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Calibration of nonlinear car-following laws for traffic oscillation prediction ☆,☆☆

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ABSTRACT

Frequency-domain analysis has been successfully used to (i) predict the amplification of traffic oscillations along a platoon of vehicles with nonlinear car-following laws and (ii) measure traffic oscillation properties (e.g., periodicity, magnitude) from field data. This paper proposes a new method to calibrate nonlinear car-following laws based on real-world vehicle trajectories, such that oscillation prediction (based on the calibrated car-following laws) and measurement from the same data can be compared and validated. This calibration method, for the first time, takes into account not only the driver's car-following behavior but also the vehicle trajectory's time-domain (e.g., location, speed) and frequency-domain properties (e.g., peak oscillation amplitude). We use Newell's car-following model (1961) as an example and calibrate its parameters based on a penalty-based maximum likelihood estimation procedure. A series of experiments using Next Generation Simulation (NGSIM) data are conducted to illustrate the applicability and performance of the proposed approach. Results show that the calibrated car-following models are able to simultaneously reproduce observed driver behavior, time-domain trajectories, and oscillation propagation along the platoon with reasonable accuracy.

1. Introduction

Drivers in congested traffic find it extremely difficult to maintain a steady speed; instead, they often engage in frequent acceleration-deceleration cycles—a phenomenon commonly referred to as "stop-and-go traffic" or "traffic oscillation". This phenomenon causes a range of problems including safety hazards, extra fuel consumption, extra emissions, travel delay, and driver discomfort. For decades, researchers have been developing theoretical and empirical methods to better understand the mechanism of the traffic oscillation phenomenon and to seek solutions to mitigate its adverse effects.

Theoretical efforts to study traffic oscillation can be traced back to the 1950s (Chandler et al., 1958; Herman et al., 1959). The main goal of these efforts is to reveal root causes of traffic oscillation in a platoon and quantify the impacts of individual driver's car-following behavior on its evolution. In congested traffic flow, a platoon of vehicles can be modeled as cascading dynamic systems, each consisting of a pair of consecutive vehicles with a certain car-following law describing the driver's behavior (Chandler et al., 1958). Each vehicle trajectory can be considered to consist of two components: a nominal

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component that describes the macroscopic characteristics (e.g., flow, density, average speed) and an oscillation component that describes the microscopic characteristics (e.g., oscillation period and amplitude) (Li et al., 2010). To accurately model a platoon, a good car-following law must reproduce both of these components, and yet, accuracy in the oscillation component is essential for studying traffic oscillation. While the nominal component can be naturally studied in the time domain, it is generally convenient to analyze the oscillation component in the frequency domain. For example, earlier analyses of linear car-following models by frequency-domain techniques yielded insightful closed-form analytical results (Herman et al., 1959). A well-known problem of linear analysis, however, is that the predicted oscillation amplitude would grow exponentially as the oscillation propagates along the platoon. This result obviously contradicts the bounded amplitude growth that we observe in reality (e.g., vehicles do not travel backwards, and they do not collide). Some researchers believe that the inaccuracy associated with the linear models probably lies in the lack of physical operational bounds, such as lower and upper acceleration/speed limits for a driver. Various nonlinear car-following laws have been developed to more accurately explain and reproduce traffic oscillation propagation (Gazis et al., 1961; Gipps, 1981; Bando et al., 1995; Treiber et al., 2000). For example, Newell's parsimonious piecewise linear car-following law (Newell, 1961) reproduces traffic evolution quite well while using only a few parameters. Such nonlinear models, however, are typically much more difficult to analyze in closed forms, and they often are studied via numerical simulations. Just recently, Li and Ouyang (2011) made some progress in overcoming this challenge by developing a describing function approach (DFA) framework to analytically characterize oscillation propagation properties under a general class of nonlinear car-following law.

Empirical studies on traffic oscillation were traditionally conducted on aggregated traffic data, e.g., those from loop detectors (Koshi et al., 1983; Ferrari, 1989; Kuhne, 1987; Zielke et al., 2008). Recently, availability of microscopic data such as vehicle trajectories provided the opportunity for more detailed observation and analysis. Most work thus far, however, has only measured traffic oscillation characteristics in the time domain. For example, Neubert et al. (1999) conducted a statistical analysis based on a single vehicle trajectory in the time-space diagram. Treiber and Helbing (2002) implemented data fusion methods to extract traffic state information from a spatiotemporal traffic profile consisting of a platoon of vehicle trajectories. Laval (2011) proposed a method based on kinematic wave theory to measure traffic flow variables. Recently, the advantages of applying frequency-domain analysis techniques to obtain more accurate measurements of oscillation characteristics have become apparent. Li et al. (2010) proposed a short-time Fourier transform method to measure oscillation properties. This framework was later extended to wavelet analysis methods (Zheng et al., 2011) and an extended spectral envelope method (Zhao et al., 2014).

Given these findings and insights of traffic oscillations based on various car-following laws, it would be ideal to validate the theoretical predictions with field observations. The availability of detailed microscopic traffic trajectory data significantly helps achieve this goal in two aspects. First, such data could be used to calibrate suitable car-following models, which can then be used as the basis for theoretical prediction of oscillations. Second, traffic oscillation properties could be properly measured from the same field data for comparison with the theoretical predictions, and in so doing serve as the benchmark for cross validation. In this way, both the theoretical predictions and the field measurements are validated, and the oscillation mechanism can be better understood. However, calibrating a car-following law is not trivial, especially when the car-following model is nonlinear, since both time-domain (such as location, speed, and acceleration) and frequency-domain properties (such as oscillation amplitude and periodicity) should be considered. Limited attempts have been made to quantitatively develop a suitable nonlinear car-following model that can closely match with field data. Most validation attempts have focused only on finding models that can reproduce time-domain properties (Kesting and Treiber, 2008; Treiber and Kesting, 2012). For example, Ciuffo et al. (2007) propose a calibration framework integrating model sensitivity analysis and validate their results via simulation.

Such models tend to ignore frequency-domain properties and normally yield inaccurate predictions of oscillation propagation. In light of this, recent studies begin to focus on the possibility of calibrating oscillation properties from the field data. Several efforts have been made through calibrating parsimonious models, which normally consist of a simple car-following law sharing by all vehicles as a base and certain driver specific parameters to partially capture the heterogeneity. In this stream, Chen et al. (2012) calibrate a specific behavioral car-following law based on vehicle trajectories to study the oscillation. Laval et al. (2014) further develop a stochastic model to relate the oscillation to the uncertainty when vehicle accelerates. These models, although only considering time-domain information, can generate oscillation propagation from a macroscopic perspective. To accurately reproduce the oscillation propagation, frequency-domain tools have to be implemented directly in the calibration. In light of this, Li et al. (2012) proposed a way to calibrate a car-following model from field trajectory data with extracted frequency-domain characteristics. However, there are two issues limiting its applicable field in practice: the shortage of time-domain traffic characteristics and the homogeneous driver's behavior setting in the calibration process. As a result, while this method yields a rather accurate reproduction of oscillation propagation in average, it fails to match the prediction of time-domain trends in vehicle trajectories and the details of stepwise oscillation propagation. As such, a new method is needed—one that can calibrate car-following laws for a platoon of heterogeneous drivers and properly reproduce both time- and frequency-domain properties.

To fill this gap, this paper proposes a new framework that calibrates the parameters of nonlinear car-following laws using field vehicle trajectories. Our framework focuses on calibrating the car-following law for each pair of consecutive vehicles, while explicitly incorporating frequency domain characteristics. Through a simulation algorithm, for the first time, the calibrated laws are capable of reproducing oscillation properties such as periodicity and magnitude, as well as location and speed profiles of vehicle trajectories. In addition, we obtain theoretical prediction from DFA as cross-validation to the sim-