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Measurement and estimation of traffic oscillation properties

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ABSTRACT

The paper proposes a frequency spectrum analysis approach to improve measurements of traffic oscillation properties (e.g., periodicity, magnitude) from field data. The approach builds on standard signal processing techniques to effectively distinguish useful oscillation information from noise and nonstationary traffic trends. Compared with conventional time-domain methods, the proposed methodology systematically provides a range of information on oscillation properties. This paper also shows how to estimate oscillations experienced by drivers using detector data. Applications to real-world data from two sites show that the dominant oscillation period remains relatively invariant at each site when an oscillation propagates. Although the average oscillation periods displayed in detector data significantly vary across sites, the range of oscillations experienced by drivers are found to be more consistent.

1. Introduction

Traffic oscillations, also known as the "stop-and-go" traffic, refer to the phenomenon that congested traffic tends to oscillate between slow-moving and fast-moving states rather than maintain a steady state. Traffic oscillations create significant driving discomfort, travel delay, extra fuel consumption, increased air pollution, and potential safety hazards. Its importance and complexity have stimulated intensive research. Efforts have been made to develop theoretical models (which attempt to reproduce the phenomenon and reveal root causes) and to analyze empirical data (with the goal of quantifying oscillation properties and identifying contributing factors).

The efforts to develop traffic flow models to capture traffic oscillations can be traced back to early studies on temporal and asymptotic stabilities of linear car-following models, investigated with frequency analysis tools half a century ago (Chandler et al., 1958; Herman et al., 1958). Later on, various non-linear models (e.g., Gazis et al., 1961; Gipps, 1981) were proposed to better reproduce traffic evolution, but nonlinearity imposed significant difficulties to instability analysis. For example, Bando et al. (1995, 1998) developed a nonlinear optimal velocity model (OVM) to study stop-and-go traffic. The local stability properties were analyzed approximately after linearization of the car-following law. The OVM model was later used as the building block for a set of extended models (Helbing and Tilch, 1998; Jiang et al., 2001; Sawada, 2002; Davis, 2003; Zhao and Gao, 2005). Numerical traffic simulations were usually conducted to demonstrate that the proposed models can reproduce real-world oscillation phenomena.

Empirical studies on periodical traffic oscillations have also produced fruitful results. Earlier studies analyzed oscillation properties by directly observing time series of raw traffic data (Koshi et al., 1983; Kuhne, 1987; Paolo, 1989). Particularly, Kuhne (1987) matched speed data profiles with pure sinusoidal curves to estimate oscillation period and amplitude. Later, in the synchronized flow context (Kerner and Rehborn, 1996, 1997; Kerner, 1998), Helbing et al. (1999) and Kerner (2002)

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categorized the observed oscillations into different patterns. Treiber and Helbing (2002) developed a non-linear spatio-temporal filter to smooth detector data and to reveal oscillation propagations. Recent studies observe oscillations in queue discharge flows at capacity drops (Cassidy and Bertini, 1999a,b; Bertini and Leal, 2005), and associated oscillations with lane changes near merges, diverges (Mauch and Cassidy, 2002; Bertini and Leal, 2005; Cassidy, 2005; Menendez, 2006; Laval and Daganzo, 2006; Laval et al., 2007, 2009; Ahn and Cassidy, 2007), and roadway geometric features (Jin and Zhang, 2005). Traffic data were often preprocessed to improve oscillation measurements.

Despite numerous past efforts, a few measurement issues seem to remain worthy of further investigation. In empirical studies, it is important to extract oscillation attributes (e.g., period and magnitude) from observed traffic data, because such attributes are useful for calibration and testing of car-following models. In the literature, oscillation attributes have largely been measured in an ad-hoc manner or with certain time-domain methods. These methods, while being effective at confirming important oscillation attributes, may not be good for revealing unclear or unknown oscillation phenomena. Hence, this paper proposes a new data analysis framework to extract oscillation attributes based on frequency-domain signal processing techniques. This approach is effective at unveiling oscillation properties from noisy raw data. Case studies with real-world data are used to illustrate this framework and to demonstrate how oscillation periodicity and magnitude vary as an oscillation propagates.

Note that detectors, the most prevailing data source for empirical studies, only capture traffic status at discrete locations. They do not directly reflect an individual vehicle's experience that most analytical car-following laws and stability analysis describe. Therefore, this paper investigates the relationship between the oscillations experienced by the drivers and those measured from detector data. Methods are proposed to estimate periodicity and magnitude of oscillations that the drivers experience. Empirical analysis suggests, in particular, that although observed oscillation periods from detector data vary significantly across roadway sites, the oscillations that drivers experience are much more consistent.

The remainder of this paper is organized as follows. Section 2 provides a frequency-domain perspective on field data processing and oscillation measurements. We discuss existing time-domain methods for oscillation measurements, and propose a new data analysis framework. Section 3 presents two empirical case studies. Section 4 presents a method to estimate trajectory oscillation periods and magnitudes. Section 5 suggests future research.

2. Field data processing and measurements

In the past, various time-domain techniques have been used to process data and measure oscillation properties (periodicity and magnitude). In this section we first provide some discussions on these methods. Then we will propose a frequency spectrum analysis framework to characterize oscillation properties.

2.1. Time-domain methods

We use $\{x_m\}_{m=0}^{M-1}$, to denote a finite discrete-time detector data sequence, where each data element is aggregated over an interval of length Δ (e.g., 20 s). The magnitude of oscillations is often measured by the root mean squared error (RMSE),

$$\left[\frac{1}{M}\sum_{m=0}^{M-1}(x_m-\bar{x})^2\right]^{\frac{1}{2}}, \quad \text{where } \bar{x} \approx \frac{1}{M}\sum_{m=0}^{M-1}x_m. \tag{1}$$

From a frequency-domain perspective, a detector data sequence is the superposition of three sets of sinusoidal components, representing low-frequency trend (i.e., slow variations of traffic state, due to traffic demand changes, bottleneck activation, etc.), high-frequency noise (i.e., local random perturbations), and mid-range oscillations (i.e., accelerating–decelerating cycles of interest), respectively. The RMSE measure (1) depends on not only the oscillation components but also trend and noise. Hence, this measure does not reliably estimate the mid-range oscillations.

Neubert et al. (1999) study oscillation properties with auto-correlation,

$$\frac{\sum_{m=0}^{M-d-1}x_m x_{m+d}/(M-d)-\bar{x}^2}{\sum_{m=0}^{M-d-1}x_m^2/(M-d)-\bar{x}^2}, \quad \text{for any integer lag } d, \tag{2}$$

and the separation between neighboring peaks on the correlogram is used as an estimate of the oscillation period. Unfortunately, the peaks in the correlogram are not directly related to the periodicity of any single frequency component,[1] and if there are multiple comparable frequency components in the data, the correlogram will not exhibit distinct peaks. Furthermore, the auto-correlation value always falls in $[-1, 1]$ and hence does not quantify the oscillation magnitude.

To remove trend and noise from the data, another popular data processing approach is to take the second-order difference of the cumulative data sequence (e.g., vehicle counts), $f_m := \sum_{i=0}^{m}x_i$, with a moving time window (Mauch and Cassidy, 2002; among many others); i.e.,

[1] The auto-correlation value depends on a set of frequency components whose period equals a divisor of d.