Evaluation of travel time estimation based on LWR-v and CTM-v: A case study in Stockholm
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Abstract—Real-time estimations of current and future traffic states are an essential part of traffic management and traffic information systems. Within the Mobile Millennium project considerable effort has been invested in the research and development of a real-time estimation system that can fuse several sources of data collected in California. During the past year this system has been adapted to also handle traffic data collected in Stockholm. This paper provides an overview of the model used for highways and presents results from an initial evaluation of the system. As part of the evaluation process, GPS data collected in an earlier field-test and estimations generated by the existing system used by the TMC in Stockholm, are compared with the estimations generated by the Mobile Millennium system.

Given that the Mobile Millennium Stockholm system has not undergone any calibration, the results from the evaluation are considered promising. The estimated travel times correspond well to those measured in the field test. Furthermore, the estimations generated by the Mobile Millennium system can be regarded as superior to those of existing traffic management system in Stockholm. The highway model was found to perform well even with a reduction in the number of sensors providing data. The findings of this study indicate the robustness of the Mobile Millennium system and demonstrate how the system can be migrated to other geographical areas with similar sources of available data.

I. INTRODUCTION

The need for better estimations of current and future traffic states is growing in cities all over the world, both from a traffic management and a traffic information perspective. In parallel to this need, considerably more traffic data is being collected and made available. As a result of these developments, the traffic state estimation task is becoming increasingly more complex and consequently more innovative research is required.

Most of the previous research in this area is conducted in relation to the off-line case and focuses on single corridors or links. An exception is the Mobile Millennium project [1] at UC Berkeley where considerable effort has been put into the research and development of a real-time estimation system for networks containing both arterial and highways. The highway model that has been developed is based on a first-order traffic model with velocity as the state variable, as described in [2]. This makes it possible to efficiently fuse data from loop detectors with probe vehicle data. The estimations of traffic state are performed using an ensemble Kalman filter.

During the last year the Mobile Millennium real-time highway traffic estimation model has been adapted to handle traffic data collected in the greater Stockholm area. This paper provides an overview of the integral highway model that has been adapted and implemented for Stockholm conditions and presents the results of an initial evaluation.

The purpose of the study reported in this paper is to evaluate the overall suitability of the highway model for Stockholm conditions, and to determine if the model will improve the quality of travel time estimations generated by the current system at the Traffic Management Centre in Stockholm. The model settings used in the adapted highway model are practically identical to those used for estimations in the San Francisco Bay Area, and therefore the validation results will also provide an indication of the robustness of the model and the model settings. Furthermore, the results will indicate the need for further calibration due to differences in the data sources and driving behavior between Stockholm and California. In the evaluation process, GPS data collected from an earlier field test and travel time estimations generated by the current traffic management system in Stockholm [3] are compared with the estimations generated by the Mobile Millennium system.

The paper is structured as follows. Firstly, the Mobile Millennium and associated Mobile Millennium Stockholm projects are briefly described along with an overview of the current travel time estimation system used at the Traffic Management Centre in Stockholm. In the following section the pre-processing of collected radar data is described together with the traffic state estimation model. Thereafter the validation results are presented and, finally, the conclusions and future work are discussed.

II. BACKGROUND

In this section, the Mobile Millennium and associated Mobile Millennium Stockholm projects are presented together with an overview of the prerequisites for Stockholm.

A. Mobile Millennium

Mobile Millennium is a research project developed at the University of California, Berkeley. It focuses on the design, implementation, and operational deployment of novel algorithms and innovative techniques to address current road traffic challenges. The project [1] was launched jointly with Nokia and NAVTEQ, under the umbrella of the California and US Department of Transportation in November 2008. This followed the Mobile Century experiment [4], which successfully demonstrated on a large scale the added value of user-generated GPS probe data. The project represents state-of-the-art research on traffic modeling and estimation, routing directions and pollution estimation.

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The Mobile Millennium system architecture is organized around the concept of a model graph which consists of a graphical abstraction of the road network together with a minimal set of information required for traffic state estimation [5]. This representation is shared by all processes running in the system and practically serves as a geographic information system layer dedicated to statistical and model-based traffic estimation. The simplicity of this representation and the standardized methods developed for generation from classical digital maps, facilitate the portability of this part of the system to other locations.

Measurements collected by fixed traffic sensors (loops, radars, toll transponders), and probe vehicles (GPS point speeds, GPS travel-times) are filtered in real-time and map-matched to the model graph. These measurements are assimilated by physical and statistical traffic models and are optimally combined with historical knowledge to produce best estimates of current traffic conditions. Due to the different properties associated with the traffic dynamics of highway and arterial networks, and various dissimilarities in the data sources that are available, different algorithmic approaches for traffic estimation are applied for each network type.

B. Mobile Millennium Stockholm

A future aim of the Swedish Transport Administration is to have a system that can generate travel time estimations and predictions in real-time for all major roads in Stockholm, Gothenburg and Malmö. An important part in the realization of this aim is to develop and improve possibilities and processes for data fusion. As a result, the Mobile Millennium Stockholm project was initiated in 2010 [6]. The main goals of this project are threefold: to assimilate the knowledge gained from the Mobile Millennium project at UC Berkeley; to build a platform for continued research; and to develop new data fusion methods for the available data sources in Stockholm. Another important part of the project is to examine whether the number of fixed sensors can be reduced as a result of the use of probe data and advanced models for data fusion.

In the first phase of the project, the original Mobile Millennium system was adopted and adapted to handle traffic data from greater Stockholm and visualize estimations of the traffic state. The traffic data collected in Stockholm is in many ways similar to that collected in the San Francisco Bay Area, thereby simplifying the adaptation process. There are, however, subtle differences in the data that, together with probable differences in driving behavior, may influence the overall quality of the estimations generated by the system.

C. Current status in Stockholm

Fixed detector data and GPS data from taxi probes are the two real-time data sources that have been available to the Mobile Millennium Stockholm project up to the present date. The highway model evaluated in this paper only uses radar data from fixed detectors but is also configured to handle point-speed measurements from probe vehicles. Unfortunately, the positional data from taxi vehicles in Stockholm is only reported at one minute intervals and does not include speed measurement. This makes it unsuitable for the current highway model implementation.

In the current travel time system implemented at the Traffic Management Centre in Stockholm, a simple data fusion algorithm is applied to links where travel times are calculated from two or more data sources. A travel time is calculated for each data source and distributed over a link in accordance with the assigned speed limit. In the algorithm, a quality value allocated to each measurement is used for weighting purposes [3]. For links where no real-time data is available, the travel time is calculated from historical data as well as data from neighboring links. The links that form this network are generally quite long and estimations are generated only once every five minutes.

III. MODEL DESCRIPTION

In this section the preprocessing of radar data is described along with the model used for the real-time estimation of traffic state on highways in Stockholm.

A. Radar data pre-processing

The radar data used in the Mobile Millennium Stockholm project is collected by detectors that are an integral part of a Motorway Control System on the main highway that passes through Stockholm. Radar detectors are located approximately every 500 meters and record data specific to each traffic lane. Speed and traffic flow data is collected and aggregated at one-minute intervals.

Before the radar data is fed into the highway model it is pre-processed. The pre-processing has two main purposes: to aggregate data for several lanes, and to filter out high speeds. The highway estimation model is not lane dependent, and an aggregation of data is necessary where data is lane specific. For each lane where a measured speed and flow is available, a density is calculated by dividing the flow with the speed. This is done in accordance with the fundamental equation of highway traffic flow [7]. The calculated density is used as a weight when an aggregated speed is calculated for the detector site.

Measured speeds that are higher than the speed limit are filtered due to the fact that very high speeds can create problems for the estimation model. This is due to characteristics of the fundamental relationship between speed, flow and density.

B. Highway Model

The Mobile Millennium highway traffic estimation model [2] is based on a first order traffic model, the Lighthill-Whitham-Richards for velocity (LWR–v). It is a velocity based partial differential equation consistent with the classical LWR PDE [8, 9]. Traffic state is discretized into cells of approximately 300 meters and at every time step, the discretized partial differential equation is solved numerically using the CTM-v [2]. Since the state variable is velocity it is possible to combine different types of speed measurements such as aggregated data from fixed detectors and single point speed measurements from probe vehicles.

Available pre-processed measurements from radar detectors are assimilated into the highway model every 60 seconds. The measurements are modeled as linear observations of the current traffic state. The conditional distribution of the traffic state, given the measurements, is then computed using the ensemble Kalman filter [10]. The
ensemble Kalman filter is an extension of the classical Kalman filter that involves representing the state estimate distribution as a set of ensembles. This allows optimality guarantees even in the case of non-linear dynamics. The output of the filter is a minimal variance estimate given the traffic model and the measurements.

In the evaluated version of the highway model, the fundamental diagram parameters, such as maximum density and shock wave speed are equal for all links and are the same as those used in the model for the San Francisco Bay Area.

IV. Evaluation of estimated traffic state

In this section the results of the evaluation are presented for estimated traffic state and travel times. The estimation output has been evaluated against GPS-data collected in an earlier pilot project and is also compared against travel times estimated by the current system used by the Traffic Management Centre in Stockholm [3]. Furthermore, estimation output from a model setting where only every other sensor is used has been compared to a setting with values from all sensors. This analysis is useful to determine the possibility to reduce the number of radar detector sites.

A. Data collection

In 2010 a small field test involving ten probe vehicles with GPS-equipped cell phones was carried out in Stockholm. The field test took place on the main highway passing through Stockholm and the vehicles drove back and forth on a test stretch during morning and afternoon peaks on the 16th and 23rd of March. The GPS-data from the field trial has been map-matched and travel times and trajectories have been extracted. In the current evaluation of estimated traffic state, attention has been focused on the northbound traffic during the morning peak period between 7:30 and 9:30 and the afternoon peak between 16.00 and 17.00 for the 16th of March. During the morning peak there was some heavy congestion while the afternoon peak showed only moderate levels of congestion. The test stretch in either direction was approximately 4.5 km and included 15 radar detector sites, see Fig. 1. The spacing between the detector sites on this stretch varies between 150 and 450 meters. The posted speed limit for the test stretch is 70 km/h.

B. Evaluation of space-time plot

In the first step of the evaluation, the GPS-trajectories and the estimated velocities have been compared, see Fig. 2. The number of trajectories is limited, approximately 20 during a two hour period, making it difficult to draw any definitive conclusions. It is, however, possible to identify a number of phenomena that can be seen in both the space-time plot of estimated velocities and the plot of trajectories. The trajectories are consistently smoother during the afternoon peak due to the free-flow conditions. During the morning peak however, the trajectories are more deviant illustrating the stop and go conditions that are consistent with congestion.

In Fig. 2c there is a green area in the time-space plot between 9:00 and 9:30 during the first 2.5 km. This indicates a situation where the queue dissolves and the velocities are higher and more stable. This situation is also evident in Fig. 2a where the inclination of the trajectories becomes steeper suggesting higher velocity over time. Furthermore, in the top left hand corner of Fig. 2b and Fig. 2d there are corresponding areas in both figures where congestion occurs and causes a reduction in velocity. Even though the number of GPS-trajectories is limited the data is correspondent with the characteristics of the space-time plots of estimated traffic state. The fixed sensors are quite densely spaced on the studied test stretch allowing the possibility to eliminate a number of sensors and instead use these as a de facto ground truth.

Figure 1. Studied test stretch at E4/Essingeleden in Stockholm.
In Fig. 3, the results from two scenarios with different numbers of sensors are compared. Fig. 3a visualizes the estimated traffic state using all sensors, while Fig. 3b visualizes a scenario where the estimated traffic state is based on every other sensor. As expected the figures indicate that as long as the traffic is in the same state, in this case congestion, the estimations are very similar. However, when congestion dissolves the scenario with fewer sensors takes considerably longer to identify the change in state. This is expected since the highway model currently uses fixed sensor data only. Furthermore, with the current parameter setting the Kalman gain is high which means that the Kalman filter puts more weight on measurement rather than prediction in the traffic model.

Fig. 3c illustrates the absolute difference between Fig. 3a and Fig. 3b. In all cells that are black the difference in estimated velocity is larger than 10 km/h. As observed earlier, great differences occur when the traffic state changes at a position of approximately 1.5 km and time 9.00. There is also one cell located around position 3.5 km where there the difference between the two scenarios is large.

Fig. 3d visualizes the absolute difference between the pre-processed measurements and the estimated velocities from the scenario where only every other sensor is used. All cells where no measurements are available are colored white in the figure. The pre-processed velocities are assigned to the corresponding network cell containing the detector site. Each cell is approximately 150 meters long throughout the studied road stretch due to several on and off-ramps and densely spaced detector sites. For some sections of the studied road stretch the sensors are so densely spaced that most cells include a radar detector site. The fact that the ensemble Kalman filter is more reliant on measurements rather than prediction from the traffic model, in cases where measurements are available, becomes very apparent in this figure. For cells where pre-processed measurements have been used for estimation there are only minor differences between pre-processed and estimated velocities. The differences between estimated velocity and pre-processed velocity for cells that have not been included in the estimation vary considerably. One explanation to this is that the model output has a resolution of 30 seconds compared with a 60 second resolution for the pre-processed data. The differences are generally smaller than 10 km/h but there are some areas where the difference is much larger. These areas are basically the same as those in Fig. 3c and can be explained by the change in traffic state.
A. Validation of estimated travel times

While the space-time plots are interesting to study for a comparison of estimated traffic state for different scenarios, the most important output from the model is the estimated travel time. In Fig. 4 the estimated travel time from three different scenarios has been compared with the travel time estimated by the current system implemented at the Traffic Management Centre in Stockholm as well as measured travel times from the field test described in Section IV.A. The estimations generated by the current traffic management system are based on the same data as the estimations generated by the Mobile Millennium system, i.e. only data from the radar detectors.

From the figure it can be concluded that, irrespective of whether all sensors or only one sensor per kilometer is used, there is little difference in the estimated travel times. Furthermore, the estimated travel times from the Mobile Millennium system follow the same trend as the measured travel times from the field test. It is also noted that the estimations made by the current traffic management system seem to underestimate travel times and react more slowly to changes in state. The fact that the estimations generated by the current system react more slowly to changes in state can be explained by the use of a smoothing procedure and an arithmetic mean to aggregate travel times that is updated once every five minutes. Furthermore, in the current system travel times on a specific link are estimated by calculating an arithmetic mean from the available measurements. For the studied road section there are 19 links and the link length varies between 20 meters and 1 km. In contrast, the Mobile Millennium system calculates a space mean speed for each of the 35 cells that represents the studied road stretch. This makes the Mobile Millennium system more detailed and better equipped to follow trends compared to the current traffic management system given the same data sampling frequency.

V. CONCLUSIONS AND FUTURE WORK

According to the results from the evaluation of the estimated travel times presented in this paper, the highway model implemented in the Mobile Millennium real-time system has a good potential to improve the estimation of travel times in the greater Stockholm area. Given that the highway model used has not undergone a thorough calibration against the available data in Stockholm, the
results can be interpreted as very promising. The estimated travel times generated by the Mobile Millennium system correspond relatively well to the measured travel times of the earlier field test, even when the number of sensors is reduced. This suggests that the real-time system developed at UC Berkeley is robust with regard to the underlying data sources used. Furthermore, the study indicates that the system can be migrated to other geographical locations with relative ease. It is important to note that a more extensive validation is necessary and that this should focus on time intervals where changes in traffic state frequently occur.

Even though the initial results are promising they also indicate that there is a potential to improve estimation even if the number of sensors is reduced. There are parameters related to the fundamental diagram and the ensemble Kalman Filter that can be finely calibrated for Stockholm conditions. As a part of this work, sensitivity analyses will need to be made where the different parameters are systematically varied in order to analyze and interpret the effects that occur. One way to develop the highway model would be to have a more dynamic parameter setting that is dependent on the current traffic state and incorporate link characteristics or other factors that can influence estimation. This type of dynamic adaptation could, for example, take into consideration the fact that radar detectors have known problems with the detection of vehicles at low passage speeds during periods of heavy congestion.

A useful addition to the fixed sensor data would be to introduce more probe vehicle data in order to utilize the full potential of the Mobile Millennium system. The highway model used in Stockholm is currently undergoing further development and one area of research concerns adapting the model to handle spatially dynamic section speeds from taxi probe vehicles; a data source that currently is available to the project.

During the summer of 2012 travel times will be collected for the road stretch studied in this paper using Bluetooth devices. These travel times will be considered as a ground truth in the continued validation of the estimated travel times. With the Bluetooth measurements available, performance measures for each scenario can be calculated.

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