Digital Road Map Accuracy Evaluation: A Buffer-based Approach

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Abstract

The quality of digital road maps plays a critical role in many GIS applications. For example, the next generation of automatic road user charge systems will need to be able to identify the road on which a vehicle is traveling and report the total number of miles driven by a vehicle. This requirement imposes a new challenge on the accuracy of digital road maps. Certainly, failure to manage/evaluate errors in digital road maps may limit or invalidate road user charge assessment. Most previous work on the evaluation of the accuracy of digital road maps was focused on point-based approaches and was not scalable to large road networks. In this paper, we present a spatial framework for evaluating digital road map accuracy. First, we applied a buffer-based line-string colocation measure to select a field test site in order to discover high affinity road patterns, i.e., roads located very close together. This served two functions: (1) to determine the magnitude of the problem and (2) to identify the location where map accuracy needs to be evaluated. We then proposed a line-string based digital road map accuracy measure that uses a well-defined buffer computation. Our experiments on a Minneapolis-St. Paul base map demonstrate that our approach is applicable to large road networks and is effective for assessing positional accuracy in

digital road maps. Further, we found that the accuracy of existing digital road maps do not satisfy the requirements required for applications such as road user charge systems. The fact is that current digital road maps were not designed for road user charge systems and if used may lead to inaccurate and unfair charges.

1 Introduction

With the emergence and evolution of GIS technology, digital road maps are now starting to play an important role in many GIS applications such as road user charge systems and modern traffic management. GIS services have traditionally used digital road map data and related functionalities to perform basic geo-processing tasks such as target location, map image display, and routing. However, the next generation of automatic road user charge systems will impose new requirements for identifying the road on which a vehicle is traveling and reporting the total number of miles driven by the vehicle on a specific road. This requirements pose a direct challenge to the accuracy of digital road maps. Accuracy is especially a concern where parallel roads such as highways and frontage roads, are located in close proximity to each other. Failure to manage/evaluate errors in digital road maps may limit or invalidate road user charge assessment.

In this paper, we present a spatial framework for evaluating digital road map accuracy; we also develop and evaluate a quantifiable measurement for positional accuracy. First, we applied a buffer-based line-string association measure to select a field test site. The line-string-based measure helped us discover high affinity road patterns in which road segments of different types (e.g. State highway or city street) are located togather. This served two functions: (1) to determine the magnitude of the problem and (2) to identify the locations that are vulnerable to error on digital maps. It was important to evaluate map accuracy at locations where such accuracy is most critical.

Second, we proposed a line-string based digital road map accuracy measure that uses a well-defined buffer computation. Buffer computation is widely used in many spatial applications such as in GIS. We adapted it to quantify the positional accuracy of a digital road map. As demonstrated by our experiments on the Minneapolis-St. Paul base map, our approach is applicable to large road networks and is effective for assessing positional accuracy in digital road maps. Finally, we found that the accuracy of popular digital road map does not satisfy the essential requirements of applications for road user charge systems. Experimental results for the Minnesota base map are given as a representative to show this inconsistency. In fact, current digital road maps are not designed for road user charge system and their use may lead to inaccurate and unfair charges. As the next generation of digital road maps are developed, these requirements must be considered.

1.1 Related Work

Digital road map accuracy is very important to all GIS applications. There are a considerable number of standards to define the meaning and the specific measurements for evaluating accuracy[4, 10, 11], Many groups have developed different frameworks to capture these definitions[3, 7, 5, 19].

The most widely used map accuracy standards are point-based. The US National Map Accuracy Standard (NMAS), defined in 1947, mainly gives an error threshold based on 90% of tested points for paper based map data. For example, it defines the error threshold for maps with scales greater than 1:24000 as $\frac{1}{30}$ inch and $\frac{1}{50}$ inch for maps with a scale less than 1:24000. The American Society for Photogrammetry and Remote Sensing (ASPRS) developed a standard for large scale maps and defined 3 different error thresholds for each scale. In the US National Standard for Spatial Data Accuracy (NSSDA) standard, 95 percent of points have errors less than the reported accuracy values. Accuracy is reported based on ground distances at the 95% confidence level.

Based on these point-based map accuracy standards, different frameworks have been proposed for digital road maps, capturing different map accuracy definitions. NavTech defines percent error as a linear combination of 13 component errors that are based on segment existence, name, direction and speed. It claims 97% accuracy. Etak (now Tele Atlas) claims that their map accuracy conforms to the NMAS standards. Its digital map mainly conforms to two scales. (a) a scale of 1:24000 defined for area containing 70% of the US Population, and (b) a scale of 1:100000 defined for areas containing 25% of the US Population. The TIGER digital map comes from many sources. The 90th percentile errors (NMAS) for TIGER files are much worse than the mean or median error. The TIGER group also developed the GPS TIGER Accuracy Analysis Tool (GTAAT), which calculates the distance and azimuth difference between the GPS collected point and the equivalent TIGER point.

Table 1 presents a comparison of current map frameworks based on point-based accuracy measures.

Evaluation Tool	Gold Standard	Accuracy Measure	Map Data	Positional Error (as per map data source)
Navtech	Land Survey	Point Based	Navtech File	97% Accuracy (includes attribute errors; no positional accuracy specified)
Etak	Land Survey	Point Based	Etak File	Conform to NMAS (90th percentile error 12.2-51m)
Tiger	GPS	Point Based	Tiger File	90th percentile error = 110m to 400m

Table 1: Comparison of Evaluation Tools

All of these evaluation tools use a limited number of reference points and compare these predefined reference points to a limited number of field data points. This approach has two limitations when evaluating digital roadmaps. First, it is more appropriate to think of a road network system as a set of line segments than a set of points. Using line segments as the basic evaluating data object is a natural extension for evaluating road networks. In our framework, we propose a line segment based evaluation approach has been proposed. Second, in the point-based approach, data points are collected for fixed reference points. To take sample values from fixed reference points requires personnel to locate the points, travel to them and set up the sampling instruments, making it difficult to collect and analyze a large number of sampling reference points. A road network may consist of millions of road segments, and the more sampling points collected, the more accurate the digital map analysis. A sampling method which imposes a major limit or constraint on scalability is not very useful. A new approach is proposed for analyzing the positional accuracy of a digital road map which facilitates the rapid collection of huge number of samples across large areas.

1.2 Contributions

The major contributions of this paper are as follows.

1. We present a spatial framework for evaluating digital road map accuracy. In this framework, we proposed a buffer-based line-string association measure for selecting test routes. This measure describes the strength of relationships among line strings. Thus, it can help discover high affinity road patterns, which can be used for selecting field test sites.

2. We propose a line string map accuracy measure based on buffer computation for evaluating digital road map positional accuracy.

3. We conducted extensive experiments on a Minnesota Minneapolis-St. Paul area digital roadmap. As demonstrated by our experimental results, our new measure is effective for assessing positional accuracy in digital road maps and is scalable to large road networks.

4. Using our approach, we find that the accuracy of both public and commercial digital road maps does not satisfy the requirement of applications such as road user charge systems. In fact, current maps are not designed for road user charge systems and may lead to inaccurate and unfair charges.

1.3 Overview and Scope

The remainder of this paper is organized as follows. Section 2 introduces the background and the basic concepts behind the map accuracy evaluation. The line-string based association ratio and the map accuracy ratio are also defined in this section. In section 3, we describe the spatial framework for the map accuracy evaluation problem. The experimental results on the line-string association measure and map accuracy analysis are presented in section 4. Finally, in section 5, we draw conclusions and suggest future work.

The scope of this paper is the development of a spatial framework for digital road map accuracy analysis. A case study is presented to illustrate how our framework can be helpful for digital map accuracy evaluation.

2 Background and Basic Concepts

In this section, we introduce the research background and some basic concepts that are required for evaluating digital road map accuracy.

2.1 Application Domain

The need for an accurate digital map evaluation system is being fueled by many developments in two areas. Two areas will be outlined here:

(1) Given that new technologies such as fuel cells and hybrid electric systems are likely to lead to a new generation of vehicles that are more independent of traditional fuels, there is considerable concern that funding of the transportation network will become unstable, as income from motor fuel taxes is reduced. One project, A New Approach to Assessing Road User Charges, is pursuing the development and analysis of an alternative approach for assessing road user charges based on the usage of public roadways. The system under consideration involves an onboard computer system that would use a differential GPS (DGPS) receiver, a digital map, and map-matching software as the basis for computing charges based on miles traveled, road jurisdiction, and road type. Once a vehicle equipped with a user charge system begins to move, the charge system automatically identifies the road on which the vehicle is traveling, determines the number of miles driven and calculates the tolls. An integrated DGPS/digital map system should have the ability to distinguish between different road types and/or jurisdiction for roads in close proximity in order to charge road users correctly. The main goal of the project was to develop the system requirements for both the DGPS system and the digital maps that would be part of such an onboard computer system.

(2) In the second recent development, the accurate determination of the position of moving objects has given rise to a new technology known as location-based services (LBS). A LBS uses GIS and accurate, real-time positioning and navigation systems to determine the location of a moving object. The information generated by these systems is sensitive to the current position of its user, and advises the users about current conditions such as weather and traffic among other things. The Open GIS consortium (OGC) recently initiated an Open Location Services Initiative (OpenLS) [6] which aims at the development of interface specifications that facilitate the use of location and other forms of spatial information in the wireless Internet environment. OpenLS defines five core services that involve digital road maps to varying degrees. These services require detailed and precise specifications for a highly accurate digital road maps.

Our digital map evaluation system was developed to provide the requirements for digital road maps. It can also be used to provide support for these LBS applications.

2.2 Using Line String Collocation to Find Patterns

Our framework uses a line-string approach based on spatial association rule finding to look for road segments located close togather. Association rule finding [13, 8, 9, 13, 15, 17, 18, 20] 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. Spatial association rules [14] are spatial cases of general association rules where at least one of the predicates is spatial. Association rule mining algorithms [8, 9, 12] assume that a finite set of disjoint transactions are given as input to the algorithms. In market basket data, a transaction consists of a collection of item types purchased together by a customer. Algorithms like *apriori* [9] can efficiently find the frequent itemsets from all the transactions and association rules can be found from these frequent itemsets.

Many spatial datasets consist of instances of a collection of instances of Boolean spatial features (e.g., drought, needle leaf vegetation). Figure 1 shows an instance of association patterns among extended spatial features, namely road-types, on an urban road map. In large metropolitan areas (e.g., Minneapolis-St. Paul), highways often have frontage roads nearby. In this figure, MN Highway 100 is accompanied by a frontage road, Normandale Road, and Normandale Boulevard. Identification of such line string association patterns is useful in selecting test-sites for evaluating in-vehicle navigation technology in order to guarantee the ability to uniquely determine the location of the vehicles, whether it is on a highway or frontage road, and thus ensure the "correctness" of the user charge.

In our framework, a line string based pattern discovery approach based on spatial association rule finding is used to find the closed road segments from different road types. different road types is that the types of road segments instead of road segments themselves matter in our road user charge system. Of course, our framework can also be extended to find the closest road segments of the same road type.

2.3 Buffer Computation

In our approach, buffering is used both to determine road segments that are close togather, and to measure digital map accuracy. Buffering [2] is an important analysis technique which 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. Buffer distances must be set by the user. 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. For example, ESRI's ArcInfo[1] implements this operator to generate new coverage. Lines can be buffered to one side or the other, or 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 2 shows a buffer generated around a geospatial object polyline. The solid line inside the dashed line is the polyline used to generate the buffer. The area inside the dashed line is the generated buffer around this polyline.

The basic assumption behind our use of the buffer operation for digital map evaluation 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 a bigger or smaller error distance

Figure 1: Line String Association Illustration

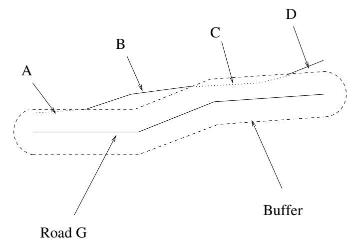

Figure 2: Buffer computation

than some given error distance, we only need to calculate how long a given segment falls into the buffer generated around the road segment with the "correct" or "actual" value. Thus, after we take a precise GPS track as the golden standard with the "correct" or "actual" value for real road segment, we can easily calculate the ratio of the length falling into the buffer that is generated around the "actual" value to the total length for a given line segment. This ratio reflects the digital map accuracy from a specific point of view according to above justification, considering our basic assumption.

2.4 Collocation Ratio

The line string collocation ratio is defined in order to capture the closeness of one line segment dataset to another line segment dataset with a specified buffer size. For example, it is used to evaluate the closeness of the line segment dataset of road type 1 to the line segment dataset of other road types. First, a buffer is generated around a line segment dataset. Then the length, iLen, of a specified or analyzed another road type that falls into the buffer is calculated. At the same time, the total length, tLen, of the specified road type is calculated. The collocation ratio is defined to be **line string collocation ratio** $= \frac{iLen}{tLen}$.

Figure 2 shows how we can use this buffer operation to calculate the line string association ratio and evaluate the digital map accuracy.

For calculation of the line string association ratio, the digital map dataset is divided into two sub datasets. One is for the specified or analyzed road type, which includes road segments A, B, C, and D in Figure 2. The second dataset is for other road types that includes road segments on road G in Figure 2. The buffer is generated around the segments belonging to the other road types. The ratio of the road length of the specified road type that falls into the buffer to the total length of the specified road type is calculated as the collocation ratio.

2.5 Map Accuracy Ratio

The map accuracy ratio measures the accuracy of the digital road map dataset using a line string based buffer computation model. First, dual frequency differential GPS position data with accuracies on the order of a decimeter for selected test routes are collected as "gold standard data", i.e., the "actual" value for these test routes. A buffer is generated around

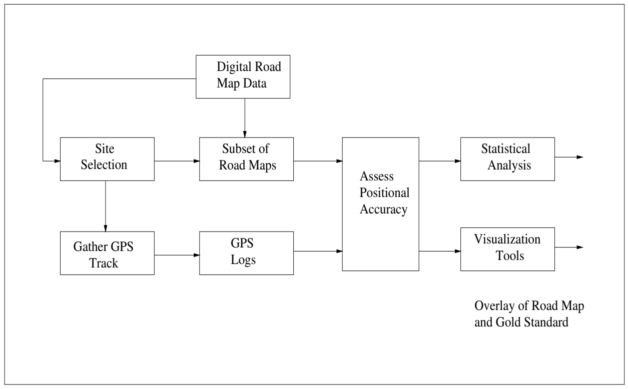

Figure 3: Framework for Positional Accuracy Analysis

the GPS gold standard dataset. The length, iLen, of the test routes in the digital road map dataset that falls into the buffer is calculated. At the same time, the total length, tLen, of the test routes in the digital map dataset is calculated. The map accuracy ratio is defined such that the **map accuracy ratio** $= \frac{iLen}{tLen}$.

3 A Spatial Framework for Digital Road Map Evaluation

Figure 3 shows our spatial framework for digital road map evaluation. The framework comprises six core activities.

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

We discuss these activities in the following subsections.

3.1 Digital Map Data Acquisition

We began by surveying the currently available digital road maps commonly used in today's GIS applications, namely NavTech from NavTech Inc., PC*MILER from ALK Inc., Topo USA from Delorme company, Etak from Tele Atlas, the Mn/DOT base map from the Minnesota Department of Transportation, and the TIGER map from the US Department of Commerce Census Bureau.

We then considered the requirements for the road use charge system application, the road data availability, i.e., whether the data could be processed by our evaluation software, and the claim of data accuracy, and chose one commercial digital map, and one public digital map for evaluation.

3.2 Field Test Site Selection

Generally, a GIS digital map database includes a large amount of data. Since it is impossible to evaluate all of this data, we had to sample the data. Sampling is a heuristic issue. For our application domain, there are specific requirements for the digital map system. A digital road map system for road charges requires national coverage. It must work in different environments such as urban, rural and hilly areas. An especially important requirement is that it has to differentiate between roads in close proximity to each other.

We designed a line string association discovery algorithm to identify high-affinity road patterns. High-affinity here means that two or more types of roads are too close to be distinguished by GPS in the face of errors in a digital road map.

We proposed an approach based on buffer computation for the high affinity road identification. For a specified road type, the digital road dataset is partitioned into two datasets. One dataset is for the specified road type. The other dataset is for other data types. We designed two algorithms for the high affinity road identification. The first approach uses a brute force nested loop join. The second approach constructs an index on a line segment dataset on which the buffer has been generated, which is a single loop join. Then it uses an indexed spatial join for the computation. The resulting dataset is the intersected line segments that fall into the buffer. These line segments then are sorted and merged into longer segments to compute the total intersected length. This computation also produces the line string association ratio for measuring the road affinities for different road types.

Arc/Info of ESRI provides a buffer function for buffer computation. However, it is a general tool and takes a considerable amount of computation time, e.g., more than half an hour to compute 3000 segments. Since our data include about half a million line segments, we developed our own buffer computation tools using the C language.

3.3 GPS Track Data Gathering

We used reliable signals from the high-accuracy dual-frequency GPS receiver Trimble MS750 as the gold standard data for our map accuracy analysis. We chose this Trimble unit because the results of a GPS receiver evaluation experiment [16] showed “that the Trimble MS-750 GPS receiver exhibits sub-decimeter dynamic accuracy at different speeds for both short and long baselines”.

3.4 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

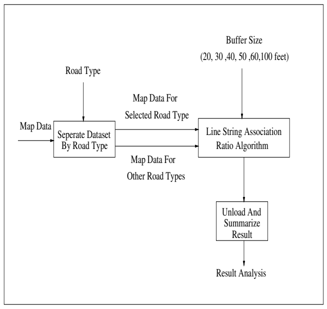

Figure 4: Experiment Design for Collocation Ratio Analysis

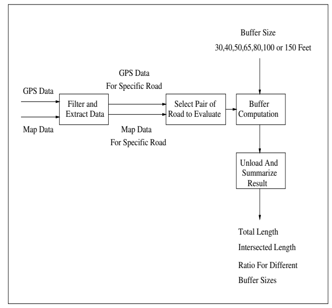

Figure 5: Experiment Design For Map Accuracy Analysis

about positional accuracy and proposed a buffer-based line string digital map accuracy measure, i.e., map accuracy measure.

After we conducted field tests to collect reliable highly accurate GPS signals, we used them as the gold standard and selected corresponding digital road map data for these field test routes. Then we generated a buffer around the reliable GPS data and computed the intersections of this buffer and the selected road map data from the digital road map dataset. Finally, we calculated the line string map accuracy ratio.

3.5 Statistical Analysis

In total 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 charged fee. Thus in a statistical analysis, we summarized the total intersected road length and the total road length by road types and calculated the line string association ratio and map accuracy ratio for the different road types.

3.6 Raw Data and Results Visualization

We developed software to display the road map and overlaid the GPS signals on the underlying digital road map. This software can load different types of digital road maps and leave an open interface for other module installations. It can also be used both to generate the statistical analysis results and visualize the results.

4 Experimental Results

In this section, we present the experimental design and the results of the line string association ratio and digital map accuracy analysis. First, we introduce the experiment setup. Second, we show the changing pattern of line string association ratio with the change of buffer size for different road types and line string association patterns in the Mn/DOT base map. Finally, we illustrate the increasing mode of the map accuracy ratio with the increment of buffer size for different base map road types.

4.1 The Experimental Setup

The dataset is in ShapeFile format from the Mn/DOT base map and consists of seven counties, i.e., Ramsey, Hennepin, Washington, Anoka, Scott, Dakota, and Carver, in the Twin Cities metropolitan area. The data in this dataset was transformed into a text file which includes projected coordinates information, the road type information for each segment and other information, using the GIS software package ArcInfo. The dataset had a total for 511361 line segments. The explanation of the road types in Mn/DOT base map can be found in Appendix A.

We have two experimental setups. One is for the line string colocation analysis, and the other is for the map accuracy analysis.

4.1.1 Experimental Design for Collocation Analysis

The purpose of this experiment was to analyze the collocation ratio and illustrate the line string association patterns in the Twin Cities metropolitan area for the Mn/DOT base map.

Figure 4 shows the experiment design for the calculation of the collocation ratio for the Mn/DOT base map.

First, the digital map data set was divided into two groups. One group includes data for the specified road type. The other group includes data for other road types. Both subdataset were fed into the collocation ratio discovery algorithm.

4.1.2 Experimental Setup for Map Accuracy Analysis

Figure 5 shows the experiment design for the map accuracy analysis. First, a subset of digital road data in the Twin Cities area was extracted according to the line string colocation miner output as selected test sites. Then GPS data for these selected test roads was collected by driving a vehicle on these roads. The GPS sampling interval was 0.1 second. A total of five main test routes were selected. High quality GPS data from a Trimble MS-750 GPS receiver was used as gold standard data, around which buffer of different sizes were generated. Finally, the map accuracy ratio was calculated as the ratio of the length of the specified roads from the digital map that fell into the generated buffer to the total length of the specified roads.

4.1.3 Experiment Implementation Platform

Algorithms calculating the line string association ratio and map accuracy ratio were implemented in C and all experiments were conducted on a Sun Blade 100 workstation with 500 MHz CPU and 128 MBytes of memory running the SunOS 5.8 operating system.

4.2 Line String Association Ratio and Site Selection

Test route selection was based on the calculated line string association pattern. We found that most of the high affinity patterns were concentrated in highway areas. This finding directed us to select five field test routes near the highway routes.

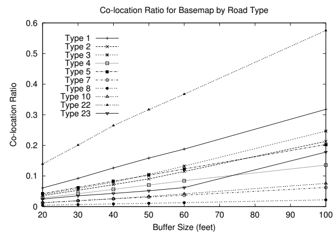

Figure 6: Collocation Ratio for Different Road Types

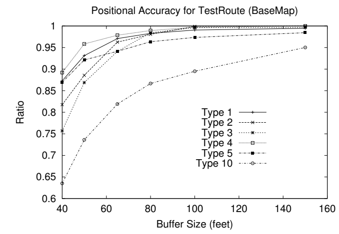

Figure 7: Digial Map Accuracy for Different Road Types

Figure 6 gives the collocation ratios for different road types and different buffer sizes. The general trend is that the line string association ratio increases with the buffer size increment for all of the different road types. The Interstate highway, road type 1 in the Mn/DOT base map, is the most interesting road type in the road user charge system. It has a 100 foot colocation ratio of about 20%. Road type 2, i.e. US highway, and road type 3, Minnesota highway, have 100 foot line string colocation ratios of about 11%. This means that the current digital road maps are not approapriate for road user charge system.

4.3 Map Accuracy Analysis

Figure 7 shows the map accuracy for different road types in the Mn/DOT base map. The general trend is that the positional accuracies increase with the increment of the buffer size. If we assume the vehicle speed is 60 miles per hour, the total number of GPS points in the analysis is 38700 for road type 1 (Interstate highway). Road types 1 (Interstate highway), 2 (US Highway), 3 (MN Highway) have 77% - 87% accuracy. No road type in the base map had over 90% accuracy level within the 40 feet buffer on test routes. Ninety percent accuracy occurred only for a buffer size of +/-50 feet. This result suggests that the current Mn/DOT base map is not appropriate for the road user charge system.

5 Conclusion and Future Work

In this paper, we explored the problem of digital road map evaluation for large road network systems.

We conducted a case study to evaluate the accuracy of the Basemap of the Minnesota Department of Transportation. To do this, we developed a spatial framework to determine pattern where roads were in close proximity and map evaluation in which we formalized a line string association problem and used it to select the field test routes for GPS data collection as sampling procedure. Then we proposed a line segment based digital road map evaluation approach. Use of this spatial framework led us to conclude that the Mn/DOT basemap is not appropriate for a road user charge system and may lead to incorrect and unfair charges.

We are continuing to work further on the digital map system and developing a new generation of digital road map for future applications. In this new generation of digital road map, we plan to prioritize roads selected for more accurate digitizing according to the co-location output and the road types. Another important issue is to consider digital road map accuracy evaluated using specific map matching algorithms. We have indeed incorporated a map matching algorithm into our evaluating, but that is a subject of a different paper.

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Appendix A

Type	Meaning
01	Interstate Trunk Highway
02	U. S. Trunk Highway
03	Minnesota Trunk Highway
04	County State-aid Highway
05	Municipal State-aid Street
07	County Road
08	Township Road
09	Unorganized Township Road
10	Municipal Street
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	Ramp
23	Private Jurisdiction Road

Table 2: Road Types For Mn/DOT Digital Base Map