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Field tests of a dynamic green driving strategy based on inter-vehicle communication

Hao Yang[a], Lawrence Andres[b], Zhe Sun[b], Qijian Gan[b], Wen-Long Jin[b,*]

[a] Department of Civil and Environmental Engineering, Lamar University, Beaumont, TX 77710, USA
[b] Department of Civil and Environmental Engineering, University of California, Irvine, Irvine, CA 92619, USA

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ABSTRACT

This paper presents the design and results for field tests regarding the environmental benefits in stop-and-go traffic of an algorithmic green driving strategy based on inter-vehicle communication (IVC), which was proposed in Yang and Jin (2014). The green driving strategy dynamically calculates advisory speed limits for vehicles equipped with IVC devices so as to smooth their speed profiles and reduce their emissions and fuel consumption. For the field tests, we develop a smartphone-based IVC system, in which vehicles' speeds and locations are collected by GPS and accelerometer sensors embedded in smartphones, and communications among vehicles are enabled by specially designed smartphone applications, a central server, and 4G cellular networks. Six field tests are carried out on an uninterrupted ring road under slow or fast stop-and-go traffic conditions. We compare the performances of three alternatives: no green driving, heuristic green driving, and the IVC-based algorithmic green driving. Results show that heuristic green driving has better smoothing and environmental effects than no green driving, but the IVC-based algorithmic green driving outperforms both. In the future, we are interested in field tests under more realistic traffic conditions.

1. Introduction

The heavy volumes of urban passenger and freight vehicles result in increasing emissions of local air pollutants including hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), carbon dioxide (CO_2), and other greenhouse gas emissions. In 2016, U.S. Environmental Protection Agency reported that, in the U.S., the transportation sector is responsible for almost 26% of greenhouse gas emissions, 80% of which are caused by passenger cars and freight trucks (EPA, 2016). Globally, the situation was worsening with the rapid increase in the number of motor vehicles in developing countries (Faiz, 1993). There are various causes of high emissions generated by vehicles. Rakha et al. (2003) and Barth and Boriboonsomsin (2008) showed that frequent accelerations in stop-and-go traffic are one major cause of greenhouse gas emissions in transportation systems. Moveover, when a vehicle travels at an excessive speed over 65 mph, air pollutant emissions and fuel consumption will increase dramatically (Barth and Boriboonsomsin, 2008).

Various speed control strategies have been proposed to reduce pollutant emissions and fuel consumption Oh and Oh (2005). Some traditional methods, such as speed bumps (Pau and Angius, 2001) and police enforcement (Vaa, 1997), which are designed to improve road safety, were able to control excessive speeds and smooth traffic conditions, but they showed moderate environmental impacts. In Smulders (1990) and Kuhne (1991), variable speed limits (VSL) based on the average speeds on freeways were displayed

* Corresponding author.
E-mail address: wjin@uci.edu (W.-L. Jin).

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on road-side message boards for drivers to increase the stability of traffic streams; in contrast, Papageorgiou et al. (2008) proposed to determine VSLs based on occupancy levels on roads. Carsten and Tate (2005) developed an in-car speed limiter based on intelligent speed adaptation (ISA) systems to control vehicular speeds. The speed limiter determined from loop detector data has been shown to bring environmental benefits on freeways and arterial roads (Barth and Boriboonsomsin, 2009; Wu et al., 2010). Yang and Jin (2014) constructed a green driving strategy based on inter-vehicle communication (IVC) technologies to smooth green driving vehicles' speed profiles as well as reducing emissions and fuel consumption. In addition to un-interrupted roads, there are many studies to assist vehicle perform green driving on arterial corridors with signalized intersections under the connected vehicle environment, such as optimal velocity planning algorithms (Mandava et al., 2009; Barth et al., 2011; Asadi and Vahidi, 2011; Xia et al., 2013), green light optimized speed advisory (GLOSA) (Katsaros et al., 2011a,b; Seredynski et al., 2013b,a), eco-cooperative adaptive cruise control (Eco-CACC) (Rakha and Kamalanathsharma, 2011; Kamalanathsharma and Rakha, 2013; Kamalanathsharma et al., 2015; Yang et al., 2016; Ala et al., 2016; Yang et al., 2017), etc. Most studies applied IVC and vehicle-to-signal communications to collection both vehicle dynamics and signal timing information to estimate the optimal speed for individual vehicles to pass intersections with the minimum fuel consumption.

The aforementioned IVC-based green driving strategies require reliable vehicle wireless communications. However, the market penetration rate of dedicated short range communication (DSRC) or Wireless Access in Vehicular Environment (WAVE) is quite low. In contrast, smartphones and cellular networks form a viable platform for enabling vehicle-to-vehicle communications and, therefore, implementing traffic management applications. A recent survey of the smartphone market showed that almost 80% of consumers in U.S. owned smartphones in 2016, and globally, the rate was about one third (ComScore, 2016). Most smartphones are equipped with GPS devices, accelerometers, and gyroscopes, which can collect various real-time traffic information, including locations, speeds, acceleration rates, and directions. Thus smartphones have been widely used in transportation applications (Campolo et al., 2012): they have been used to monitor traffic conditions (Thiagarajan et al., 2010; Herrera et al., 2010; Bhoraskar et al., 2012; Picone et al., 2012; Händel et al., 2014), mitigate traffic congestion (Roy et al., 2011; Zhu et al., 2015), and improve the safety of motorcycle drivers (Spelta et al., 2010; Guido et al., 2012; Lee and Chung, 2012). Jin et al. (2012) developed a smartphone-based inter-vehicle communication (SPIVC) system to enable communications among vehicles. In this system, smartphones are used to collect vehicular information, such as location and speed from GPS devices and acceleration from accelerometers, and a central server connects all smartphones through dedicated applications.

In this paper, we present the design and results of the field tests with two cars for the IVC-based green driving strategy developed in Yang and Jin (2014). Vehicles' locations and speeds are collected by smartphones and shared through a smartphone-based inter-vehicle communication (SPIVC) system. In the tests, the leading car mimics stop-and-go traffic patterns, and the following car employs no green-driving, heuristic green driving based on his/her experience, or algorithmic green driving with the advisory speed limits calculated based on the green-driving strategy in Yang and Jin (2014). Moreover, the VT-Micro Emission model (Rakha et al., 2004) is applied to estimate emissions and fuel consumption with the trajectories obtained in the field tests. The environmental impacts of different strategies are compared under various stop-and-go traffic patterns.

The rest of the paper is organized as follows. Section 2 presents the algorithmic green driving strategy implemented in this paper. Section 3 discusses the smartphone-based inter-vehicle communication system. Section 4 describes the experimental design of the field tests. Section 5 discusses the test results. Finally, Section 6 concludes this study and states future work.

2. A green driving strategy based on inter-vehicle communication

The algorithmic green driving strategy developed in Yang and Jin (2014) aims to achieve the following two objectives: (1) smooth equipped vehicles' speed profiles as well as reducing emissions and fuel consumption; (2) maintain the average speed and travel time without prolonging the trips of the equipped vehicles. The strategy provides IVC-equipped vehicles with advisory speed limits based on surrounding vehicles' location and speed information, and the limits of the controlled vehicles are set to be close to, but larger than the average speeds of their leaders. In that sense, the system can guarantee that the controlled vehicles can follow their leaders appropriately without leaving large gaps. Moreover, the strategy provides advisory speed limits for drivers to follow and to avoid potential risk of incidents caused by fully vehicle control, and it also allows some randomness caused by human drivers. Furthermore, due to car-following rules, the strategy can at a relatively low market penetration rate (MPR) smooth the speed profiles of vehicles that are not directly controlled or performing green driving.

In the following we briefly review the control logic of the strategy. We label N vehicles from downstream to upstream as $\{1,2,...,N\}$, i.e., vehicle $n-1$ is the leader of vehicle n ,$\forall\ n = 2,3,...,N$. The location and speed of vehicle n at time t are denoted by $x_n(t)$ and $v_n(t)$, respectively. A subset of vehicles, $\mathscr{G}$, are equipped with the green driving application, and the number of vehicles in $\mathscr{G}$ is G. The dynamic green driving strategy calculates the advisory speed limit, $U_g(t)$, for an equipped vehicle g ($g \in \mathscr{G}$). The strategy is developed at discrete time steps with an interval Δt. We denote $x_g(i) = x_g(i\Delta t)$,$v_g(i) = v_g(i\Delta t)$, and $U_g(i) = U_g(i\Delta t)$.

The advisory speed limit provided by the strategy is calculated through the following three steps.

1. The average speed of an equipped vehicle during a stop-and-go period is calculated as

$$\bar{v}_g(i) = \frac{1}{K}\sum_{k=i-K+1}^{i} v_g(k), \tag{1}$$

where $K = T/\Delta t$. T is the period of stop-and-go traffic, which is in the order of 2–4 min (Li et al., 2010).