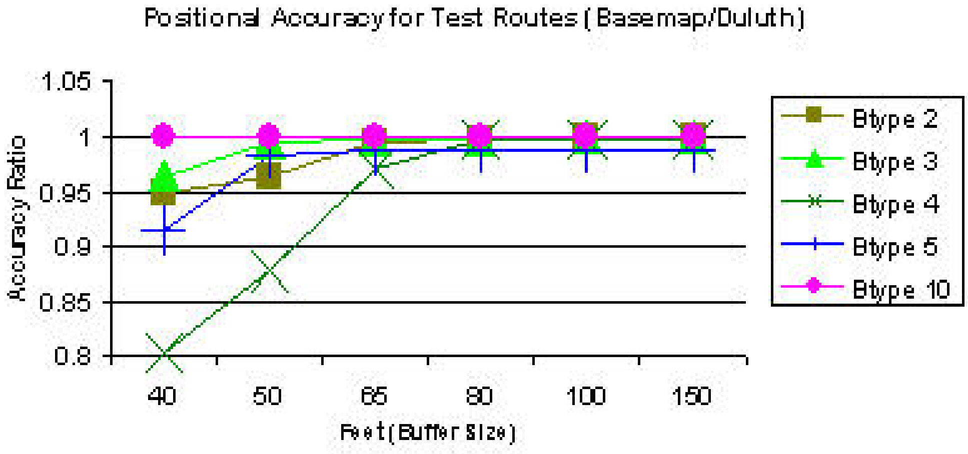


Figure 9.13 Map Accuracy for Basemap Road Map by Road Types in Duluth

### 9.3.2.5.3 Evaluation of City Map in Downtown Minneapolis

In order to evaluate the digital map accuracy in a downtown area, we collected GPS track files in the downtown Minneapolis area to be used as the gold standard data. Because tall building can block GPS signals in downtown area, it can be difficult to get reliable GPS data. As a result, we picked nine test routes that are straight roads in the downtown Minneapolis area. In this way, we ignored the unreliable data and connected all reliable GPS data as the gold standard data.
In the downtown Minneapolis area, an accurate digital map from the City of Minneapolis was obtained. We evaluated the City of Minneapolis downtown digital map in this analysis, using collected downtown Minneapolis GPS data. Our analysis of the downtown digital map showed that the map is quite accurate.

In this area, our selected test routes all belong to basemap road type 10. Because there is no road type definition in the Minneapolis city map, we used basemap road type as the road type for collected Minneapolis downtown GPS data.

The collected GPS data length for Minneapolis city map evaluation is 5.6 mile (9.0 km). Figure 9.14 illustrates the Minneapolis city map accuracy. Basemap road type 10 (municipal street) has a 91.1% positional accuracy at a buffer size of 40 ft (12.2 m). Compared to the positional accuracy of the Mn/DOT basemap for the downtown Minneapolis area, the positional accuracies for the city map road type 10 were better. Possible reason for the higher accuracy in the Minneapolis downtown area is that extra effort was expended to generate a more accurate digital map.

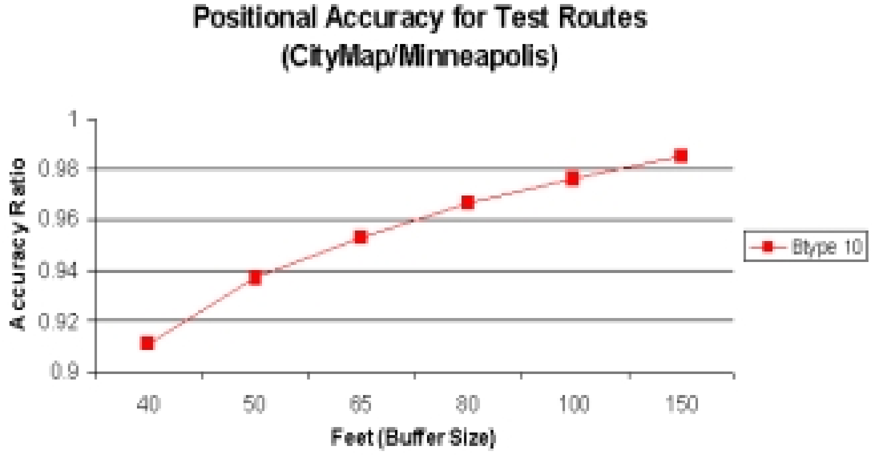


Figure 9.14 Map Accuracy for Minneapolis City Map by Road Type

### 9.3.3 Map matching analysis

A map matching algorithm measures mismatched probability of GPS data and digital road map data. We implemented a simple nearest neighbor search approach for the map matching analysis. This algorithm works as follows:

- For each GPS point, search the nearest neighbor in the digital road map, use the road type of the nearest neighbor as the road type of the GPS point
- For a road segment, if two end points belong to different road types, use a type from one point as the type for the segment. If the two end points belong to the same road type, use this road type as the type for the segment
- Result: the *classified type* of a given segment. For this given segment, we also know the *true type* because we know which road was actually driven

When implementing this approach, only “reliable” data was used as discussed before.

**Definition of map matching ratio**

*Map matching ratio* = Road length of reliable route with correct match between classified type and true type / total reliable test route length

Table 9.6 lists the total GPS sampling data we used in the map matching analysis. As discussed before, most of the data was collected from highway routes. For example, the proportion of sample GPS data from interstate trunk highways is 57.3%.

| Road Type | Definition | Total Length (km/mile) |
|---|---|---|
| 1 | Interstate Trunk Highway | 361.8/226.1 |
| 2 | U.S. Trunk Highway | 59.0/36.9 |
| 3 | Minnesota Trunk Highway | 132.0/82.5 |
| 4 | County State-aid Highway | 17.8/11.1 |
| 5 | Municipal State-aid Street | 17.8/11.1 |
| 10 | Municipal Street | 42.9/26.8 |

Table 9.6 GPS Data Used in Map Matching Algorithm

Table 9.7 displays the total driven route length, the total reliable route length, the total correctly matched road length and the ratio of overall correctly matched road length to total reliable road length.

Figure 9.15 shows a graphic illustration of the comparison of total road length, reliable road length and correctly classified road length by basemap road types.
The map matching result of a single route can be affected by various factors. To make our results more useful, we did field tests on several routes (both highway and local), and for each route, did at least two runs. After getting the classification results for each route, we can calculate the statistical result of road classification accuracy on each road class.

From the output summary result file, we can readily calculate the statistical result for different applications.

| Road Type | 1 | 2 | 3 | 4 | 5 | 10 | Total |
|---|---|---|---|---|---|---|---|
| Total Length (mile) | 361.8/226.1 | 59.0/36.9 | 132.0/82.5 | 17.8/11.1 | 17.8/11.1 | 42.9/26.8 | 631.4/394.6 |
| Reliable Length (mile) | 231.7/144.8 | 42.9/26.8 | 85.1/53.2 | 13.6/8.5 | 12.3/7.7 | 29.1/18.2 | 414.6/259.1 |
| Correctly Matched Length (mile) | 201.9/126.2 | 38.4/24.0 | 71.7/44.8 | 13.0/8.1 | 9.8/6.1 | 25.9/16.2 | 360.8/225.5 |
| Overall Correctly Matched Ratio | 87.2% | 89.6% | 84.2% | 92.3% | 79.2% | 89.0% | 87.0% |

Table 9.7 Road Length Statistics for Map Matching Algorithm

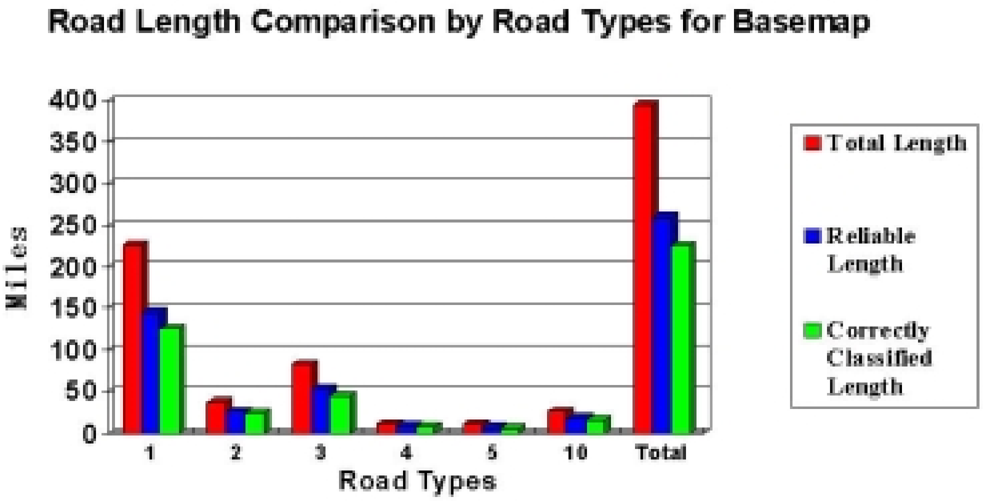


Figure 9.15 Road Length Comparison by Basemap Road Types for Map Matching Algorithm

Figure 9.16 shows the nearest map matching result. Correct map matching ratios for all road types are almost all above 80%. The best map matching ratio is for basemap road type 4 (95.3%), i.e. county State-aid highway. The worst map matching ratio is for basemap road type 5 (79.0%), i.e. Municipal State-aid Street.

We also applied the map matching algorithm on the map X. Figure 9.17 shows the map matching result comparison for map X and basemap. We mapped results of map X road types into results of basemap road types. Basemap and map X have similar trends. Road type 4 (county state-aid highway) has the best map matching accuracy for both datasets. Road type 3 Road (Minnesota Trunk highway) has the worst map matching accuracy. For map X, it is even worse (about 50%). The basemap has a better map matching ratio than map X for all road types and has better overall average map matching accuracy. The map matching ratio for basemap is 87%, while the map matching ratio for map X is 73%.

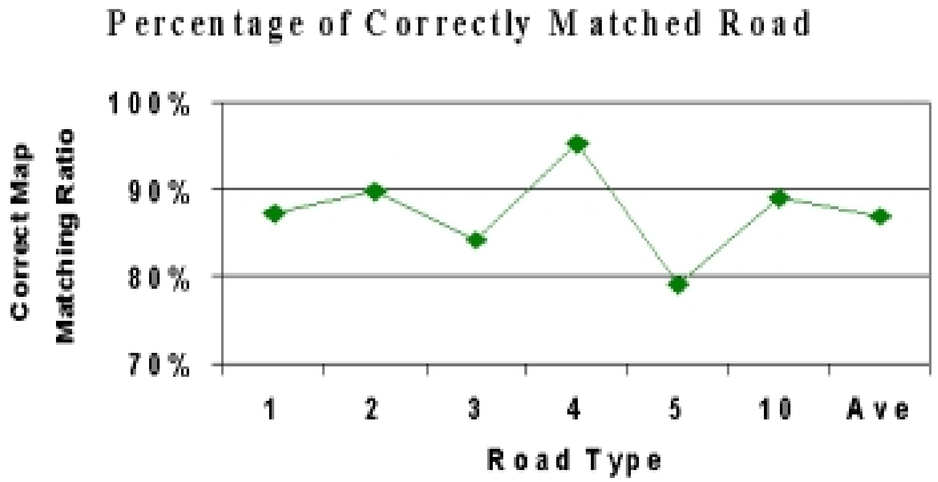


Figure 9.16 Map Matching Accuracy for Basemap

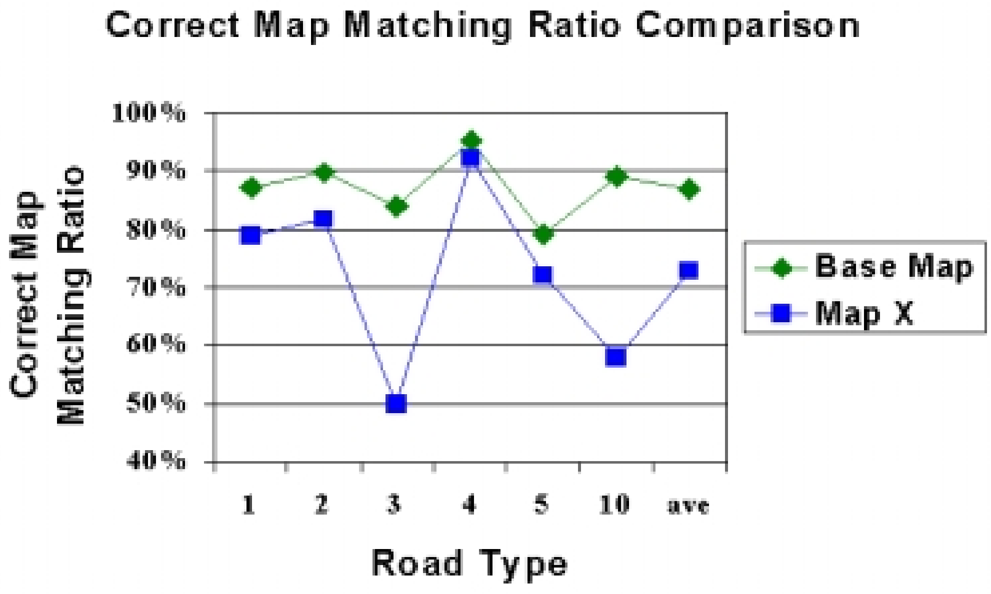


Figure 9.17 Map Matching Result Comparison for Map X and Basemap

# Chapter 10
# Conclusion and Recommendations

The main objective of the digital map portion of this project has been to conduct an analysis of digital map accuracy in order to recommend a highly accurate digital map for the road user charge system. For this purpose, we developed a spatial framework of the whole system from the digital map survey to digital map accuracy analysis approach.

In order to give more complete digital map accuracy report in different settings, we have analyzed the accuracy of a commercial digital map (map X) dataset and the Mn/DOT basemap dataset for the Twin Cities metro area, an Mn/DOT basemap dataset for hilly area (Duluth, MN) and the Minneapolis downtown city digital map. In the Twin Cities metro area, we analyzed two digital road map datasets, i.e., the map X and Mn/DOT basemap that are the representative of real driven road. Under our buffer based measurement, 40 ft (12.2 m) accuracies of both maps are below 90%. The analysis shows that the basemap is more accurate than the map X, but that the 90% accuracy of the basemap occurs only at 50 ft (15.2m) buffer size.

In the hilly area that we evaluated in Duluth, the analysis results were unexpectedly good. This indicates the elevation change did not lead to a deterioration of the digital map accuracy. However, in this hilly area, the road network density was lower, which may be the reason for the accuracy improvement compared to map accuracy in Twin Cities metropolitan area.

Overall our analysis shows that the existing digital road maps are not adequate for road user charge system. They are not designed for application of road user charge system and may lead to inaccurate and unfair charges. It is clear that a new generation of digital maps is needed which can provide us with more accurate digital road map.

In the next generation of digital road map, we need to decide the desired digital road map accuracy, considering the road width.

Figure 10.1 is the illustration of the situation that two adjacent roads are close to each other. We assume perfect GPS in this analysis.

First we define the co-location distance and separation distance in this Figure.

**Co-location Distance** = distance of center lines of two road segments.

**Separation Distance** = Co-location distance – ½ (Road1 width) – ½ (Road2 width).

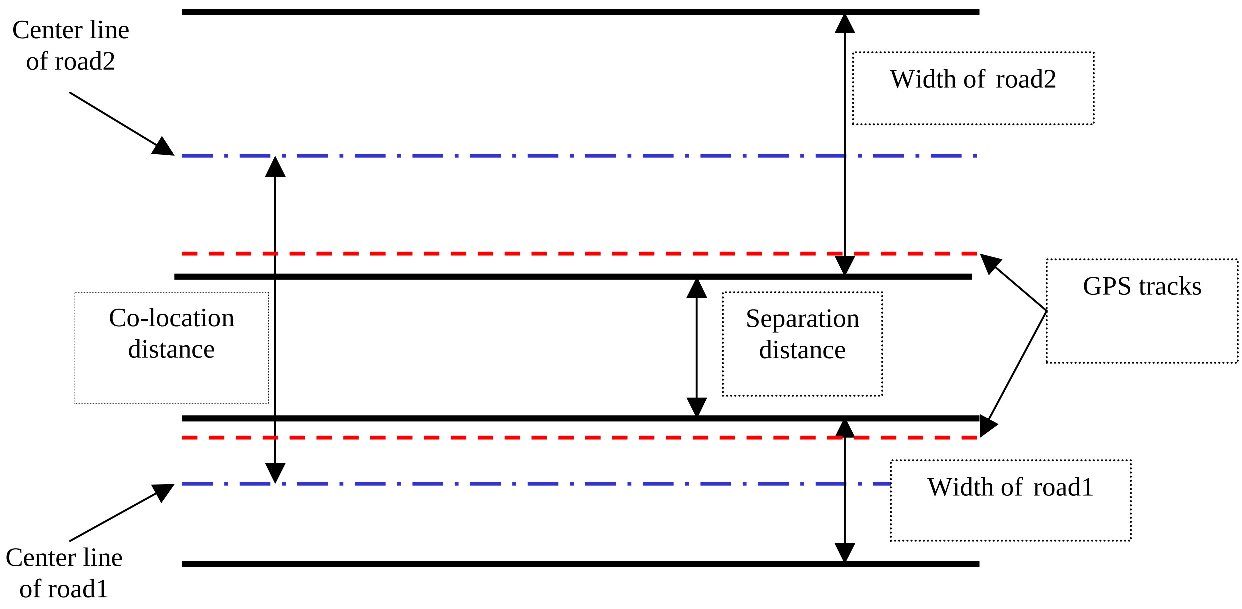


Figure 10.1 Illustration of Separation Distance

Assuming road2 is separated limited access highway (e.g. Interstate), then road2 has the minimum width of 24 ft (7.3 m). Assuming road1 is frontage road, then road1 has the minimum width of 24 ft (7.3 m).

For co-location distance equaling to 50 ft (15.2 m) (5% of Interstate highways are co-located within 50 ft. of other roads), separation distance is 26 ft (50 ft. – 12 ft. – 12 ft) (7.9 m).

Thus map positional error is less than 0.5 × 26 ft or 13 ft (4.0 m).

Vehicles are within the road so that the true GPS tracks should be within the road on which the GPS tracks are collected. In order to correctly separate two GPS tracks, i.e., to match the GPS track to the road on which the GPS track was collected, the desired map positional error must be less than half of the separation distance. That means if separation distance is smaller, we require even better accuracies.

Also in next generation of digital road maps, it is important to give priority to co-located roads and Interstate, state and county roads because co-located roads are prone to errors and Interstate, state and county roads are the skeletons of road networks. These are the roads that will play the most important role in the design of a user charge system.

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# Appendix A
# Road Type Definition of Map X and Mn/DOT Basemap

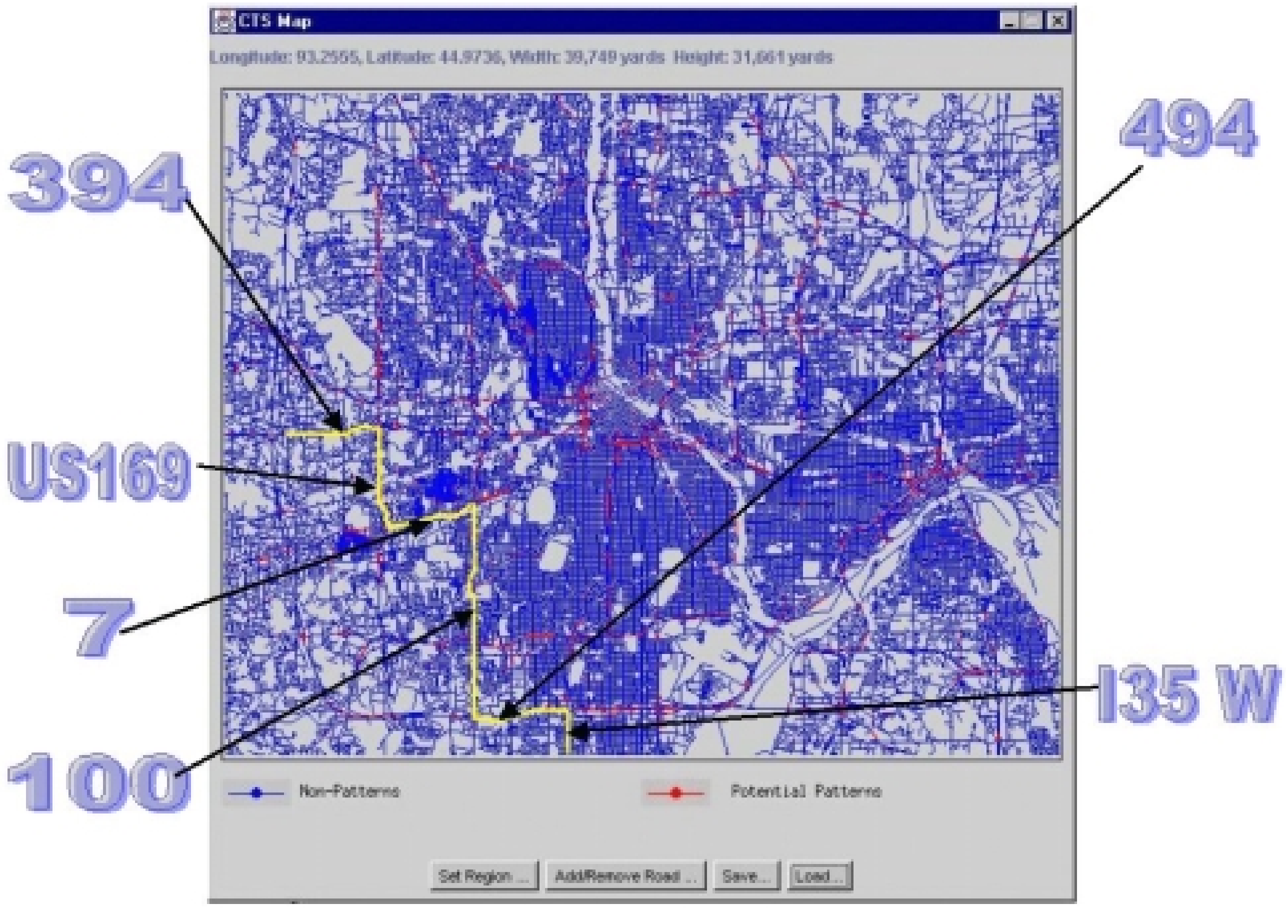
| Road Type | Definition |
|---|---|
| 0 | High-speed ramp |
| 1 | Interstate highway, U.S. highway, or other limited access highway |
| 2 | Primary state highway, subsidiary interstate highway, or subsidiary U.S. highway |
| 3 | Arterial |
| 4 | Collector |
| 5 | Light duty |
| 6 | Alley or unpaved road |
| 8 | Railroad |
| 9 | Low-speed ramp |

Table A.1 Road Type Definition for Map X

| Road Type | Definition |
|---|---|
| 01 | Interstate Trunk Highway |
| 02 | U. S. Trunk Highway |
| 03 | Minnesota Trunk Highway |
| 04 | County State-aid Highway |
| 05 | Municipal State-aid Street |
| 06 | County Road |
| 07 | Township Road |
| 08 | Unorganized Township Road |
| 09 | Municipal Street |
| 10 | Interstate Trunk Highway |
| 11 | National Park Road |
| 12 | National Forest Development Road |
| 13 | Indian Reservation Road |
| 14 | State Forest Road |
| 15 | State Park Road |
| 16 | Military Road |
| 17 | National Monument Road |
| 18 | National Wildlife Refuge Road |
| 19 | Frontage Road |
| 20 | State Game Preserve Road |
| 22 | Connector (Combination of old definition of road type 21 (legs), and road type 22 (ramp)) |
| 23 | Private Jurisdiction Road |

Table A.2 Road Type Definition for Mn/DOT Basemap Map

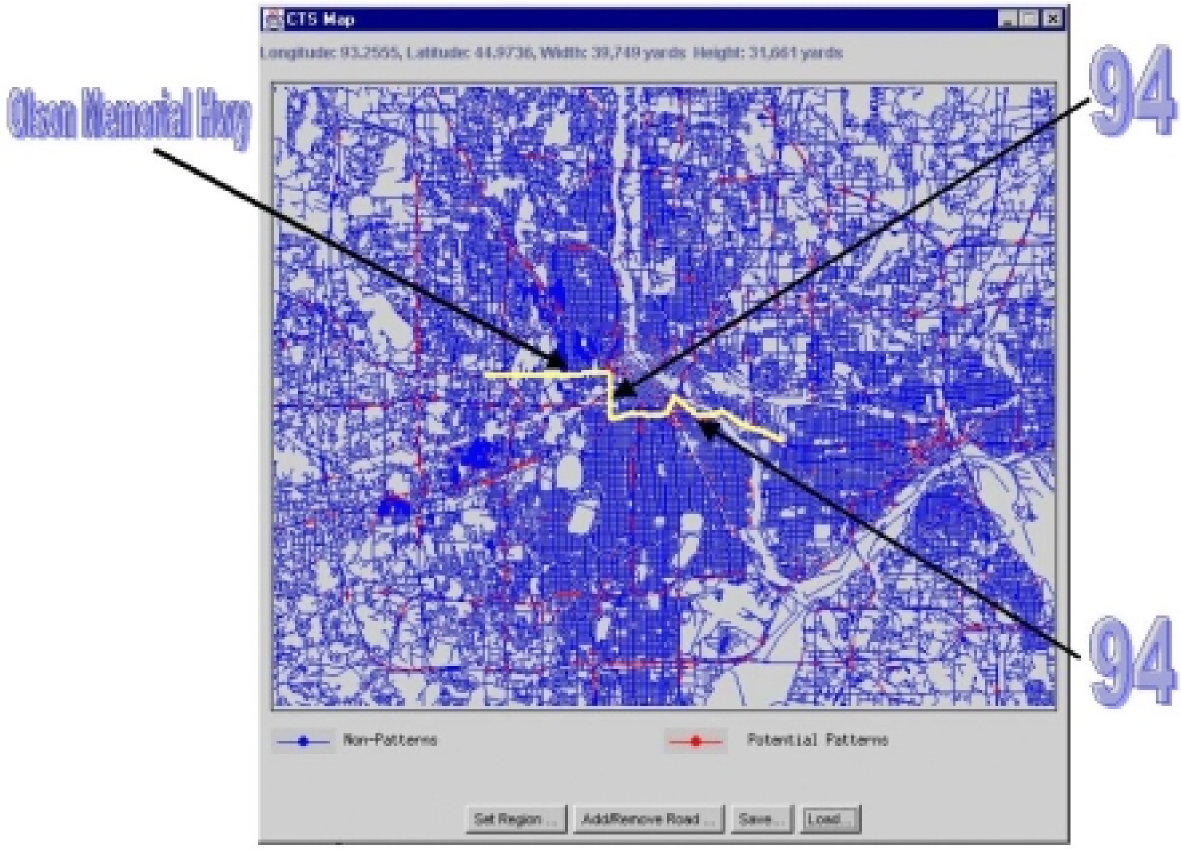
# Appendix B
# Test Routes



Longitude: 93.2555, Latitude: 44.9736, Width: 39,749 yards Height: 31,661 yards

Figure B.1 Test Route 2

The routes of test route 2:
I394 ⇔ US 169 ⇔ MN 7 ⇔ MN 100 ⇔ I394 I35



Longitude: 93.2555, Latitude: 44.9736, Width: 39,749 yards Height: 31,661 yards

Figure B.2 Test Route 3

The routes of test route 3:
Olsen Memorial Highway ⇔ I94

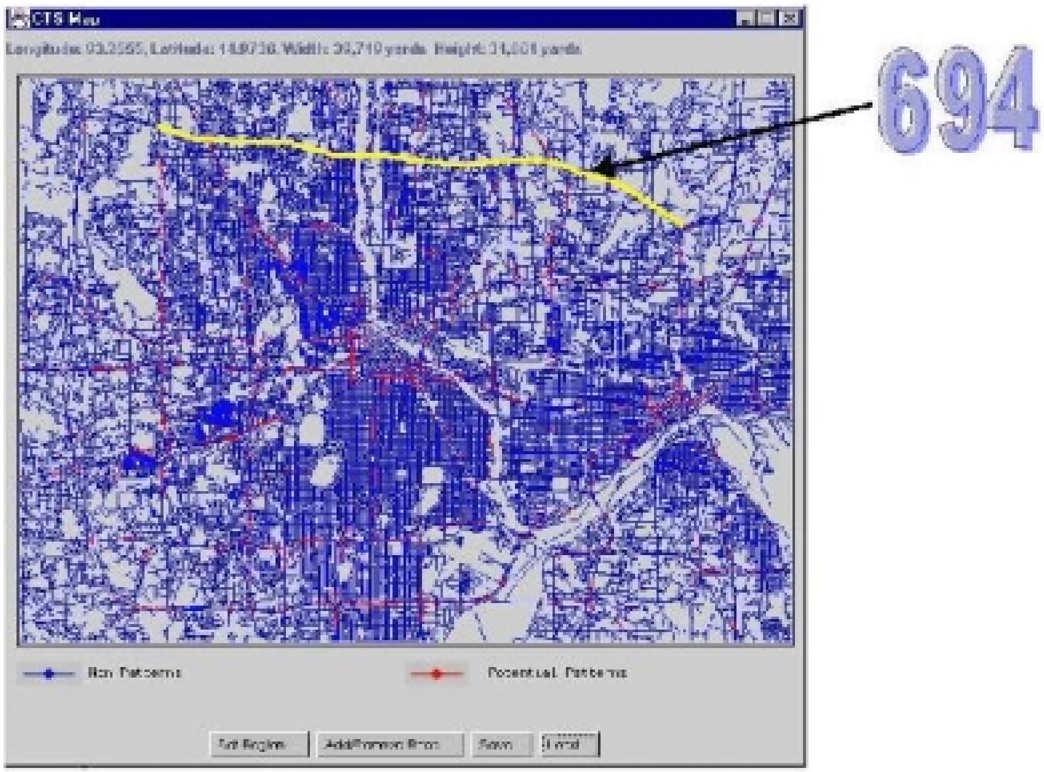


Figure B.3 Test Route 4

The routes of test route 4:
I694

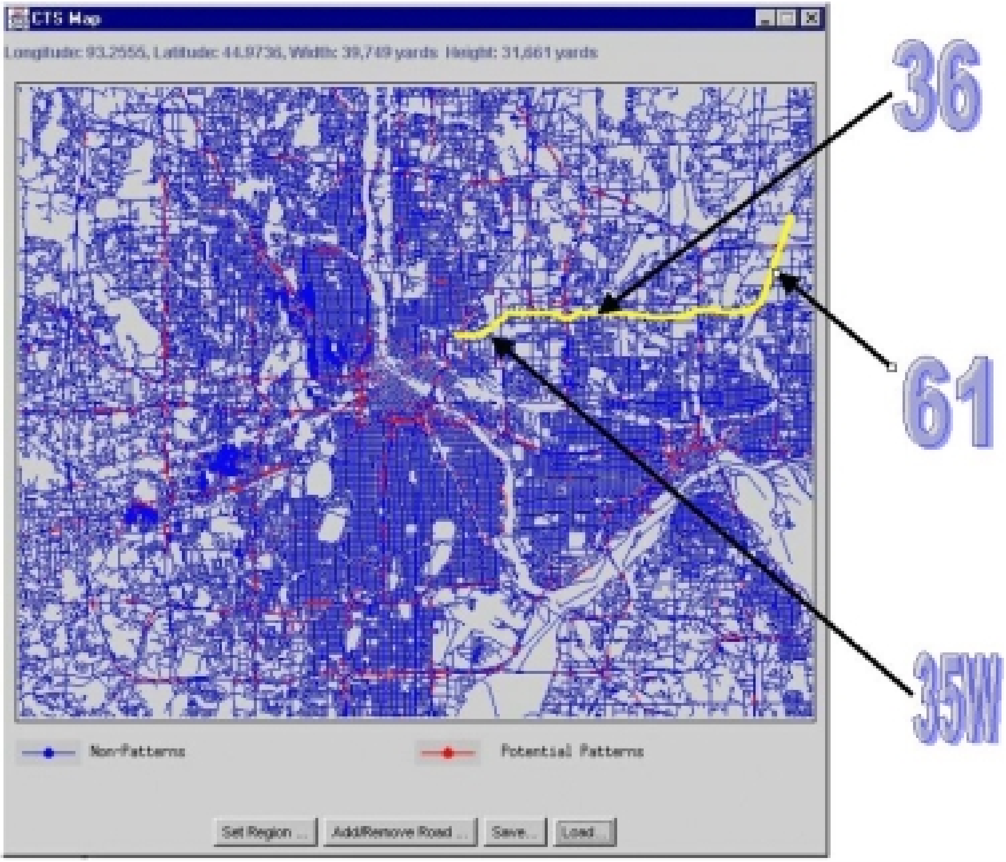

Longitude: 93.2555, Latitude: 44.9736, Width: 39,749 yards Height: 31,661 yards

Figure B.4 Test Route 5

The routes of test route 5:
I35W ⇔ MN 36 ⇔ US 61