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A phase-based smoothing method for accurate traffic speed estimation with floating car data☆

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ABSTRACT

In this paper, a novel freeway traffic speed estimation method based on probe data is presented. In contrast to other traffic speed estimators, it only requires velocity data from probes and does not depend on any additional data inputs such as density or flow information. In the first step the method determines the three traffic phases free flow, synchronized flow, and Wide Moving Jam (WMJ) described by Kerner et al. in space and time. Subsequently, reported data is processed with respect to the prevailing traffic phase in order to estimate traffic velocities. This two-step approach allows incorporating empirical features of phase fronts into the estimation procedure. For instance, downstream fronts of WMJs always propagate upstream with approximately constant velocity, and downstream fronts of synchronized flow phases usually stick to bottlenecks. The second step assures the validity of measured velocities is limited to the extent of its assigned phase. Effectively, velocity information in space-time can be estimated more distinctively and the result is therefore more accurate even if the input data density is low.

The accuracy of the proposed Phase-Based Smoothing Method (PSM) is evaluated using real floating car data collected during two traffic congestions on the German freeway A99 and compared to the performance of the Generalized Adaptive Smoothing Method (GASM) as well as a naive algorithm. The quantitative and qualitative results show that the PSM reconstructs the congestion pattern more accurately than the other two. A subsequent analysis of the computational efficiency and sensitivity demonstrates its practical suitability.

1. Introduction

For every type of traffic application as well as for traffic research, the best-possible estimate of current and historical traffic speed is fundamental. Despite the fact that there are usually only a limited number of sensors available that provide sparse measurements in space and time of the real traffic situation. The task of a traffic estimation method is to analyze the given measurements and provide an estimate of the desired traffic variable for every position on the road and every point in time with the main purpose of reconstructing and providing accurate estimates of prevailing real traffic conditions.

For traffic estimation, the quick spread of Floating Car (FC) data in recent years provides great potentials; however, still faces new challenges. One great advantage is the possibility to obtain traffic data on every position on a road, whereas fixed sensors can only provide data for pre-determined locations. Besides the high spatial resolution, another advantage is the ever-decreasing cost of this technology, which in turn increases the expectation of developing availability of FC data in the upcoming years. The installation and

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maintenance of fixed detectors, on the one hand is costly, especially when considering the vastness of networks that have to be covered. In spite of this, they still provide great benefits in the provision of macroscopic traffic speeds as well as density and flow values in short time intervals. In contrast, time intervals between two reported trajectories can vary drastically and FC data usually does not contain explicit density and flow information. Because of the sparse data and the under-determined traffic state coupled with high spatio-temporal traffic dynamics accurate traffic state estimation with FC data is a major challenge.

For decades traffic state estimation is an ongoing topic of research. A comprehensive survey of current traffic estimation approach on highways is given in Seo et al. (2017). The main approaches that consider traffic dynamics can be classified into two categories. The first category comprises analytical flow models coupled with data assimilation techniques. First order models are usually based on the Lighthill-Whitham-Richards model (Lighthill and Whitham, 1955; Richards, 1956) and use Kalman filters (van Lint and Djukic, 2014) in order to match model expectation and observation. Some examples are given in Suzuki et al. (2003), where a Kalman filter is applied in order to estimate traffic conditions based on a mix of loop detector and FC data. Also, results presented in Yuan et al. (2012) and Duret and Yuan (2017) studied the benefits of a Lagrangian model compared to Eulerian approaches when applied to detector and FC data. In addition, higher order models have been proposed that account for more sophisticated traffic dynamics in Aw and Rascle (2000). Wang and Papageorgiou (2005) describe a second order model that estimates traffic conditions on a freeway in real-time. Computational issues are addressed by van Hinsbergen et al. (2012), where the authors demonstrate the development of a localized filter that performs real-time computations. All models mentioned above rely strongly on flow and density data. In contrast, Herrera and Bayen (2010) and Work et al. (2008, 2009) focus on probe data and develop models using a fundamental diagram to be able to estimate densities from probe velocities. Furthermore, Bekiaris-Liberis et al. (2016) propose a macroscopic model for traffic density estimation using a linear parameter-varying system that relies mainly on probe velocity measurements. Although in the latter mentioned approaches most of the information is obtained from probe data, the proposed models still require flow or density measurements at the boundaries. In practical applications, the need for additional flow or density information drastically limits the applicability of an approach on a large scale since it adds further complexity to data acquisition and processing.

The second category of algorithms comprises of estimation methods that are based on empirical traffic theory. First, in Kerner et al. (2004) a model called ASDA/FOTO based on Kerner's Three Phase traffic theory (Kerner, 2004, 2009) is introduced with the purpose of providing current and predictive traffic information. The approach analyzes velocity and flow data provided by detectors and reconstructs spatio-temporal regions of free flow, synchronized flow and Wide Moving Jams. While that approach is completely based on loop detector data, Palmer et al. (2011) study the reconstruction of phase regions with trajectory data exclusively. The phase transitions in space-time of individual vehicles are identified by means of velocity and time conditions and aggregated into phase objects using a clustering approach. The advantages of this approach include the exclusive use of FC data in order to estimate velocities and phases, nonetheless, velocities inside a traffic phase are estimated to a constant over space and time, which in turn limits the accuracy of an estimation. Additionally, the trajectories without phase transitions are discarded, which subsequently results in a loss of valuable information. For example, a trajectory in free flow state passing through an estimated synchronized flow region will not influence the phase since it does not contain phase transitions. Another well-known method is the Generalized Adaptive Smoothing Method (GASM). It is based on the observation that shockwaves in congested traffic propagate upstream and shockwaves in free traffic propagate downstream (Treiber and Helbing, 2003). Using two convolution processes, traffic data is smoothed in these directions and aggregated adaptively. The advantages of the GASM are that it can be applied to velocity data of different sources (Treiber et al., 2010; van Lint and Hoogendoorn, 2009; Jiang et al., 2017) that it allows for an efficient implementation (Schreiter et al., 2010) and that it proved to be significantly more accurate than isotropic smoothing (Treiber and Helbing, 2003; Rempe et al., 2016). On the other hand, it tends to propagate low velocities up- and downstream unconditionally although they might be part of stationary congestion upstream a bottleneck (Treiber et al., 2010). Thus, when it is applied to sparse probe data the estimated velocities in stationary congestion patterns lack accuracy.

Inspired by the GASM and works by Kerner et al., a novel Phase-based Smoothing Method (PSM) is presented with the purpose of estimating traffic velocities using FC data with higher accuracy. The key idea is that the PSM distinguishes between the three states: free flow, synchronized flow and Wide Moving Jam (Kerner, 2004, 2009). The distinction between these phases allows one to account for common propagation characteristics of each phase. After identifying these phases, traffic measurements are smoothed accordingly depending on the phase they belong to, which makes it possible to incorporate prevailing traffic measurements into the estimation algorithm. This approach enables higher estimation accuracies, while keeping the efficiency and robustness of the GASM.

In the following preliminary section a summary of the Three Phase traffic theory and a description of fundamental convolution operations used frequently in the PSM are given. Section 3 describes the PSM. The first step considers the estimation of phases in space-time. Step two explains how the final velocity estimate is obtained using the combination of phase information and raw data. Evaluation of the method is described in s 4 and 5. The trajectory data reported by a huge fleet of vehicles during a congestion on German freeway A99 is used to assess the performance of the PSM. Finally, the results are discussed and future work is proposed.

2. Preliminaries

Two main concepts form the basis of the PSM. The first concept considered is Kerner's Three Phase traffic theory. In order to motivate how his theory is applied to traffic estimation algorithms, it is summarized briefly and the most important empirical findings relevant for the development of the PSM are presented. The second is the use of smoothing operations. Since FC data are prone to noise due to GPS sampling and further processing and FC data of individual vehicles constitute only a *sample* of the macroscopic traffic speed, smoothing of data is inevitable in order to remove outliers and average out velocity differences among several trajectories. In discrete space, smoothing is a standard operation and does not require an explanation, though, for reasons of generality