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Extended spectral envelope method for detecting and analyzing traffic oscillations

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ABSTRACT

We propose using a spectral envelope method to analyze traffic oscillations using data collected from multiple sensors. Spectral envelops can reveal not only the salient frequencies of periodic oscillations of traffic flow, but also the relative strength of these oscillations at different locations. This paper first introduces time dimension into the existing spectral envelope method so that it can be applied to study the evolution of vehicular traffic oscillations. The extended spectral envelope method proposed in this paper, or ESPE, discards the normalization procedure in the standard method. A new Contributing Index (CI) is proposed to measure the relative strength of oscillations at different locations. The extended spectral envelops can be constructed on long-term or short-term time scales. While the long-term analysis helps extract salient frequencies of traffic oscillations, the short-term analysis promises to reveal their detailed spatial–temporal profiles. ESPE offers two distinctive advantages. First, it is more robust against the impacts of noises. Second, it is able to uncover complicated oscillatory behaviors which are otherwise difficult to notice. These advantages are demonstrated in case studies constructed on both simulated and real data.

1. Introduction

The development of effective dynamic traffic management strategies demands better understanding of vehicular traffic flow. Freeway traffic oscillations, often known as the stop-and-go or slow-and-go traffic, have been a major source of drivers' frustrations, because they create dangerous attention fatigue and discomfort, while increasing fuel consumptions, emissions, and travel delay. Traffic engineers and researchers have tried for decades to understand the mechanism that causes traffic oscillations to form, propagate and dissipate. The causes of traffic oscillations have been attributed to car-following behavior (Chandler et al., 1958; Herman et al., 1959; Newell, 1965; Holland, 1998; Smilowitz et al., 1999), lane changing maneuvers (Gazis et al., 1962; Munjal and Pipes, 1971; Mauch and Cassidy, 2002; Ahn and Cassidy, 2007), and interactions between queues in a network (Jin, 2003, 2009; Nie et al., 2012; Nie and Zhang, 2008). However, efforts to characterize, predict and control traffic oscillations have to be built on the capability of detecting and measuring these oscillations from real data. For a couple of reasons, this poses considerable challenges. For one thing, real traffic data are always contaminated with noises that have to be filtered out for meaningful analysis. More importantly, oscillations of different frequencies, amplitudes and propagation speed may be initiated at different locations and interfere with each other to form the observed traffic patterns. Ignoring such interactions in the data processing may lead to incorrect specifications of oscillatory features.

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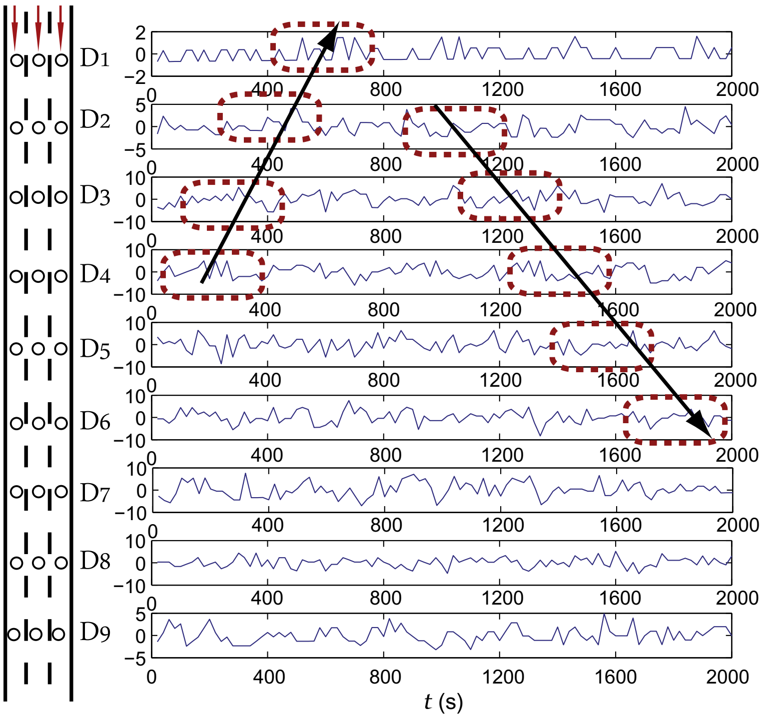

Fig. 1. Scope of this study: to understand how the oscillations of different frequencies in the traffic data propagates from one location to another.

Detection and measurement of traffic oscillations have been studied extensively in the literature. Existing methods may be categorized as time-domain analysis (Mauch and Cassidy, 2002; Koshi et al., 1983; Kuhne, 1983; Zielke et al., 2008), and frequency-domain analysis (Mika et al., 1969; Li et al., 2010; Zheng et al., 2011). The principal objective of these analyses is to extract basic properties of traffic oscillations, namely amplitude, propagation velocity, and frequency.

In time-domain analysis, two methods are often used for filtering out high-frequency noise and low-frequency fluctuations trends in the data. In the first method (see e.g. Mauch and Cassidy, 2002), the data are first integrated over a moving time window and then the second-order differences of the processed data are used to analyze traffic oscillations.[1] Another method employs autocorrelation to extract the periodic components in the data (e.g. Neubert et al., 1999). However, it is often difficult in the time-domain analysis to separate multiple oscillatory patterns when they are mixed together. A standard technique to overcome this difficulty is converting time series data into the frequency domain and performing a spectrum analysis, i.e. decomposing a time series into a spectrum of periodic signals with different frequencies.

Mika et al. (1969) analyze the power spectral density (PSD) of traffic data to identify traffic oscillation patterns. PSD is the Fourier transform (FT) of the auto-covariance function of the time series data. Li et al. (2010) propose using the short time Fourier transform (STFT) method to measure and estimate oscillation attributes embedded in noisy traffic data. Zheng et al. (2011) apply Wavelet Transform (WT) to convert time-series traffic data to the corresponding wavelet-based energy distribution, which is used to highlight the abrupt changes in the original data. WT is also adopted by Li et al. (2012) to quantify oscillation properties of vehicular trajectories, which are then used to calibrate and validate a nonlinear car-following model.

It is often useful to examine the relationship between traffic oscillations detected at different locations in order to better understand how they propagate in the traffic stream and interact with each other, as illustrated in Fig. 1. In most existing data processing methods (whether they are based on WT or FT), however, such a cross-space examination is not an integrated component, but rather performed in a manual and ad hoc manner. For example, in Li et al. (2010), the STFT technique is applied to each studied locations to detect oscillations separately. Then, the spectrums of these locations are compared manually to identify the propagation of oscillations. This is a challenging task that seems to require as much art as science. For one thing, it is difficult to identify the characteristic frequency from multi STFT spectrums, as there are always several peaks in each STFT spectrum. Some of the peaks stem from the noises embedded in the original data, which complicate the identification of the characteristic frequencies. Furthermore, for more complicated scenarios with more than one oscillation origins with different characteristic frequencies, especially when oscillations can propagate both upstream and downstream

[1] One shortcoming of this method is that the use of the time window may introduce unwanted temporal correlations. As a result, an inappropriate choice of the time window may either create fake oscillations or suppress true ones (Li et al., 2010).