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RENAISSANCE – A unified macroscopic model-based approach to real-time freeway network traffic surveillance

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Abstract

The paper presents a unified macroscopic model-based approach to real-time freeway network traffic surveillance as well as a software tool RENAISSANCE that has been recently developed to implement this approach for field applications. RENAISSANCE is designed on the basis of stochastic macroscopic freeway network traffic flow modeling, extended Kalman filtering, and a number of traffic surveillance algorithms. Fed with a limited amount of real-time traffic measurements, RENAISSANCE enables a number of freeway network traffic surveillance tasks, including traffic state estimation and short-term traffic state prediction, travel time estimation and prediction, queue tail/head/length estimation and prediction, and incident alarm. The traffic state estimation and prediction lay the operating foundation of RENAISSANCE since RENAISSANCE bases the other traffic surveillance tasks on its traffic state estimation or prediction results. The paper first introduces the utilized stochastic macroscopic freeway network traffic flow model and a real-time traffic measurement model, upon which the complete dynamic system model of RENAISSANCE is established with special attention to the handling of some important model parameters. The algorithms for the various traffic surveillance tasks addressed are described along with the functional architecture of the tool. A simulation test was conducted via application of RENAISSANCE to a hypothetical freeway network example with a sparse detector configuration, and the testing results are presented in some detail. Final conclusions and future work are outlined.

Keywords: Freeway networks; Stochastic macroscopic freeway network traffic flow model; Extended Kalman filter; Traffic surveillance; Traffic state estimation; Traffic state prediction; Travel time estimation; Travel time prediction; Queue tracking; Incident alarm; RENAISSANCE

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1. Introduction

Large-scale freeway networks are usually equipped with a number of measurement devices of various kinds (inductive loops, video sensors, radar detectors) that deliver real-time information about the current traffic conditions in corresponding locations. Due to significant space inhomogeneities of traffic flow, however, if the density of installed traffic detectors is not very high (e.g. lower than one detector per 0.5 or 1 km), the spatial resolution of the corresponding real-time traffic measurements may not be sufficient for direct use or further exploitation of the measurements. This creates the need for a traffic state estimator that would deliver in real time a complete image of the traffic state for a whole freeway network considered, based on a more or less limited amount of real-time noisy traffic measurements. Moreover, a number of further real-time traffic surveillance tasks including short-term traffic state prediction, travel time estimation and prediction, queue tail/head/length estimation and prediction are also of interest to traffic operators for various uses.

The freeway *traffic state estimation* normally refers to estimating traffic flow variables (flows, mean speeds, and densities), along freeway stretches, with an adequate spatial resolution (e.g. 500 m or less) at each time instant based on a limited amount of real-time traffic measurements. The traffic state estimation is a fundamental task for freeway traffic surveillance and control, which has attracted a lot of investigation efforts in the past three decades, see Wang and Papageorgiou (2005) for a review therein. Related research proposed traffic state estimation algorithms that were almost exclusively based on macroscopic traffic flow modeling and (extended) Kalman filtering. Following a similar avenue, this topic was recently investigated further, and a general approach to the design of traffic state estimators for freeway stretches based on the *extended Kalman filer* (EKF) was proposed by Wang and Papageorgiou (2005) and Wang et al. (in press). One major innovative aspect of this recent work is the *on-line model parameter estimation*, i.e. the *joint estimation* in real time of both the traffic flow variables and some important model parameters (free speed, critical density, capacity), which leads to some significant adaptive capabilities for the designed traffic state estimator (Wang et al., 2006). On the other hand, the short-term *traffic state prediction* attempts to predict at each time instant the traffic flow variables within a freeway network over a future time horizon (see e.g. Wang et al., 2003). The freeway *travel time estimation/prediction* aims to estimate/predict the instantaneous/experienced travel time along any specified route inside a considered freeway network at each time instant. Travel time estimation and prediction have attracted much attention of researchers and traffic engineers, due to their fundamental significance for real-time traffic information and guidance systems. In the case of dense detector installation (e.g. one detector per 0.5 km), travel time estimation can be simply performed using real-time speed measurements. In the case of sparse detector installation, however, travel time estimation has to be performed on the basis of traffic speed estimation along the route. On the other hand, travel time prediction may be conducted on the basis of historical data with suitable extrapolation methods (e.g. time series or neural networks) or by employment of dynamic traffic flow models in real time, or via a combination of both. The technical literature addressing freeway travel time estimation and prediction is quite vast, see e.g. Park et al. (1999), Wunderlich et al. (2000), Chen and Muller (2001), Coifman and Cassidy (2001), Coifman (2001), Kachroo et al. (2001), Rice and Van Zwet (2001), Van Lint et al. (2005). The freeway *queue tail/head/length estimation and prediction* aims to estimate/predict at each time instant the locations of any queue tail and head existing currently/to appear over a future time horizon, along any specified route within a considered freeway network. With the identified locations of queue tails and heads, the queue lengths are readily estimated and predicted. An increasing number of traffic control centers wish to issue queue-length information or queue tail warnings (to avoid secondary accidents). The operational systems of this kind are typically based on simple spatial interpolation of traffic measurements collected by detectors. If, however, the density of detector stations is relatively low, spatial interpolation may lead to inaccurate queue tail/head/length estimation and prediction, and hence more comprehensive queue tracking methods are needed (see e.g. Wang et al., 2003).

This paper first extends the general approach to real-time traffic state estimation for freeway stretches (Wang and Papageorgiou, 2005) to the case of freeway networks. Freeway traffic is a large-scale nonlinear dynamic process; in particular, traffic dynamics of freeway networks is more complex than that of freeway stretches. Considering also the sub-optimality of the EKF-based solution to state estimation of nonlinear systems, real-time traffic state estimation for freeway networks is surely not a trivial task. As a matter of fact, this is the first time to report on freeway-network traffic state estimation and this is actually a major contribution