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A control theoretic formulation of green driving strategies based on inter-vehicle communications

Hao Yang, Wen-Long Jin *

Department of Civil and Environmental Engineering, Institute of Transportation Studies, University of California, Irvine, CA 92697, United States

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ABSTRACT

Various green driving strategies have been proposed to smooth traffic flow and lower pollutant emissions and fuel consumption in stop-and-go traffic. In this paper, we present a control theoretic formulation of distributed, cooperative green driving strategies based on inter-vehicle communications (IVCs). The control variable is the advisory speed limit, which is designed to smooth a following vehicle's speed profile without changing its average speed. We theoretically analyze the performance of a constant independent and three simple cooperative green driving strategies and present three rules for effective and robust strategies. We then develop a distributed cooperative green driving strategy, in which the advisory speed limit is first independently calculated by each individual vehicle and then averaged among green driving vehicles through IVC. By simulations with Newell's car-following model and the Comprehensive Modal Emissions Model (CMEM), we demonstrate that such a strategy is effective and robust independently as well as cooperatively for different market penetration rates of IVC-equipped vehicles and communication delays. In particular, even when 5% of the vehicles implement the green driving strategy and the IVC communication delay is 60 s, the fuel consumption can be reduced by up to 15%. Finally we discuss some future extensions.

1. Introduction

According to the Intergovernmental Panel on Climate Change, the transportation sector in the US was responsible for one third of greenhouse gas emissions in 2004, of which 80% was from passenger cars and freight trucks in roadway systems (Change, 2007). Globally, the situation has been worsening with the rapid development of motor vehicle transportation in developing countries (Faiz, 2007). Traffic oscillations, especially stop-and-go traffic waves, can cause extra greenhouse emissions in a road network due to frequent accelerations and decelerations (Rakha et al., 2003; Barth and Boriboonsomsin, 2008).

Some traditional speed control methods, including speed bumps (Pau and Angius, 2001) and police enforcement (Vaa, 1997), have been shown to have some smoothing effects on traffic oscillations. Recently, some advanced technologies, such as changeable message signs, have been introduced to display variable speed limits for critical road sections so as to reduce traffic oscillations and vehicles emissions in real time (Oh and Oh, 2005). In Smulders (1990, 1992), Van Den Hoogen and Smulders (1994), variable speed limits were calculated based on the average speed of road traffic and shown to significantly improve the stability of traffic flow. In (Kuhne, 1991), variable speed limits were determined by the standard deviation of

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* Corresponding author. Tel.: +1 949 824 1672; fax: +1 949 824 8385.
E-mail address: wjin@uci.edu (W.-L. Jin).

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speeds. In (Wilkie, 1997) shockwave prediction algorithms, average speed measurements, and environmental factors are combined to determine variable speed limits in order to smooth stop-and-go waves in heavy traffic. In (Lin et al., 2004), variable speed limits were determined by the traffic flow rate and congestion levels in highway work zones. In (Hegyi et al., 2005a,b), optimal variable speed limits were determined from the model predictive control approach and shown to decrease travel times and reduce the risk of vehicle accidents. In (Papageorgiou et al., 2008), variable speed limits were determined by traffic occupancy levels on roads. Note that such variable speed limits are mandatory for all vehicles on a road segment.

With the development of wireless communication and autonomous vehicle technologies, it is possible to advise or enforce speed limits for individual vehicles (Almqvist et al., 1991; Varhelyi and Mäkinen, 2001). One example is the intelligent speed adaptation (ISA) system (Carsten and Tate, 2005), which leverages road congestion information to provide advisory speed limits for individual drivers on specific road sections (Servin et al., 2008; Barth and Boriboonsomsin, 2009a). Experiments showed that ISA strategies can potentially mitigate congestion and reduce fuel consumption and pollutant emissions by smoothing vehicles' trajectories in congested traffic (Duynstee and Martens, 2000; Oei and Polak, 2002; Van Loon and Duynstee, 2001). Note that, in traditional ISA systems, vehicles are still manually driven, and traffic information is usually obtained from loop detectors and navigation maps.

Recently, inter-vehicle communication (IVC) technologies, which can enable the exchange of information among vehicles through dedicated short range communications (DSRC), have been proposed to develop advanced traveler information systems (Yang and Recker, 2005; Jin and Recker, 2006; Recker et al., 2008). IVC has been applied to implement cooperative adaptive cruise control (CACC) systems, which can help to improve driving safety, comfort, and fuel efficiency (Van Arem et al., 2006; Shladover et al., 2009). Different from those in ISA systems, vehicles in CACC systems are automatically controlled, once the desired speed is set the drivers.

In this paper, we propose and analyze IVC-based green driving strategies within the framework of feedback control systems. In this system, vehicles are still manually driven, the control variable is an advisory speed limit for each IVC-equipped green driving vehicle, and the control objective is to smooth vehicles' movements and reduce air pollutant emissions and fuel consumption in stop-and-go traffic. At the same time, we require that a green driving vehicle still follow its leader without increasing its travel time. In a sense, this is a hybrid CACC and ISA system. We first theoretically analyze the performance of a constant independent and three simple cooperative green driving strategies and derive three rules for effective and robust strategies. We then propose a distributed cooperative green driving strategy, in which the advisory speed limit is first calculated independently and then cooperatively. In our study, Newell's car-following model (Newell, 2002) is used to describe vehicles' movements, and the Comprehensive Modal Emission Model (CMEM) (Barth et al., 2001) is used to calculate vehicle emissions and fuel consumption. With simulations, we also examine the impacts on the performance of green driving strategies of market penetration rates (MPRs) of equipped vehicles and communication delays.

The rest of the paper is organized as follows. In Section 2, we describe Newell's car-following model, CMEM emission model, and a feedback control system with green driving strategies. In Section 3, we theoretically analyze a constant independent and three simple cooperative green driving strategies and discuss the requirements of designing green driving strategy. In Section 4, we construct a distributed cooperative green driving strategy and evaluate its smoothing effect on vehicle trajectories and environmental impacts with simulations. In Section 5, we conclude with discussion on some future research topics.

2. Control system description

In this section, we introduce Newell's car-following model for simulating vehicle movements and the CMEM emission model for calculating emissions and fuel consumption. Moreover, a feedback control scheme will be proposed to construct green driving strategies.

2.1. Newell's car-following model

In our study, we use Newell's car-following model to describe vehicles' movements. Compared with other car-following models, such as Gipps' model (Gipps, 1981) and General Motors models (Gazis et al., 1959), Newell's model is mathematically more tractable, and the advisory speed limit can be simply incorporated, since the speed limit is one parameter of the model. In addition, Newell's model has been verified with real-world observations in the literature (Ahn et al., 2004; Ma and Ahn, 2008; Chiabaut et al., 2010).

On a single-lane road, if vehicle n, whose location is denoted by $x_n(t)$, follows vehicle $n-1$, then Newell's car-following model can be written as (Newell, 2002; Daganzo, 2006)

$$x_n(t+\tau) = \min\{x_{n-1}(t) - s_j, x_n(t) + v_f\tau\}, \tag{1}$$

where s_j is the jam spacing, v_f the free-flow speed limit, and τ is the time gap. In this model, a following vehicle advances its location as far as possible, while maintaining a minimum safe distance (s_j) away from the leading vehicle without exceeding a speed limit. The model has two regimes: in congested traffic, $x_n(t+\tau) = x_{n-1}(t) - s_j$; in uncongested traffic, $x_n(t+\tau) = x_n(t) + v_f\tau$. Taking the derivatives on the both sides of Eq. (1), we have $v_n(t+\tau) = v_{n-1}(t)$ in congested traffic. Hence a disturbance in the leader's speed will remain the same in the follower's, and Newell's model is stable. On the other hand,