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TRAFFIC NETWORK CONDITION MONITORING VIA MOBILE PHONE LOCATION REFERENCING - AN EMERGING OPPORTUNITY

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ABSTRACT: Advanced traveller information systems (ATIS) constitute one of the key elements of ITS. ATIS consist of three basis functional capabilities, namely: obtaining traffic network data from various sensors/sources; estimating the traffic condition (e.g. travel time) of each road segment within the network; and disseminating this information to travellers. A great deal of research conducted over the past decade has examined various aspects of these functional capabilities. However, currently the most significant factor limiting the wide spread deployment of ATIS is the lack of a cost effective method of obtaining data reflecting network travel conditions.

Recent advances in wireless communication technologies provide the capability to autonomously determine the location of wireless communication devices (e.g. mobile phones). This capability provides an opportunity to acquire large quantities of traffic data without the need to deploy a large and costly network of dedicated traffic sensors. To date, such a system has not been deployed in North America. However, a number of projects, including a recent project in Ottawa, Ontario, have been initiated to examine the feasibility of such an approach. This paper explores the potential that such an approach could have in terms of supporting traffic management and traveller information services. Specifically, this paper examines the key technical challenges that must be overcome before such a system can be implemented.

1. INTRODUCTION

The provision of accurate, relevant and timely road conditions information has long been recognised as of value to travellers and traffic system management personnel. Currently, the state of practice with respect to the provision of traffic information is rather limited. Congestion information is provided at a very small number of fixed points along selected major freeways (i.e. changeable message signs) and qualitative information is provided periodically over AM and FM radio. While these methods of disseminating traffic information are of some value, they are significantly limited in terms of spatial coverage, accuracy, and timeliness of delivery to the traveller.

One of the most significant stumbling blocks in the widespread deployment of full function Advanced and In-Vehicle Traveller Information Systems (A/IVTIS) is the difficulty in obtaining adequate traffic conditions data. Current technologies for obtaining traffic data, such as loop detectors, video imaging, DSRC (i.e. tag), radar, etc., are infrastructure intensive, and therefore are prohibitively expensive to deploy over large geographic areas. Consequently, most traffic management centres in North America have deployed traffic surveillance infrastructure only along the most heavily travelled corridors. Furthermore, jurisdictional issues associated with private sector firms installing traffic surveillance equipment on public roadways inhibits the private sector development of A/IVTIS. The result is that while there is generally adequate traffic data available for major freeways within most large urban centres in North America, there is typically very little or no data available for the remainder of the transportation network.

One solution that has been proposed to obtain traffic condition data over large networks without large capital expenditures for dedicated traffic monitoring infrastructure is to anonymously track the location of mobile phones. Wireless service providers have been legislated in the US, Canada, and elsewhere to provide the capability to determine the location of a mobile phone when a call is made to 911. This capability already exists for wired phones and is used to provide expedient emergency response as the location from which the call originated is automatically determined. In the United States, the Federal Communications Commission (FCC) decided in 1996 to require all wireless service providers to provide location information to enhanced 911 (E911) public safety services. In Phase I, wireless service providers were required by March 1998 to report the originating phone number and location of the cell site receiving the originating call. In Phase II, wireless service providers are required to provide the originating phone number and estimates of the latitude and longitude of the caller's position. The FCC established a four-year window beginning in October 1, 2001 and ending December 31, 2005, during which these requirements must be met. The FCC has stipulated that position estimates must be within 100 meters for 67% of the calls and 300 meters for 95% of the calls.

It is clear that while the motivation for incorporating location referencing capabilities is compliance with the FCC ruling, the implementation of these location referencing capabilities presents a number of interesting opportunities for meeting other needs, such as obtaining traffic network condition data. For example, the periodic location estimates for a phone in a vehicle can be used to determine the speed at which the vehicle is moving.

Obtaining traffic information using mobile phone tracking has several significant advantages over existing traffic surveillance approaches. First, the number of potential probes (e.g. phones in vehicles) is very large. For example, in Canada the Canadian Wireless Telecommunications Association (CWTA) reports that there are currently (as of the end of Q3 2004) 14.4 million cellular/PCS subscribers, with an annual growth rate of approximately 12% (CWTA, 2005). Second, these probes are sufficiently dispersed throughout the network that the number of active probes on any specific road segment in any given interval (say 15 minutes) is likely to be sufficient to provide travel time (or average speed) estimates of adequate reliability. Third, this approach is low cost, as the vehicle side infrastructure (i.e. wireless device) is already owned by the traveller, and the hardware required by the wireless operator will already be in place to meet other needs (e.g. E911 requirements).

The objective of this research is to investigate the potential to derive useful road network traffic condition information by anonymously locating mobile phones and to develop models and algorithms that can support this functionality. In the following sections, the problem of using mobile phones as traffic probes is formally defined and various associated challenges are examined. Current literature on this topic is then reviewed to identify the issues and drawbacks in the existing approaches. Lastly, a new methodology is proposed and some preliminary results are discussed.

2. USE OF MOBILE PHONES AS TRAFFIC PROBES: PROBLEM DEFINITION AND CURRENT METHODS

Consider a hypothetical case in which a vehicle is currently traveling on a road network as shown in Figure 1. The vehicle is equipped with a mobile phone and its location (longitude and latitude) can be anonymously determined by the wireless network service provider. The problem of interest is to infer the road network traffic condition (e.g. average travel speed or travel time) of the road segment(s) or link(s) that the vehicle has recently traversed or is currently traversing. Information available for the estimation includes time-stamped location measurements (up to current time) and a database of the road network including road geometry and network topology. The problem can be divided into two sub-problems as follows:

1. Determine the links the vehicle has traversed and is currently traversing and the position of the vehicle on the link associated with each time-stamped location measurement. This sub-problem is commonly referred to as *map matching* problem;

2. Estimate the traffic condition variables (e.g. average travel speed or travel time) on those links that the vehicle has recently traversed and is currently traversing.

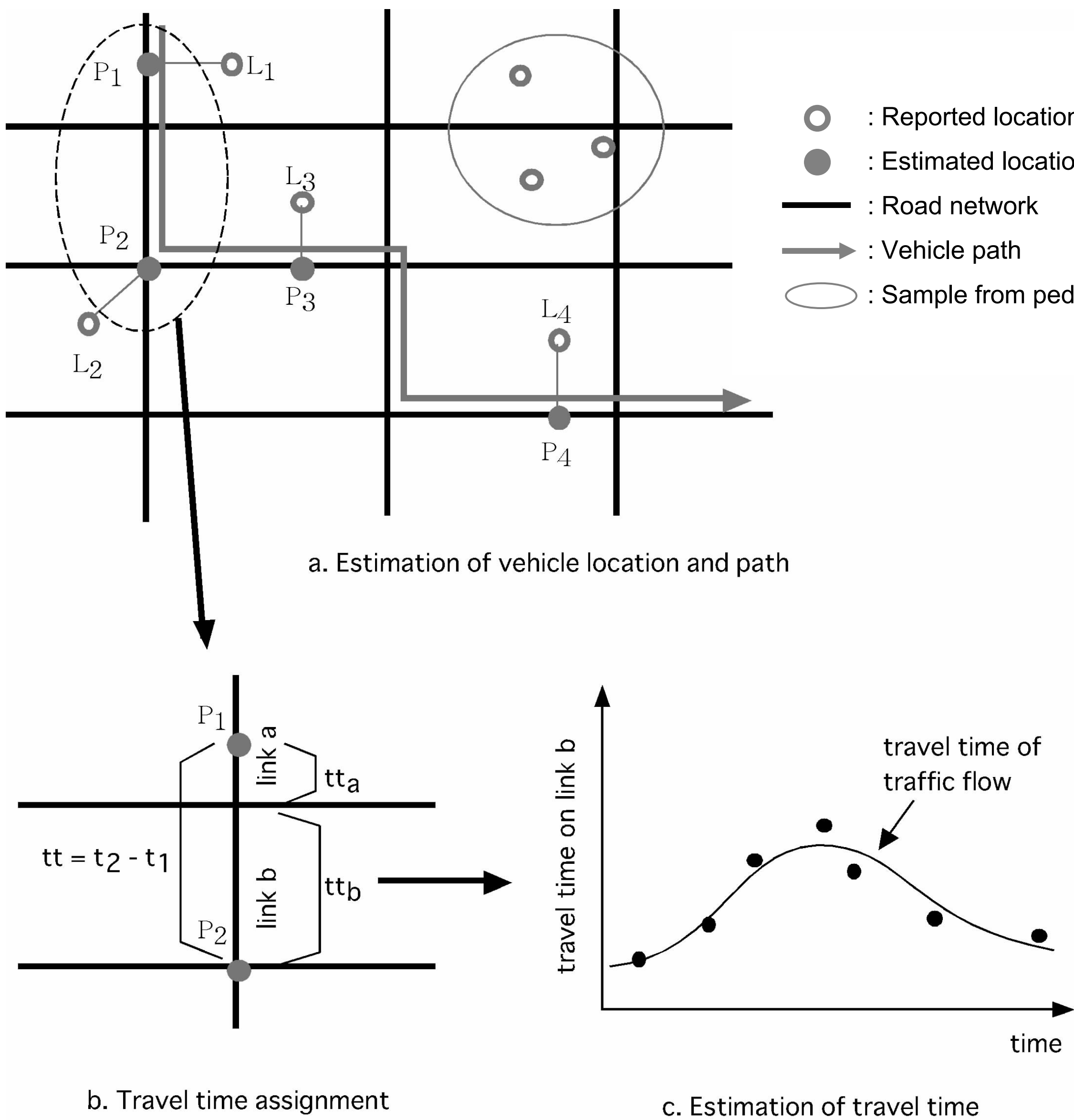

Figure 1: Estimating road network traffic conditions from mobile phones

The attempt to identify autonomously the location of a moving vehicle began with the use of in-vehicle navigation systems during the last decade. The typical positioning components of those systems were global positioning system (GPS) and/or dead reckoning (DR). When these components are installed on a vehicle, the vehicle is able to determine its position. Knowing that the vehicle must be on the road network, the position is combined with a database of the road network to estimate the vehicle's position on one of the road links.

The challenge in using this approach arises from the error contained within the position estimated by the positioning components. Typically, this error is sufficiently large that some *map matching* method for location estimation is required. With regard to this estimating method, many approaches have been proposed.

The simplest method (Streit et al., 1998) is to match the measured point to the closest link on the road network using the Euclidean distance metric (point-to-link match). It is true that this method may provide accurate estimates, however there is no assurance that it always gives proper estimates. Some other approaches (Kao and Huang, 1994; Scott and Drane, 1994 and 1995; Enescu and Sahli, 2002) introduced more sophisticated map-matching methods utilizing fuzzy logic or Kalman filtering. However, these methods make use of additional information such as vehicle heading, and are therefore generally not applicable when position estimates are obtained infrequently (i.e. on the order of 1 minute)

The earliest known North America operational test of the feasibility of obtaining vehicle location and travel time information tracking mobile phones occurred in 1996 (University of Maryland Transportation Studies Center, 1997). However, the study concluded that the location referencing hardware was insufficiently reliable to permit an evaluation of the concept.

More recently, there have been reports that another field test is underway in Virginia. The U.S. Department of Transportation (USDOT) and Virginia Department of Transportation (USDOT) have partnered to help fund a feasibility test of new technology under development by AirSage Inc of Georgia. This study is still in its beginning stages and no detailed information is yet available describing the proposed methods or test results.

In 2004 Transport Canada funded a project in which road traffic conditions were estimated on the basis of speeds obtained by tracking mobile phones equipped with assisted GPS functionality. The operation field test, which was conducted in Ottawa, Canada, compared the average speeds obtained from 15 mobile phones in separate vehicles to reported speedometer speeds. Vehicles travelled a known route through a mixed freeway and arterial network. The results of this field test demonstrated the feasibility of obtaining estimates of road network traffic conditions from autonomously locating mobile phones.

While significant improvements have been made in the methods and technologies available for estimating the position of a mobile phone, included assisted GPS, the accuracy of the reported position is not as high as for in-vehicle systems that combine GPS with supplemental systems such as dead-reckoning. Furthermore, and possibly more importantly, in-vehicle systems are able to obtain position estimates at high frequency (on the order of one position estimate per second). In contrast, it is likely that position estimates from mobile phones would not be obtained more frequently than once or twice per minute. Consequently, the challenge is to develop a new location estimator that is applicable given the magnitude of position estimation errors and constraints on the frequency of obtaining location data.

While many of the existing map-matching methods are not appropriate for our purposes, some researches (Bernstein and A. Kornhauser, 1996; White, 2000) have proposed map-matching methods that can be used as a starting point for our discussions. These researchers have proposed four different types of map-matching methods (including one similar to the point-to-link match method we introduced earlier). The difference between the four methods is the constraints that are introduced when considering the set of possible vehicle locations. These constraints reflect “topological information”, such as vehicle traveling distances, road network topography and connectivity, etc. in reducing the location solution space. The use of these constraints provides results that are more accurate than the point-to-link match method.

Thus, in spite of the variety of the positioning components, the fact is that there is no definitive method to obtain a sufficiently accurate vehicle location. The work described in this paper identifies the context within which the authors are developing a new method for location estimation.

3. LIMITATION OF EXISTING METHODS AND REMAINING ISSUES

Noticeable efforts have been initiated in the past to examine the feasibility of using vehicles with a location referencing system as probes to derive traffic conditions information. Most of these efforts however assume the availability of a vehicle-based location system such as GPS and Dead Reckoning and have mainly focused on the problem of map matching. Limited research has been undertaken to go beyond solving the location problem and derive traffic information based on a mobile phone-based location system with limited location accuracy and frequency. Despite the progress made in the past, a number of technical issues still remain to be addressed:

1. Errors in location estimates will create corresponding errors in the estimated average speeds or travel time. Furthermore, calculated speeds (or travel times) must be associated with a unique segment of roadway. Errors in the position measurement make this association difficult. This issue can be illustrated using a simple example as shown in Figure 2. Assume that position estimates are obtained for mobile phones located in two vehicles (vehicle *A* and *B*). The true location of the phone is unknown, but the position returned from the location referencing system (LRS) is accurate with some known error distribution (as indicated by the dashed circles centred on vehicle *A* and *B*). In this particular illustration, assume that the position returned by the LRS is given as the solid red circle. The challenge is to correctly determine which road segment each vehicle is traversing. Vehicle *A* is travelling on the freeway, but the position measurement indicates it is on the parallel service road. Conversely, vehicle *B* is actually travelling on the parallel service road, but the position measurement indicates it is on the freeway.

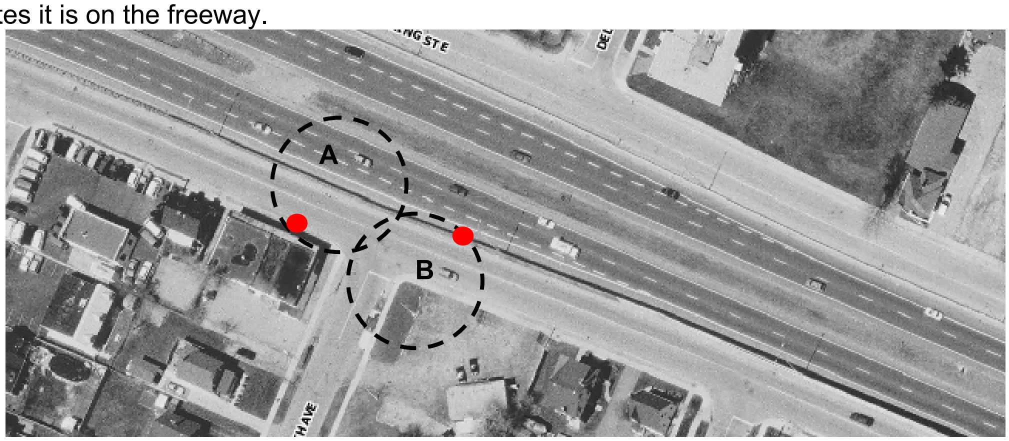

Figure 2: Effect of positioning error on map matching

2. As with all vehicle-based data collection methods, issues arise with respect to sample size and bias in the sample. These issues have been examined in the context of other probe-based applications (for example; Hellinga and Fu, 2002; Hellinga and Gudapati, 2000; and Hellinga and Fu, 1999), but will need to be examined in this context as well. In particular, it would be important to develop relationships that permit the estimating of the sample size required to achieve some desired level of reliability in the travel time estimates (or conversely, relationships that permit the estimation of the reliability for a given sample size).

3. Sampling frequency will likely be constrained by the number of mobile units sampled and the LRS system characteristics. Less frequent sampling of a mobile unit's position may reduce communication system loadings, but also provides a lower level of spatial resolution in terms of traffic condition data. The explicit trade-off will depend on the characteristics and constraints of the LRS and communication system.

4. In most existing map matching systems, the vehicle location at the beginning of a trip is assumed to be available (i.e. entered or confirmed by the driver) and therefore does not have to be identified autonomously. In contrast, a mobile phone-based tracking system requires a mechanism to determine the initial location of a vehicle trip.

5. In order to obtain the correct traffic condition estimates, the consistency of each vehicle's travel path must be maintained. In other words, the matched links for the same vehicle must constitute a continuous feasible path. Besides the requirement of path consistency, some restrictions on general vehicle behaviour should also be considered. Examples include cyclic sub-path, U-turn, and violation of traffic rules. The challenge is, however, that while these behaviours are unusual, they are not entirely impossible.

6. Most existing map matching algorithms considers only the geometry and topology of the road network and information on traffic control is not taken into consideration. Knowing a vehicle's likely behaviour at an intersection due to traffic control should help improve the performance of map matching algorithm.

7. The mobile unit (positioning module) may not be attached to a vehicle, and therefore there is an issue of how to distinguish between mobile phones in traveling vehicles and mobile phones at other locations (i.e. pedestrians on sidewalk, in a building, underground or above ground concourse, etc)

8. Most existing models consider one vehicle (mobile unit) at a time and do not consider the availability of location information of other mobile units in the vicinity.

4. OVERVIEW OF PROPOSED METHODOLOGY AND PRELIMINARY RESULTS

This research proposed a new map matching model aimed to overcome the main technical challenges and the limitations of the existing models described in the previous section. While the development of this new method is still in progress, its main features can be summarized as follows:

1. The objective of the model is to estimate the vehicle location corresponding to the measured point and match it to the most reasonable travel path for the associated trip;

2. The estimation process considers a variety of constraints concerning position error of the location referencing system, network geometry and topology at the vicinity of the measured location;

3. It considers both current and recent location measurement and matching history;

4. It incorporates the concept of confidence level of matched points, which aims to make the estimation more reliable.

A simulation model is being developed to evaluate existing and proposed map matching algorithms. The inputs to the simulation model include network data and parameters to characterize the LRS. The model simulates the movement of a given vehicle traveling along a randomly generated route and records relevant information such as true positions and links, "measured" positions generated along the input parameters, matched links and matched positions.

For the purpose of illustration, a small-scale sensitivity analysis is performed to examine several critical factors that might influence the performance of a map matching algorithm. A hypothetical road network consisting of 146 nodes and 363 links with an average link length of 105 meters was modelled (Figure 3).

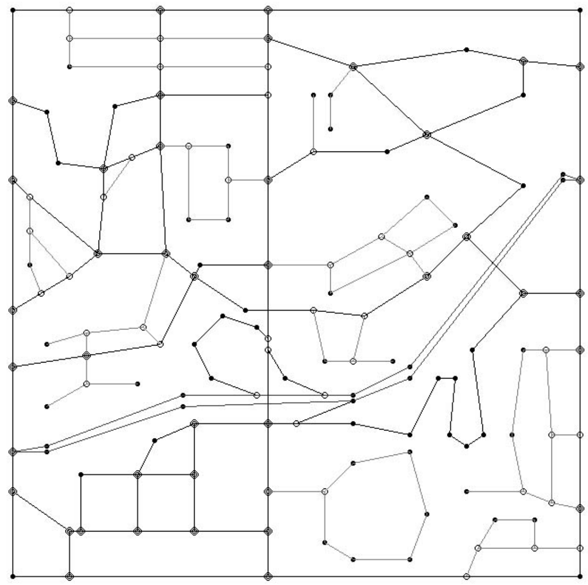

Figure 3: Road network tested for location estimation.

The performance of the location estimation is measured by the matching rate, which is defined as the ratio of correct matches to the total number of all the estimated locations. When an estimated location belongs to the link on which the true location exists at a sampled time, it is counted as a correct match. This metric is more restrictive than that of White et al. (2000), because their correctness is based on arcs, which could be composed of more than one link, as illustrated in Figure 4.

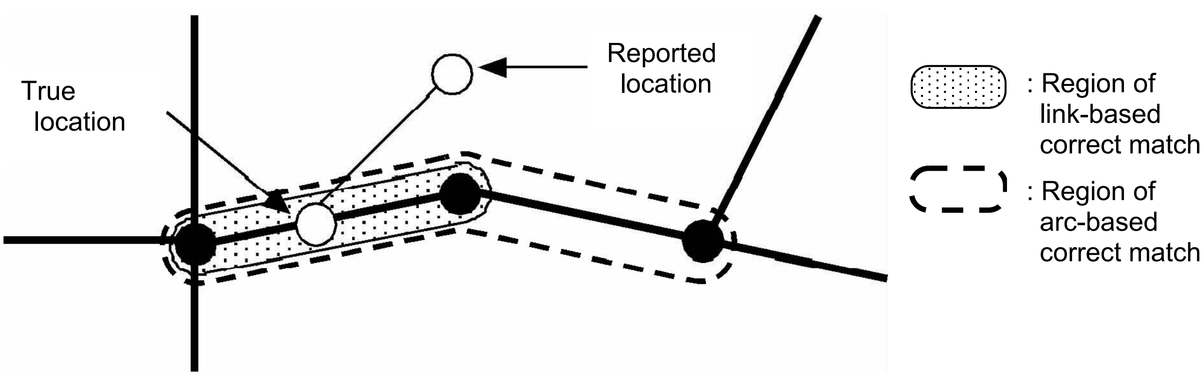

Figure 4: Illustration of measuring correct match for location estimation.

Figure 5 shows the matching rate for the different conditions of location error and sampling frequency. The estimated location is deemed accurate when the error of the sampled location is small or the sampling frequency is set to a short interval. The bold line bounded by black dots on the graph indicates the range of the field test performance by White et al. (2000). The maximum location error is set at 150 meters in their test, which is presumably equivalent to the location error with the standard GPS deviation of 50 meters. When the sampling frequency is set to 15 seconds, the estimates in this research indicate higher matching rates on average than the best result cited by White et al. (2000), with a sampling frequency of one second and a more relaxed metric of correct match.

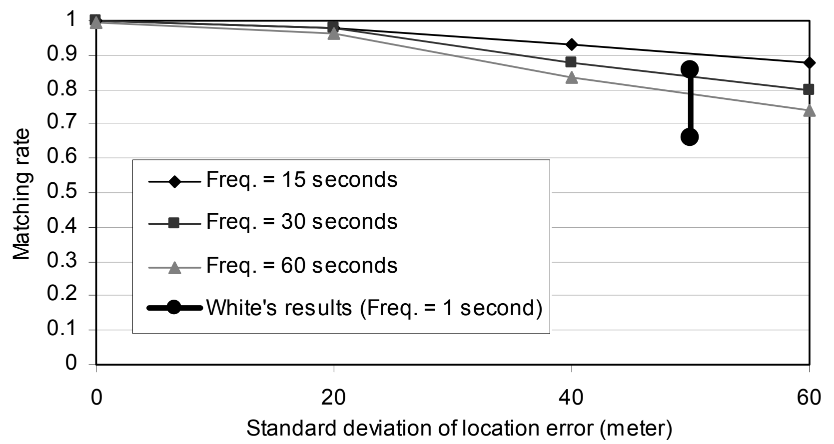

Figure 5: Performance of location estimation.

As expected, the performance of the map matching algorithm is inversely related to the position error. Furthermore, the matching rate increases as location data are obtained more frequently.

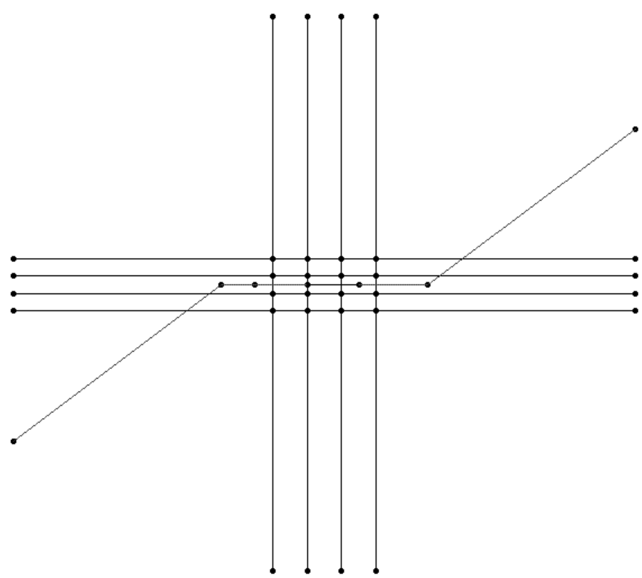

Figure 6: Road network tested for link travel time estimation.

Figure 6 shows the road network used for examination of the performance of link travel times derived from the proposed model. Four arterial flows hypothesized from each of four directions merge at the center of the network. Northbound and Southbound arterial links have 100 or 50 meter road segments, and Eastbound and Westbound arterial links have 200 meter road segments. A bi-directional freeway line also crosses at the center of the network, and has a set of on and off ramps overlapping on the freeway line. All the nodes crossing between vertical and horizontal arterial segments have traffic signals. All vehicles start or end their trips at one of the zones of the periphery of the network. The traffic flow on the network is generated using INTEGRATION, a microscopic traffic simulation model. Probe reports are generated randomly on the basis of second-by-second location data generated from INTEGRATION.

Figure 7 shows preliminary results of link travel time estimation for this network. The traffic is set to a light volume through the network. Five percent of the vehicles are probes from which location data, with measurement errors, are obtained at a frequency of 30 seconds. The proposed model estimates link travel times from these location data. The performance is tested in three levels differentiated by the standard deviation of measurement error. The longer links joining the periphery zones with the network are not included in the results. The x-axis of the graph in Figure 7 is categorized into the types of link. The y-axis is the average absolute discrepancy between the estimates of link travel times from probe vehicles and true link travel times from all vehicles. Each discrepancy is provided with a difference of the average travel times of latest 15 minutes between the estimate and the true link travel time. For example, if a 15 minute average of true travel times is 10 seconds, and the estimated 15-minute average travel time is 12 seconds, then the resulting discrepancy is calculated as 0.2 (i.e. |10 – 12|/10). The results indicate that the accuracy of the prediction model is highest for freeway links and lowest for very short arterial links.

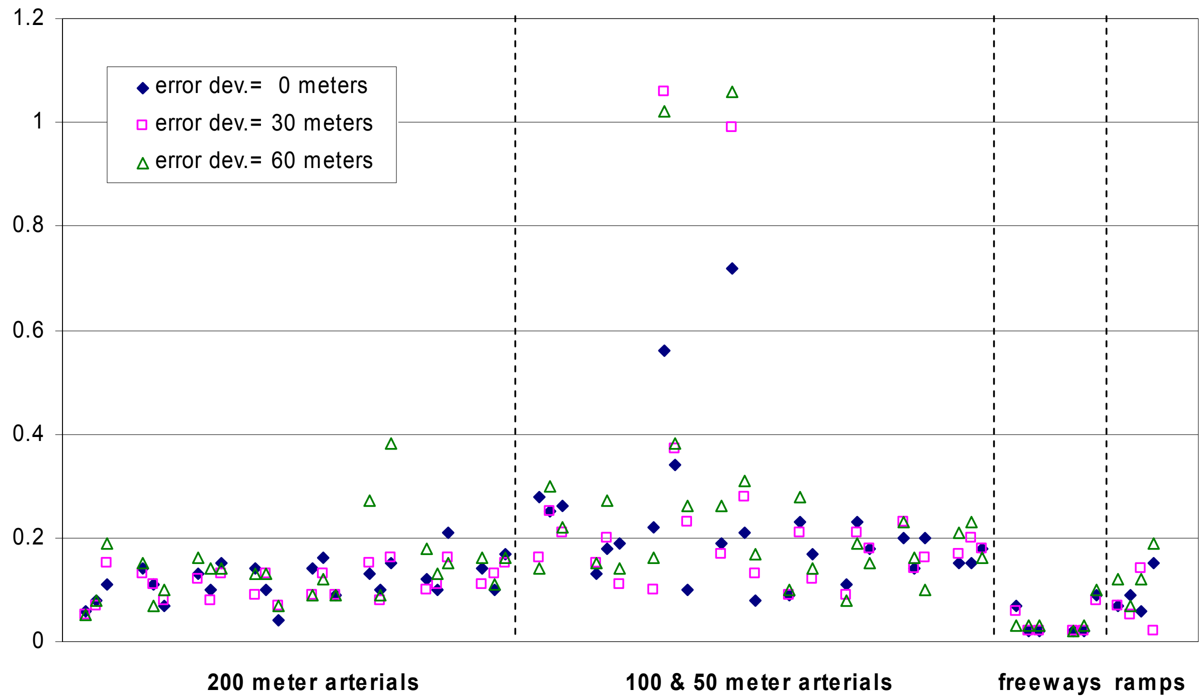

Figure 7: Accuracy of link travel times.

5. CONCLUDING REMARKS

The potential of being able to obtain traffic information from the anonymous polling of mobile phones is enormous: it will practically turn a large portion of vehicles on road into probes, making it possible to monitor real time traffic conditions throughout the whole network and over all time periods without the need for an infrastructure-intensive traffic surveillance system. There are however several challenges that need to be overcome before such potential can be realized including the determination of the number of probes required to achieve a desired level of reliability in the traffic network condition data, suitable probe sampling frequency, and identifying those phones that are in a vehicle on the road versus phones not in vehicles.

Research efforts at the University of Waterloo continue to focus on devising solutions to these challenges. New models and algorithms are being developed that can provide reliable estimates of the travel time, speed and other traffic conditions variables based on the location history of mobile phones. Preliminary research results indicated that many of the issues can be resolved by integrating multiple data sources with advanced pattern recognition and state estimation techniques.

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