Evaluation of Digital Maps for Road User Charging Applications

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ABSTRACT

Advances in alternative fuel technologies and increasing motor vehicle fuel efficiency may result in a decline or flattening of demand for conventional fuels in the U.S. in the coming decades. One outcome of this development maybe a reduction in state and federal income from motor fuel taxes, the primary source of funding to maintain and improve the transportation infrastructure. To keep pace with future transportation needs, a new funding mechanism is needed to supplement or replace the current road financing mechanism. One possible approach is to charge for road use based directly on a measure of travel on public roadways using onboard computers coupled with Global Positioning Systems (GPS) and digital maps.

The main goal of this research was to develop the system requirements for a digital map that is a major component of an in-vehicle road user charging system. The focus was to evaluate 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 the on-board system must be able to place the vehicle on the correct road.

Extensive testing of existing digital maps found that they are 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 differential GPS and such high accuracy digital maps, the ability to design a road user charging system with high geographical resolution can become a reality.

INTRODUCTION

Rationale for a Road User Charging System

Motor fuel taxes have been a major source for financing public roadways in the U.S. for many years. The rationale for using an excise tax on fuel is that road use should be charged as a utility – the more a driver uses the road, the more that driver should pay for the upkeep. The motor fuels tax approximates the distance driven by a given vehicle user and thus approximates the amount of road usage. However, 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 now based on hybrid-electric drive-trains, and in the future on fuel-cell technology. While there are still relatively few of these vehicles on the road, the numbers will increase as automobile manufacturers respond to the ever-increasing environmental restrictions placed by both federal and state governments on vehicle emissions and as consumer demand for fuel efficiency grows. As a result, the revenues generated from motor fuel taxes, the funds that pay for much of the construction and maintenance of our road and highway system, will likely continue to decrease.

Another issue impacting the transportation infrastructure is the increase in the number of vehicles on the roadway system. This increase has resulted in severe congestion problems as demand for road space has out-paced supply. The most obvious evidence of this is in urban areas, where vehicles crawl on interstate highways at average speeds of less than 20 MPH during rush hours (e.g., Los Angeles, New York). This problem will pressure governments to increase road capacity and improve maintenance.

Clearly, new funding mechanisms are needed to more closely approximate the use and costs imposed by drivers and their vehicles on the system. The shortfall in revenues from motor fuel taxes and the increase in demand on surface transportation are not only problems in the U.S. In fact, many parts of the world have more serious problems than the U.S. and there is a movement to charge road users based on various forms of technology, including transponders, computer vision systems, and Global Positioning System (GPS) satellite-based location. Other sensing systems are constantly being added to the mix. Many countries and cities have introduced electronic road pricing, distance-based charging, and higher urban zone charges.

In New Zealand, public roadways are financed through levies in the price of fuels and road user charges (*1*). In Singapore, Electronic Road Pricing (ERP) has been in use for years (*2*). In this electronic road pricing system, charges can vary according to time and congestion levels. In Japan, an Electronic Toll Collection (ETC) service was launched in 2001 to “verify the function of ETC equipment and the effects of ETC on the smoothness of traffic flow.”(*3*). Subsequently, 1.8 million ETC on-board units (OBU’s) have been installed with coverage of over 8000 km of roads; the OBU price has dropped by 1/3 during this time period. These OBU’s were designed to be multifunctional with the wireless communications to each OBU allowing for 2 way communications, with the extra channel used for safety purposes. By 2007, predictions are that the installation base will reach 10 million. In Europe, there is a multi-city and multi-nation demonstration road pricing project, PRoGR€SS (Pricing Road user for Greater Responsibility, Efficiency and Sustainability in citieS), that is currently underway (*4*). This project intends to demonstrate and evaluate the effectiveness and acceptance of integrated urban transportation pricing schemes to achieve transportation goals and raise revenue. In Switzerland, every commercial truck is equipped with a GPS-based on-board system and is required to pay road use charges based on the total mileage driven in the country (*5*). Similarly, in Germany the government is implementing a GPS-based automatic road-tolling system for commercial trucks (*6*). After many months of lengthy delays, the Toll-Collect Consortium has completed the first phase of testing on 41 trucks in July 2004. It will start a second phase of trials on 4,000 trucks in autumn 2004 and is expected to be fully operational by January 2005 (*7*). In London (U.K.), the city government has implemented a “Traffic Management Zone” that charges motorists £5 per trip for entering the zone (*8*). Cameras were installed to read license plates and determine whether vehicles have entered the tolling area. This scheme has shown that the traffic levels inside the charging zone has been down by 10 ~ 15% and the congestion has been reduced by 20 ~ 30%. In 2004, Oregon Department of Transportation and the Oregon State University demonstrated that it is feasible to determine and collect mileage-based user fees (*9*). This demonstration was to respond to a state legislation passed in 2001 to develop a revenue collection system funded through user pay methods that will eventually replace the current fuel tax revenues for maintaining and improving Oregon’s roads and highways.

GPS and Digital Maps as the basis of a Road User Charging System

GPS based location is now available at higher accuracies for civilian applications since selective availability was turned off by Presidential Directive and with new Differential GPS (DGPS) corrections available ubiquitously (such as WAAS in North America and EGNOS in Europe). When implemented together with digital maps, DGPS and an on-board computer system can locate vehicles accurately on the road and make road specific user charges a reality. The charge can be based on the distance traveled along particular roads plus other externalities like environmental charges, time of day charges, and location charges. Such a system can be utilized to generate revenues to fund the transportation needs of the future.

The framework for this concept comes from a national pooled-fund project titled “A New Approach to Assessing Road User Charges” (*10*). That project considered both the institutional and technical issues associated with a new user charging system. This new approach applies DGPS and digital maps to compute road usage and assess user charges in real-time. A previous paper examined the technical issues associated with using GPS technologies (*11*). This paper focuses on the digital map and related technical requirements for their use in road user charging applications. The methodology discussed below applies to many other applications where a specification for road or lane separation can be developed, and where the digital map accuracy affects the system’s ability to meet this specification.

Although multiple systems already exist which take advantage of a combination of GPS and digital maps, no charging system has the resolution and accuracy needed to distinguish between roads in close proximity. This is a significant issue because often these roads are managed by different jurisdictions (e.g. frontage roads next to highways), and are likely to be charged at different rates (and some not at all). Incorrectly charging a user for being on a ‘priced’ road when they are actually on a non-tolled road will seriously affect the credibility of such systems among the traveling public.

Map Errors

Map accuracy is defined as the degree to which information on a map or in a digital database matches the 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. When discussing digital road maps, the most commonly considered parameters 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 illustrates the lateral accuracy and the longitudinal accuracy of a digital map. For road user charging applications, the lateral accuracy of a digital map is more important than its longitudinal accuracy. 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.

Digital Map Accuracy Standard

The National Map Accuracy Standard (NMAS) was adopted in 1947 and provided the first version of accuracy standards for published maps (*12*). This standard defines positional accuracy in both horizontal and vertical directions. It requires that 90% of tested points on published paper maps should be smaller than a threshold. On maps with scales greater than 1:24,000, the threshold is 1/30 inch, which is equivalent to an error of 66.6 ft (20.3m). On maps with scales smaller than 1:24,000, the threshold is 1/50 inch with an error of 40 ft (12.2m).

Currently, there are no national or international standards for the accuracy of digital maps. However, most major digital map vendors claim that their maps all conform to the NMAS.

Desired Accuracy of Digital Maps for Road User Charge Applications

Given an appropriately accurate digital map, the on-board computer will be capable of distinguishing roads in close proximity at a reasonable confidence level. Figure 2 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

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

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

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

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

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, the separation distance (S) can be computed as:

$$S = 15.2\text{m} - 3.6\text{m} - 3.6\text{m} = 8\text{m} \quad \text{or} \qquad (3a)$$

$$S = 50\text{ ft} - 12\text{ ft} - 12\text{ ft} = 26\text{ ft} \qquad (3b)$$

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

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

$$E = \tfrac{1}{2} \times 26\text{ ft} = 13\text{ ft} \qquad (4b)$$

Please note that by examining Equations 1 and 2, 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 needed to achieve the same level of confidence in computing the correct road usage.

It should be noted that GPS error is not included here (i.e., perfect GPS locations are assumed) when considering the desired accuracy of a digital map. However, GPS positioning errors do exist; theses have been considered separately in REF A. The on-board computer needs to interact with both components in order to compute the correct road usage for charging. As such, a road user charge system needs to meet both the requirements specified for GPS and for digital maps in order to achieve the stated confidence level for computing road usage.

Objectives

- 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.

Research Questions

The goal of this study was to evaluate digital maps that hold the most potential for providing the location, distance traveled and time of day and serving as the basis of a road user charge system. There have been many studies on the accuracy of digital maps. This study focused on the following questions:

- How often are roads located in close proximity? How "close" is "close"?
- Do existing digital maps meet the accuracy specifications for road user charging applications? If so, which are they? If not, can alternatives be proposed that overcome their limitations?

SELECTION OF DIGITAL MAPS

In this study, navigable digital road maps from both the private and public sectors were studied. The Minnesota Department of Transportation (Mn/DOT) basemap is a 1:24,000 scale digital map. It includes a road network which is represented by road centerlines information and individual data layers such as transportation features (roads, railroads and navigable waters), boundary information (state, county, and municipal boundaries, Mn/DOT district boundaries, civil, and congressional townships, state forests and parks, military reservations, Indian reservation lands, and national forests and parks), and stream and lake locations. Since the basemap was digitized from a US Geological Survey (USGS) 7.5-minute quadrangles paper map, its accuracy is not expected to exceed the accuracy of the source and the NMAS, which is ±40 ft (12.2m) on a 1:24,000 scale map.

Commercial digital maps are produced from many sources. Many of them are improved versions of the U.S. Department of Commerce Census Bureau's Topologically Integrated Geographic Encoding and Referencing (TIGER) digital map. One digital map studied in this project claims that it has an absolute accuracy of 40 ft (12.2m) and a relative accuracy of 16 ft (4.9m) in the urban areas in U.S. It also has an absolute accuracy of 160 ft (48.8m) and a relative accuracy of 60 ft (18.3m) in all other areas.

STUDY OF ROAD PROXIMITY

Digital Maps for Road User Charging

Patterns of roads that are close to each other in large road networks are hard to distinguish by GPS when the underlying digital road map has large errors. For a road user charge system to work correctly and fairly, the system must be able to distinguish not only roads that are far away from each other but also roads that are close to each other. In this study, the "close road" pattern is defined 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 because of errors in the digital road map. A newly developed co-location data miner was used to find and study co-location patterns in digital road maps.

Co-Location Data Miner

In road networks, of most concern was the closeness of a set of line segments belonging to one road type to another set of line segments belonging to other road types. A new co-location mining method based on a buffer computation was developed to identify close road-pairs in a digital road map. This method was specially designed to process the line segments in the road network of a digital map in order to search for close road pairs as measured by a co-location ratio. The co-location ratio is defined to capture the closeness of a line segment to another line segment within a specified buffer size. For example, road type A has a co-location ratio of *X*% with a buffer size of *Y* ft means that *X*% of road type A are within *Y* ft of roads that belong to other road types.

Figure 3 shows the co-location patterns in the metropolitan Twin Cities area in the Mn/DOT basemap with a buffer size of 30 ft (9.1m). Clustered dark line segments indicate road segments that are co-located within 30 ft. It is also found that these closely co-located roads are located around the major interstate and state highways in the Twin Cities. Figure 4 shows the co-location ratios of different road types in the Mn/DOT basemap. The ratios were computed using buffer sizes of 20, 30, 40, 50, 60, and 100 ft (6.1, 9.1, 12.2, 15.2, 18.3, and 30.5 m) respectively. The figure shows that the road type 22 (connector) and type 1 (interstate highway) have higher co-location ratios than the other road types. Co-location patterns are affected by the buffer size; the co-location ratio increases as the buffer size increases.

EVALUATION OF DIGITAL MAPS

Test Route Selection and Data Collection

Routes were selected that would highlight the problem associated with distinguishing between roads that were parallel and adjacent to each other (i.e., co-located roads). Results from the co-location data mining were used to identify such roads in a digital map. A total of nine routes were selected in the metropolitan Twin Cities area: four routes covering 991 km (616 miles) were on interstate and state trunk highways and five routes covering 365 km (226 miles) were on city streets.

The best way to evaluate the accuracy of digital maps is to compare them against a more accurate system (*13*). Since the accuracy of digital maps is on the order of 10 meters, a dual-frequency GPS receiver with a sub-decimeter dynamic accuracy was used as a “gold standard” to evaluate the accuracy of digital maps on these routes (*11*). For this study, this high-accuracy GPS data was collected on all test routes for the analysis of digital map accuracy.

Analysis of Positional Map Accuracy

Map positional accuracy can be quantified by the percentage of roads in a digital map that are “located” within a specified range of the true physical roadway. A buffer-based computation was used to calculate the ratio of road length for specified roads from a digital map that falls within a buffer zone of the actual road data. Such a ratio is defined as the map accuracy ratio. The following describes the method used to analyze the accuracy of a digital map:

1. Test routes were selected and extracted from a digital map.
2. A high-accuracy GPS receiver was used to collect the actual road data that would be used to compare against the same road segments in a digital map.
3. Different buffer sizes were used to compute map accuracy ratios. A buffer size represents the range in which the results are considered accurate: the larger the buffer, the lower the map accuracy. On the other hand, when a buffer is fixed, the greater the accuracy ratio value, the higher the map accuracy.

Please note that a buffer is two-sided. An error with a buffer size of *x* ft means that the error is actually ± *x* ft in both directions perpendicular to a road segment.

Results of the Positional Accuracy Analysis

Six different road types (Interstate highways, US trunk highways, Minnesota trunk highways, county state-aid highways, municipal state-aid streets and municipal streets) with a total length of 225.8 km (141.1 miles) were extracted from the test routes for the buffer-based analysis. Figure 5 shows the accuracy results for the Mn/DOT basemap. 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. It can be found that the accuracy of the basemap becomes very good when the buffer size is greater than 65 ft (19.8m). The accuracies for all road types are around 95% except for basemap road type 10, which represents municipal roads. Generally speaking, it was found that the Mn/DOT basemap had a much higher accuracy than the commercial digital map that we evaluated, whose accuracy for all road types was found to be around 95% when the buffer size was greater than 150 ft (45.7m). Figure 6 shows the error distribution determined for the Mn/DOT basemap. From the figure, we can see that 83% of roads in the basemap have an error less than 40 ft (12.2 m), and 7% of roads have an error between 40 and 50 ft (12.2 ~ 15.2 m).

Analysis of Positional Map Accuracy

Map matching accuracy can be quantified by the percentage of roads traveled that are correctly identified. A map matching algorithm based on the nearest neighbor search was implemented to calculate the mismatched portion of the roads traveled in a digital map. The percentage of roads that are correctly matched in a digital map is defined as the map matching ratio.

Results of the Positional Accuracy Analysis

Six different road types (Interstate highways, US trunk highways, Minnesota trunk highways, county state-aid highways, municipal state-aid streets and municipal streets) with a total length of 414.6 km (259.1 miles) were extracted from the test routes for the map-matching analysis. Figure 7 illustrates the results for the Mn/DOT basemap. Correct map matching ratios for all road types is about 87%. The best map matching ratio was 95.3% for county state-aid highways. The worst map matching ratio was found to be 79% for municipal state-aid streets. We found that the Mn/DOT basemap exhibited better map matching ratios than the commercial digital map that we evaluated which had an overall map matching ratio of 73%.

CONCLUSIONS

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. Also, this study treated 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 discussed 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.

This implies that existing digital road maps are NOT adequate for most 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. However, newer more accurate digital maps have been developed that overcome this problem. These new maps facilitate their use for charging in High Occupancy Tolling (HOT) lane systems which need to distinguish between travel in adjacent lanes.

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LIST OF FIGURES

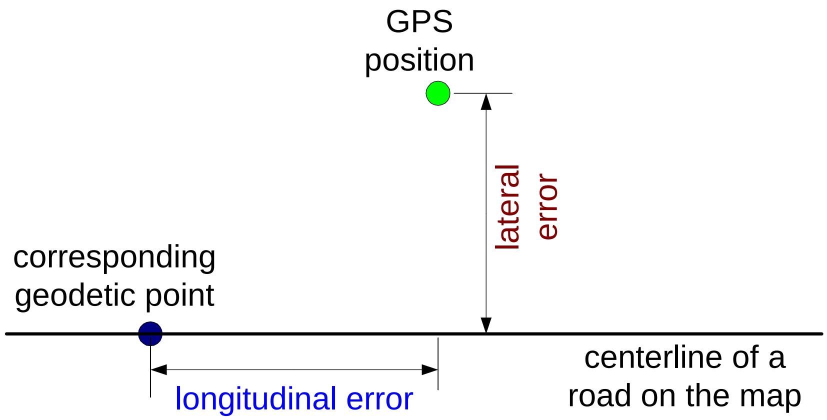

FIGURE 1 Definition of map positional accuracy.

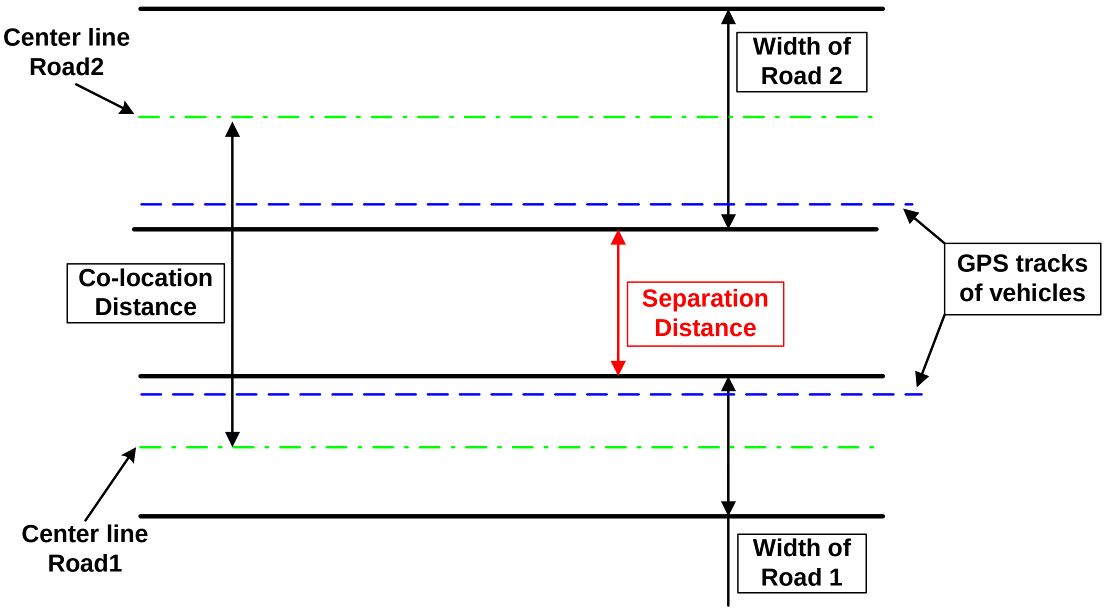

FIGURE 2 Desired accuracy of a digital map in a road user charge application. GPS tracks are based on the assumption that the vehicles are traveling in the lane closest to the adjacent road.

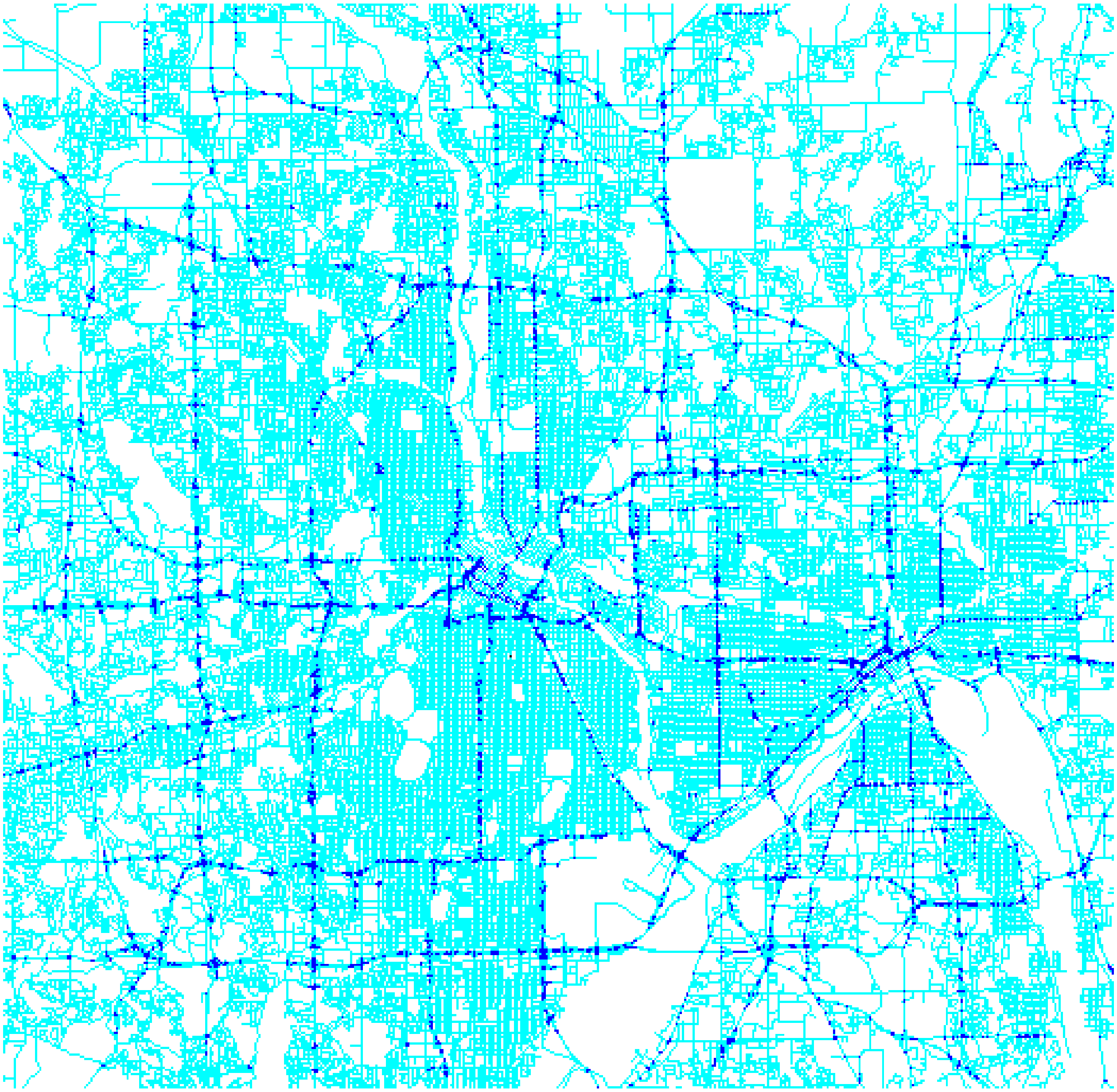

FIGURE 3 Co-location patterns in the Twin Cities Metropolitan area (30 ft buffer; source: Mn/DOT basemap).

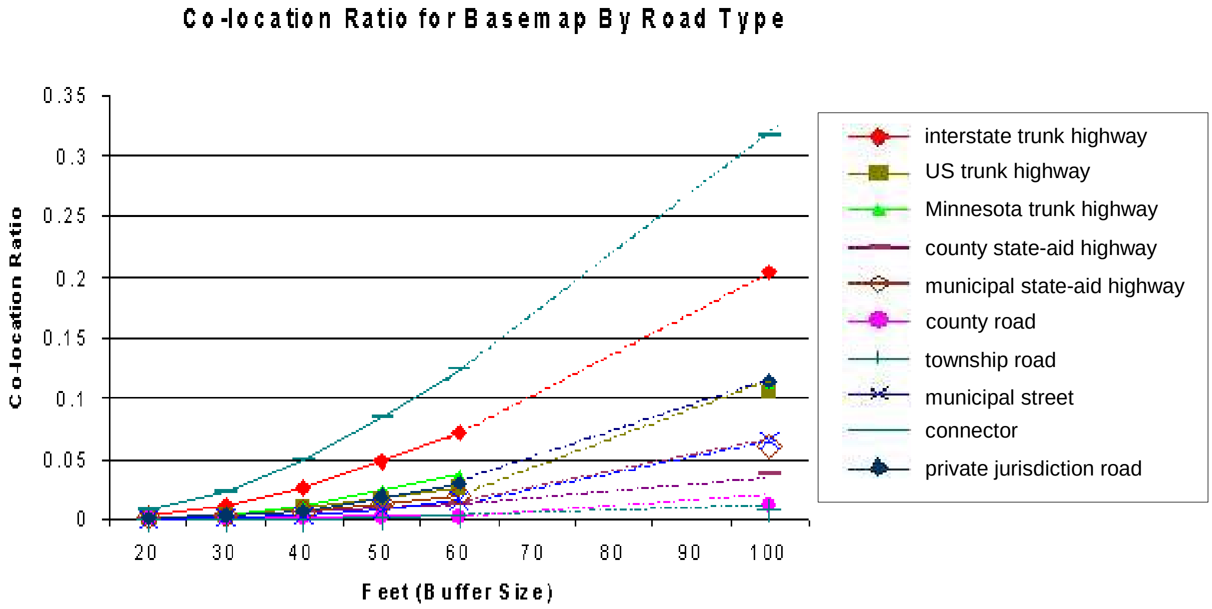

FIGURE 4 Co-location ratios for different types of roads in the Mn/DOT basemap.

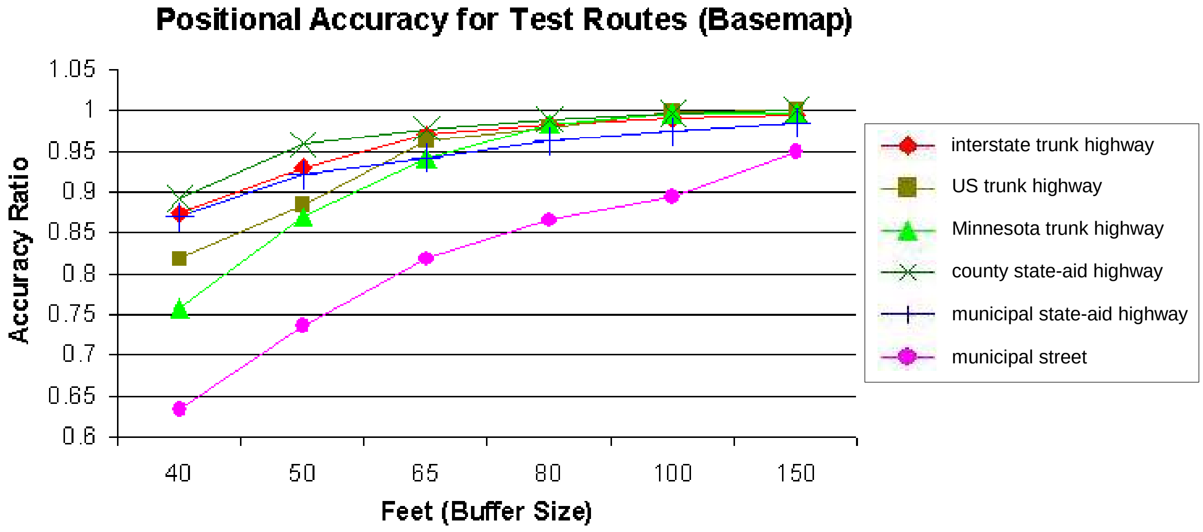

FIGURE 5 Map accuracy of the Mn/DOT basemap by road types in the Twin Cities Metropolitan area.

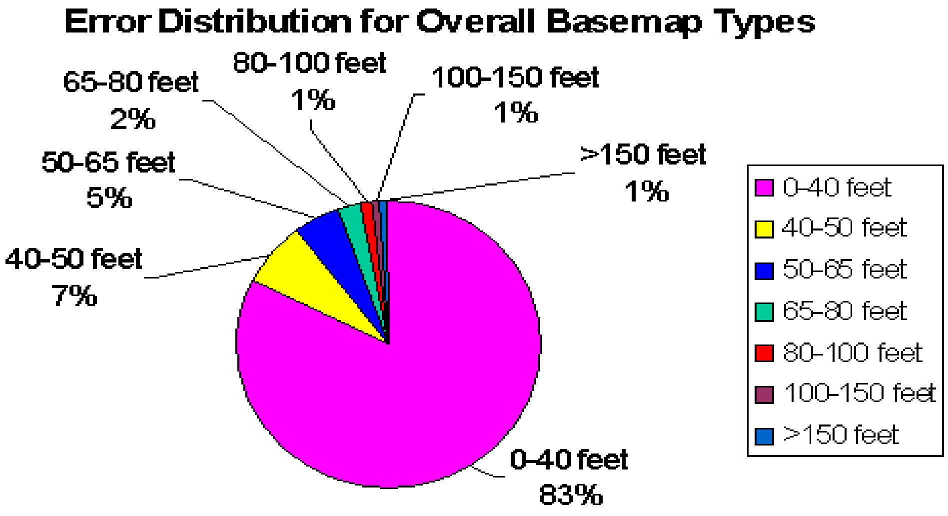

FIGURE 6 Error distribution of the Mn/DOT basemap.

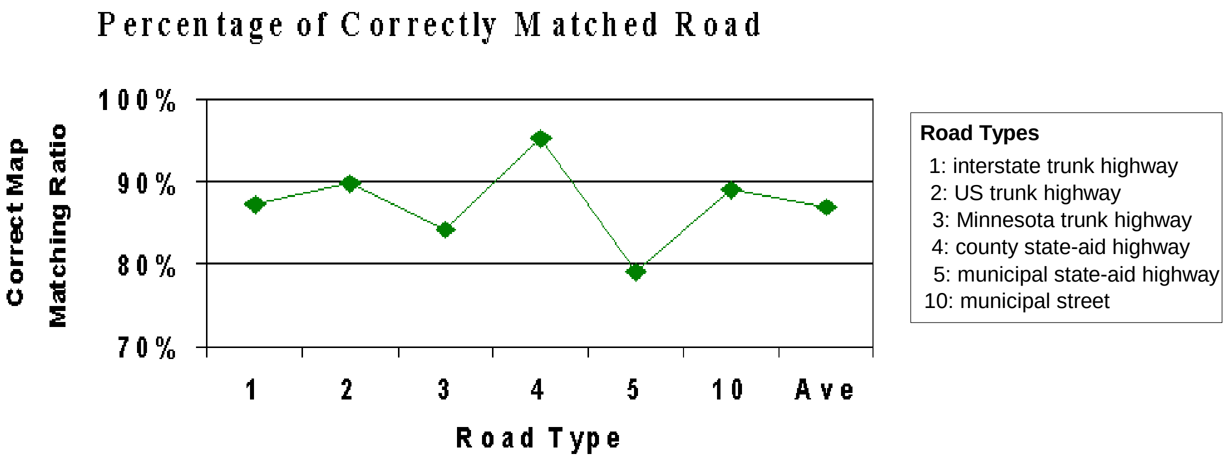

FIGURE 7 Map matching accuracy for the Mn/DOT basemap.