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Stop-and-go traffic analysis: Theoretical properties, environmental impacts and oscillation mitigation

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A B S T R A C T

This study aims (i) to analyze theoretical properties of a recently proposed describing-function (DF) based approach (Li and Ouyang, 2011; Li et al., 2012) for traffic oscillation quantification, (ii) to adapt it for estimating fuel consumption and emission from traffic oscillation and (iii) to explore vehicle control strategies of smoothing traffic with advanced technologies. The DF approach was developed to predict traffic oscillation propagation across a platoon of vehicles following each other by a nonlinear car-following law with only the leading vehicle's input. We first simplify the DF approach and prove a set of properties (e.g., existence and uniqueness of its solution) that assure its prediction is always consistent with observed traffic oscillation patterns. Then we integrate the DF approach with existing estimation models of fuel consumption and emission to analytically predict environmental impacts (i.e., unit-distance fuel consumption and emission) from traffic oscillation. The prediction results by the DF approach are validated with both computer simulation and field measurements. Further, we explore how to utilize advantageous features of emerging sensing, communication and control technologies, such as fast response and information sharing, to smooth traffic oscillation and reduce its environmental impacts. We extend the studied car-following law to incorporate these features and apply the DF approach to demonstrate how these features can help dampen the growth of oscillation and environmental impact measurements. For information sharing, we convert the corresponding extended car-following law into a new fixed point problem and propose a simple bisecting based algorithm to efficiently solve it. Numerical experiments show that these new car-following control strategies can effectively suppress development of oscillation amplitude and consequently mitigate fuel consumption and emission.

1. Introduction

1.1. Background & motivation

The stop-and-go traffic, also known as traffic oscillation, refers to the phenomenon that highway vehicles in congested traffic, instead of maintaining a steady speed, are often forced to be engaged in repeated deceleration–acceleration cycles. This phenomenon, cited as "a nuisance for all motorists throughout the world" (Laval and Leclercq, 2010), likely incurs a number of adverse impacts to highway traffic efficiency and sustainability, including excessive travel delay, less driving

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comfort, increased safety hazards and extra fuel consumption and emission, particularly when traffic congestion is severe (Treiber et al., 2009; Treiber and Kesting, 2013). Researchers have conducted numerous studies investigating traffic oscillation with empirical observations and theoretical models. With observations from inductive loop detectors, empirical studies associated formation of traffic oscillation to highway bottlenecks, such as highway lane drops (Bertini and Leal, 2005), lane changes near merges and diverges (Mauch and Cassidy, 2002; Cassidy, 2005; Menendez, 2006; Laval and Daganzo, 2006; Laval et al., 2007; Ahn and Cassidy, 2007) and roadway geometries (Jin and Zhang, 2005). They also showed clear periodical patterns of traffic oscillation when it is developed (Koshi et al., 1983; Kuhne, 1987; Ferrari, 1989; Zielke et al., 2008; Mauch and Cassidy, 2002; Ahn, 2005). Measures of oscillation characteristics (e.g., period and amplitude) were initially proposed using time domain analysis (Neubert et al., 1999; Mauch and Cassidy, 2002; Treiber and Helbing, 2002; Laval, 2011; Treiber and Kesting, 2012). It was later shown that these measures have certain biases in describing oscillation characteristics (e.g., amplifying certain oscillation periods while dampening the others), and later studies proposed analytical tools in the frequency domain to remedy these issues (Li et al., 2010, 2012; Zheng et al., 2011). Scholars further introduced the concept of synchronized flow and categorized traffic oscillation into different patterns (Kerner and Rehborn, 1996; Kerner and Rehborn, 1997; Kerner, 1998; Kerner, 2002; Kerner and Klenov, 2006). Recent studies further associated measures from point sensor data that only sample traffic states at fixed locations to oscillation patterns that each individual vehicle trajectory experiences (Li et al., 2010; Laval, 2011).

Motivated by these empirical findings, numerous research efforts have been made trying to explain propagation of traffic oscillation with car-following models. A car-following model basically describes how a driver maneuvers her vehicle in response to her observations of the preceding vehicle's movements. Early studies attempted to use linear car-following models to predict the growth of traffic oscillation across a platoon of vehicles (Chandler et al., 1958; Herman et al., 1958). The linear structure of these car-following models allowed oscillation responses to be analytically measured with existing frequency analysis tools. However, since these linear models ignore fundamental physical constraints (e.g., speed limits), their analytical results are often quite unrealistic; e.g., they predict that oscillation magnitude will grow at an exponential rate to infinity (Li and Ouyang, 2011). Later people developed a number of nonlinear car-following models with certain physical bounds (Gazis et al., 1961, 1981, 1995, 1998,, 2000, 2001, 2002,,, 2003, 2005, 2010,) in hope of better reproducing reality. Multiple phases of stationary traffic (Kerner, 2013; Jiang et al., 2014), as apposed to a unique density-flow relationship, have also been investigated to explain discrepancies between field observations and car-following model predictions. See Orosz et al. (2010) and Wilson and Ward (2011) for reviews on the developments of nonlinear car-following models in the past half century. However, due to complexities imposed by nonlinearity, oscillation characteristics of these nonlinear models were mostly studied with only computer simulation (e.g., Helbing et al., 2009; Treiber et al., 2009) and qualitative stability analysis (e.g., Wilson, 2008; Orosz et al., 2009; Wilson and Ward, 2011; Treiber and Kesting, 2011). While these efforts produced useful tools and applications with nonlinear car-following models, there still remain challenges to the understanding and modeling of the traffic oscillation phenomenon, e.g., reducing computational burden, revealing problem structures and insights, and quantifying oscillation propagation. Only limited attempts were made to quantitatively match observed oscillation characteristics with car-following model results from computer simulation (Treiber and Kesting, 2012) and a describing function (DF) based analytical approach (Li and Ouyang, 2011; Li et al., 2012). These studies have shown that proper nonlinear models are able to reasonably predict oscillation amplification patterns observed in field. In particular, the DF based approach, regarded as the first attempt to analytically predict oscillation propagation for nonlinear car-following models, manifests the growing-and-flattening pattern of observed oscillation amplitude propagation in the frequency domain by experimenting specific car-following laws and leading vehicle's inputs. However, several critical properties of this analysis approach remain puzzling. For example, is the predicted propagation pattern an intrinsic property of a car-following model or is it sensitive to the leading vehicle's trajectory profile? How is the propagation pattern related to the structure of a general class of car-following laws (rather than just a specific instance)? How are critical features of the propagation patterns (e.g., oscillation amplification ratio and asymptotic maximum amplitude) quantitatively related to car-following parameters? Answers to such questions, which are yet to be found, have significant implications to understanding fundamental connections between car-following behaviors and oscillation development and to constructing proper car-following models in reproducing observed traffic oscillation patterns.

Despite these efforts trying to understand formation and propagation mechanisms of traffic oscillation, as far as our knowledge, there is little research on quantifying its adverse impacts, such as fuel consumption and emission, which are critical to monitoring traffic performance and evaluating highway services when traffic oscillation is present. On the other hand, there have been quite some developments for a vehicle's instant fuel consumption and emission measures with vehicle kinematics (Post et al., 1984; Ahn, 1998; Barth et al., 2000; Ahn and Aerde, 2002; Koupal et al., 2002; Rakha et al., 2011; Zegeye et al., 2013). For example, scholars at Virginia Tech conducted regression analysis with fuel consumption and vehicle emission data for several types of vehicles collected by Oak Ridge National Laboratory (ORNL) and found that these measures can be estimated at a reasonable accuracy by a function of vehicle's instant speed and acceleration (Ahn, 1998; Ahn and Aerde, 2002). These developments have a potential to be integrated with traffic oscillation models to quantify the environmental impacts of the stop-and-go traffic phenomenon. This will link our understanding of this phenomenon itself to its cost on transportation systems and surrounding environments.

With the knowledge of mechanisms and consequences of traffic oscillations, how to dampen this phenomenon and reduce its impacts remains a pending challenge. A handful of studies suggested general policies to smooth traffic (e.g., by restraining lane changes (Cassidy et al., 2009, 2010), which however cannot directly yield microscopic vehicular control