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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.


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*Keywords:* Car-following Law; Traffic Oscillation; Field Validation

## 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 1950's (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

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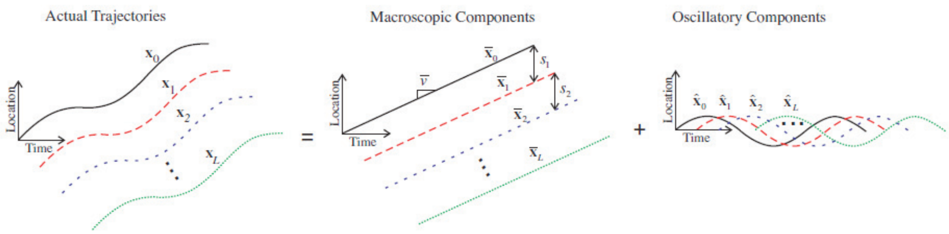


Fig. 1: Trajectory Decomposition (Source: Li et al., 2012).

law describing the driver's behavior (Chandler et al., 1958). Each vehicle trajectory can be considered to consist of two components: a nominal 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). This trajectory decomposition can be seen in 1 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).

Now that traffic oscillation propagation can be predicted for a general class of nonlinear car-following laws (Li and Ouyang, 2011), it would be ideal to validate the theoretical predictions with field observations. The detailed microscopic traffic trajectory data could be used for two purposes. 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. The first step of calibrating the car-following law, however, is not trivial, especially when the car-following model is nonlinear and when both time-domain (such as location, speed, and acceleration) and frequency-domain properties (such as oscil-