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Prediction and field validation of traffic oscillation propagation under nonlinear car-following laws

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ABSTRACT

A recent study (Li and Ouyang, 2011) proposed a describing-function approach (DFA) to analytically predict oscillation propagation properties (i.e., dominating frequency and amplitude growth) for a general class of nonlinear car-following laws. This paper presents a new graphic solution approach to DFA and proposes a systematic framework to validate DFA using observed vehicle trajectory data. A set of new empirical measures are defined to extract steady-state traffic properties and oscillation characteristics from vehicle trajectory data. A frequency-domain calibration approach based on DFA is developed to construct a proper nonlinear car-following model that fits these empirical measurements. The analytical DFA predictions of oscillation propagation patterns of the calibrated car-following law are then compared with (i) the observed oscillation properties, and (ii) the simulated oscillation characteristics from the same car-following law. Empirical experiments with real-world trajectory data show that the prediction, the simulation, and the field observation typically match very nicely. This not only validates the analytical prediction approach in the previous study, but also shows that the framework proposed in this paper is capable of calibrating a realistic nonlinear car-following law that reproduces the observed oscillation propagation phenomenon. Our proposed modeling method also brings theoretical analyses and empirical observations into one integrated framework that potentially lays the foundation to understand how nonlinearities in a car-following law affect traffic oscillation evolution, and develop possible counteracting strategies.

1. Introduction

Congested traffic seldom maintains a smooth flow; rather, it tends to display oscillatory patterns, with cyclic alternations between "stop" (or slow movements) and "go" (or fast movements). This phenomenon is often referred to as "stop-and-go" traffic in traffic flow theory. It creates a range of adverse consequences, including safety hazards, extra fuel consumption and emission, and driving discomfort. In the past several decades, researchers have conducted extensive studies on stop-and-go traffic via empirical observations and theoretical models, in attempts to discover the root causes of this phenomenon and device effective mitigation strategies.

Empirical studies used loop detector data as solid evidences of periodically oscillating patterns in congested traffic (Koshi et al., 1983; Kuhne, 1987; Paolo, 1989; Zielke et al., 2008). In the synchronized flow context (Kerner and Rehborn, 1996, 1997; Kerner, 1998), Helbing et al. (1999) and Kerner (2002) categorized observed oscillations into different patterns. Methods to extract oscillation characteristics (e.g., frequency and amplitude) from traffic data have been proposed in the

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time domain (Neubert et al., 1999; Mauch and Cassidy, 2002; Treiber and Helbing, 2002; Laval, 2011) and the frequency domain (Li et al., 2010; Zheng et al., 2011). Empirical studies have also related traffic oscillations to highway lane drops (Bertini and Leal, 2005), lane changes near merges and diverges (Mauch and Cassidy, 2002; Bertini and Leal, 2005; Cassidy, 2005; Menendez, 2006; Laval and Daganzo, 2006; Laval et al., 2007; Ahn and Cassidy, 2007), and roadway geometric features (Jin and Zhang, 2005). Motivated by these empirical findings, intensive theoretical research has been conducted to investigate oscillation formation and propagation mechanisms. Early studies on linear car-following models can be traced back to the 1950s (Chandler et al., 1958; Herman et al., 1958). Later, various nonlinear models (e.g., Gazis et al., 1961; Gipps, 1981) were developed in hope to better reproduce traffic evolution. For example, Bando et al. (1995, 1998) developed a nonlinear optimal velocity (OV) model to study the stop-and-go traffic, which became the building block of a set of extended models (Helbing and Tilch, 1998; Jiang et al., 2001; Sawada, 2002; Davis, 2003; Zhao and Gao, 2005). Treiber et al. (2000) proposed an intelligent driver model (IDM) to qualitatively reproduce observed traffic oscillations on German freeways. The IDM model has been revisited in a number of following studies, e.g., relating it to a macroscopic model (Helbing et al., 2002) and adjusting it to match observed patterns in more data sets (Hoogendoorn and Hoogendoorn, 2010; Kesting et al., 2010). See Orosz et al. (2010) and Wilson and Ward (2011) for a recent review on this topic.

In spite of these numerous attempts, however, there still exist considerable discrepancies between theoretical model results and field observations. Although linear car-following models can be easily analyzed by frequency-domain analysis tools (Chandler et al., 1958; Herman et al., 1958), they often yield unrealistic analytical predictions, e.g., unbounded growth of oscillation amplitude. Nonlinear models (e.g., Bando et al., 1995; Treiber et al., 2000) were able to better reproduce observed oscillation patterns. However due to the difficulty imposed by nonlinearity, most past studies on nonlinear model analysis relied on computer simulations (e.g., Helbing et al., 2009; Treiber et al., 2009) and qualitative stability analyses (e.g., Wilson, 2008; Orosz et al., 2009; Wilson and Ward, 2011; Treiber and Kesting, 2011). Due to such methodological constraint, many nonlinear models were mainly used to qualitatively reproduce observed oscillation patterns (e.g., Wilson, 2008; Treiber et al., 2009; Helbing et al., 2009; Treiber and Kesting, 2011). Only limited attempts have been made to accurately match quantitative measurements from field data with nonlinear model predictions (Kesting and Treiber, 2008; Treiber and Kesting, 2012), which however only focused on calibrating time-domain measurements. Analytical quantification of the oscillation responses of these nonlinear models had remained a significant challenge until the recent development of a describing-function approach (DFA) (Li and Ouyang, 2011). It has been shown through simulation results that this new analytical approach accurately characterizes oscillation propagation for a general class of nonlinear car following laws. However, this approach has not been validated with real traffic data, and its value and potential to explain empirical quantitative measurements need to be further explored, particularly from a frequency-domain perspective.

This paper aims to connect these recent model developments with field data measurements (e.g., those from NGSIM database[1]) by proposing a systematic car-following model calibration framework from a frequency-domain perspective. On the empirical measurement side, we will extend the frequency-domain methods introduced in (Li et al., 2010; Li and Ouyang, 2011) by defining more comprehensive macroscopic (e.g., trend speed and average spacing) and oscillation (e.g., oscillation amplification rate and propagation speed) measures to characterize actual vehicle trajectories. On the theoretical car-following model analysis side, we will improve the DFA proposed in Li and Ouyang (2011) that analytically quantifies the oscillation properties of a nonlinear car-following law by introducing a graphic solution method. This graphic method provides not only more physical intuitions but also better accuracy and computational efficiency. Then we will propose a calibration framework for a general class of nonliner car-following models by matching their analytical oscillation properties with the frequency-domain empirical measurements in addition to calibrating macroscopic properties. Numerical examples will be used to demonstrate that a properly designed nonlinear car-following model for "average" car-following behavior is able to reproduce the observed oscillation patterns in terms of frequency-domain measurements. Overall, this proposed framework, for the first time, quantitatively connects the observed stop-and-go phenomenon to theoretical predictions from an analytical approach for nonlinear driving dynamics. The research results will significantly enhance our understanding of the propagation mechanisms of traffic oscillation, which in turn lays the foundation to develop effective control strategies that can mitigate or eliminate oscillations in congested traffic.

The remainder of the paper has the following structure. Section 2 defines a number of measures that extract steady-state (or macroscopic) and oscillation properties from observed trajectory data. Section 3 presents an improved DFA to predict oscillation responses for a general class of nonlinear car-following models, and proposes a recipe to calibrate car-following laws based on the trajectory measurements. Section 4 demonstrates and validates the proposed framework using NGSIM trajectory data. Section 5 concludes this paper and briefly discusses future research directions.

2. Measurement of oscillation properties of vehicle trajectories

This section borrows the definitions of the macroscopic and oscillation properties of a vehicle platoon from Li et al. (2010) and Li and Ouyang (2011) and proposes measurement methods to extract these properties from field trajectory data. We adapt an infinite-length trajectory defined for the theoretical study in Li and Ouyang (2011) to a finite length to suit a realistic vehicle trajectory profile observed in field. Then we adapt the decomposition approach in Li and Ouyang (2011)

[1] Source: http://ngsim.fhwa.dot.gov/.