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Authors

Yang, Hao
Andres, Lawrence
Sun, Zhe
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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

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

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

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

(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).

2. We increase the advisory speed limit so that it is close to but larger than the average speed:

$$\widetilde{U}_g(i) = \bar{v}_g(i) + \Delta v_g(i),$$
(2)

where the increase is given by

$$\Delta v_g(i) = K_p \cdot \min_{k=i-K+1}^{i} \left\{ \frac{c_g(k-1)}{\tau} - v_g(k) \right\},$$
(3)

where $K_p = 0.001, c_g(k-1) = x_{g-1}(k-1) - x_g(k-1) - s_j$ is the clearance of vehicle g at time step $k-1$, and τ and s_j are the time gap and jam spacing, respectively. According to Newell's car-following model (Newell, 2002), $\Delta v_g(i) > 0$, if vehicle g fails to follow its leader during the period.

3. We use the moving averaging process of $\widetilde{U}_g(i)$:

$$U_g(i) = \begin{cases} v_f, & 0 \leqslant i < K-1 \\ \frac{\sum_{k=K-1}^{i} \widetilde{U}_g(k)}{i-K+2}, & K-1 \leqslant i < 2K-1 \\ w_1 \cdot \frac{\sum_{k=K-1}^{i-K} \widetilde{U}_g(k)}{i-2(K-1)} + w_2 \cdot \frac{\sum_{k=i-K+1}^{i} \widetilde{U}_g(k)}{K}, & i \geqslant 2K-1 \end{cases}$$
(4)

where $w_2 = 0.75$ is the weight for the traffic information in the most recent period, and $w_1 = 0.25$ for the earlier information.

If there are more than one green driving cars, a fourth step will be added to average the advisory speed limits of different green driving vehicles (Yang and Jin, 2014). But in the field tests, only one car performs green driving, and $U_g(i)$ is used as the advisory speed limit.

3. Smartphone-based inter-vehicle communication system

In this study, a smartphone-based IVC (SPIVC) system is constructed to realize the dynamic green driving strategy described in the preceding section. The system has been implemented to improve the safety of bike riders (Jin et al., 2012). Fig. 1(a) shows the system structure, where there are three basic entities: a leading vehicle, a following vehicle and a server. Each car carries an Android smartphone with a dedicated application, which communicates with the server. The leader application collects the vehicle's locations and speeds and transmit them to the server; while the follower application will not only collect information of the follower and send it to the server, but also retrieve the leader's information from the server. The roles of the server include (1) collecting information from both vehicles, (2) storing information in a MySQL database, and (3) responding requests from the follower. In this system, only one-directional communications from the leader to the follower are enable to assist the follower' green driving, even though two-way directions can also be implemented.[1]

Fig. 1(b) illustrates the detailed flow-charts of different components. Here, both vehicles collect traffic information, including time stamp, longitude, latitude and speed, through GPS devices. The frequency of data collection of GPS devices is determined by the settings of minimum distance and minimum time.[2] The leader application sends this information and its vehicle ID to the server and store them in its SD card as a record. The follower application applies the same function, and it also sends one request to the server to obtain the most recent leader's information. To respond the follower's request, the server screens the whole database with vehicle ID and transmit the correct information back to the follower. Then, the distance between these two vehicles is calculated as the spacing of the follower. The follower's smartphone also implements the green driving strategy with the spacing and speed to calculate an advisory speed limit and smooth the follower's trajectory, and the limit will be displayed on the screen of the smartphones so that the drivers can easily check the suggestions.

Note that, the leader application is designed to detect the leading vehicle's location. From the green driving strategy proposed in Section 2, the location information is applied to measure the distance between the leader and the follower. In the future, with the help of distance measurement instruments, such as lidar, infrared, and camera, the distance can be measured directly. Hence, the follower application can use the information to provide suggestions for drivers to perform green driving on roads.

4. Experimental design

The field tests involve two vehicles: one as the leader, and the other as the follower. Two smartphones, Motorola Moto E and HTC Desire, are installed with the leader and follower applications for the leader and the follower, respectively.[3] Both of them are

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[1] Note that, in this study, the smartphone ends do not communicate with each other directly. The server is built as an intermediate component to communicate with the phones. Moreover, the server processes the data obtained from phones and provides the processed information to the phones so that they can implement different applications.

[2] With these two variables, minimum distance and minimum time, once the moving distance since the last update is larger than the minimum distance, or the waiting time of the devices since the last update is larger than the minimum time, the GPS devices will collect the location information and send it to the server. Hence, the updating frequency can be determined.

[3] In this test, the leader and the follower are predefined. In reality, the role of each vehicle is defined by its initial location. The one in the front of the other is defined as the leader automatically.
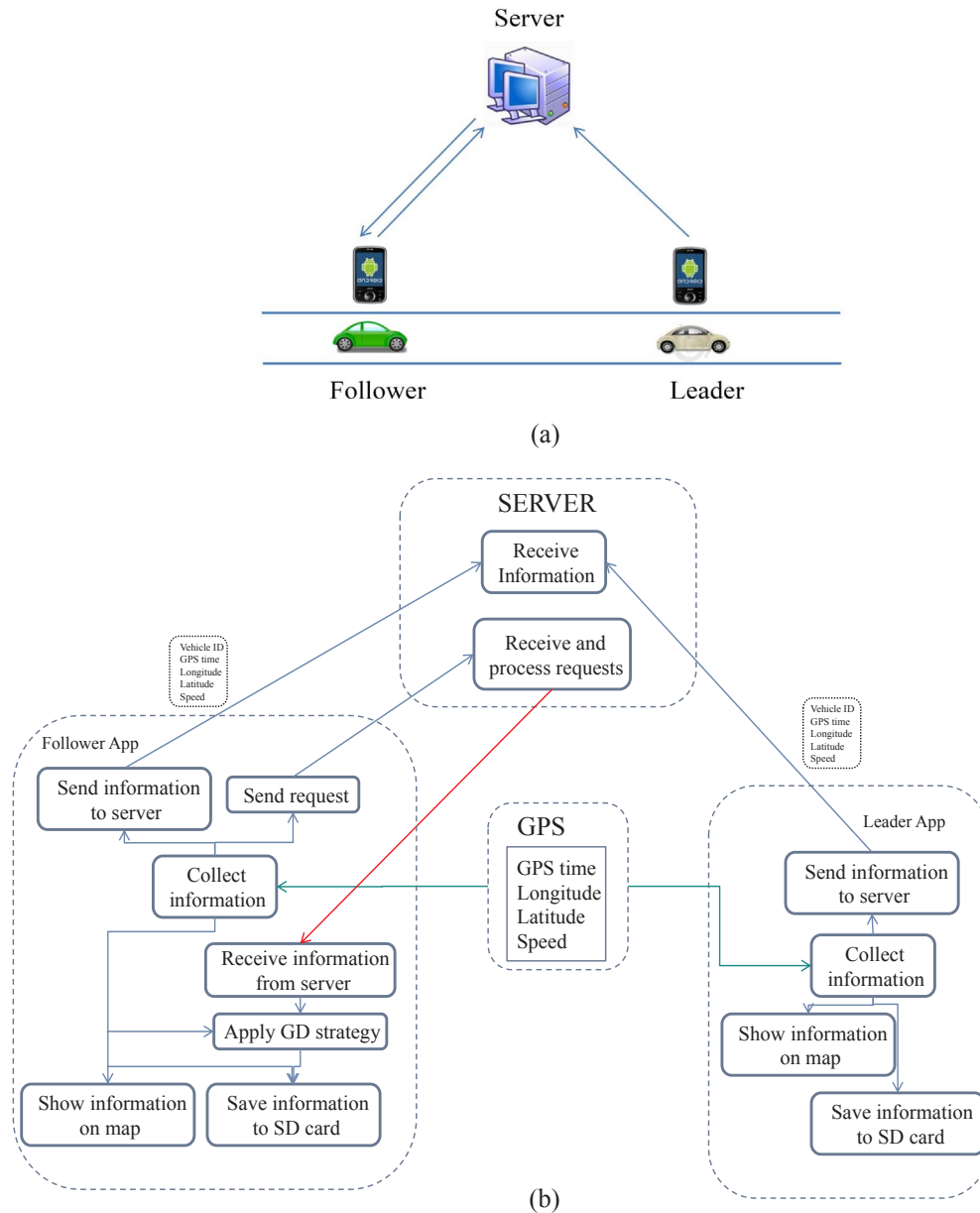
Fig. 1. Smartphone-based inter-vehicle communication system: (a) system structure; (b) component flow-charts.

embedded with GPS devices, and they are all able to access to cellular networks. In addition, the server is built under a desktop located in Institute of Transportation Studies, University of California, Irvine. The server contains two Intel XEON e5520 Nahelm CPUs, 12G DDR3 1333 SDRAM, and ASUS Z8PE-D12X mother board. A MySQL database is set on the server to collect the information from the smartphone applications.

We choose Sky Park Circle, in Irvine, CA, which is shown in Fig. 2, as the testbed. The road is flat, and its length is about 1 mile, which takes 2 min to traverse. The test road has neither traffic signal nor stop sign. In addition, the T-mobile 4G/LTE signal along the road is strong.

The objectives of the field tests include:

1. Verify the feasibility of the green driving strategy using the SPIVC system through 4G/LTE networks.
2. Investigate the effectiveness of the green driving strategy in reducing emissions and fuel consumption under various traffic patterns. In particular, we consider two types of stop-and-go traffic patterns: the leader accelerates from 5 to 50 mph and decelerates back once every two minutes in the slow stop-and-go traffic, but once every one minute in the fast stop-and-go traffic.
3. Compare the algorithmic green driving strategy with two other alternatives: no green driving, when the following vehicle's driver
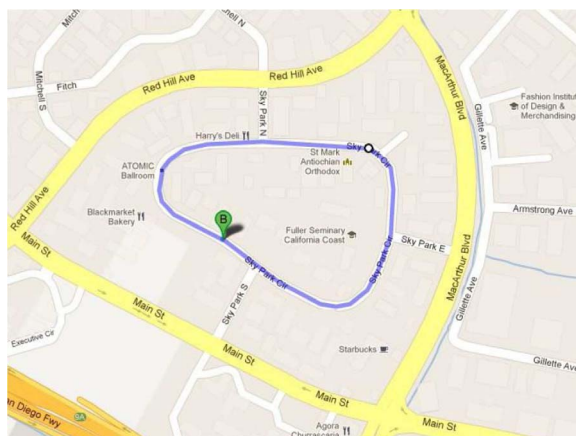
Fig. 2. A ring road for field tests.

obeys the car-following rule, and heuristic green driving, where the following vehicle's driver attempts to smooth its speed profile heuristically.

Six testing scenarios are considered, as shown in Table 1: for two types of stop-and-go traffic: slow with low oscillating frequency and fast with high oscillating frequency, we test the three different strategies: (1) None, where the follower travels with the labeled speed limits on the road, and it tries to follow the leader as close as possible but leaves a safety distance based on car-following mechanisms; (2) Heuristic, where the follower adjusts the speed based on his/her observations of the leader's movements without the help of the smartphone application; and (3) Algorithmic, where the application is activated, and the follower applies the advisory speed limit provided by the smartphone to smooth its movements. And, in all scenarios, the movements of the leading vehicles are set arbitrarily.

To more effectively and safely inform the following vehicle's driver regarding the dynamic speed limits, we implement a number of practical adjustments: (i) even the advisory speed limit is updated once every second, it is only displayed once every ten seconds, to minimize the distraction; (ii) the advisory speed limit is rounded at every 5 mph; and (iii) the follower always comply with the advisory speed limit in the algorithmic green driving scenarios. In addition, to minimize the impact of the surrounding traffic, all tests are conducted during 10 am to 3 pm on weekdays, when the traffic on the road is extremely low. We also carefully check the other vehicles on the road to make sure that none of them will cut in between the two testing vehicles.

5. Results

In this section, we present the field test results for the six scenarios in Table 1.

5.1. Slow stop-and-go traffic

Under the slow stop-and-go traffic, which corresponds to scenarios 1–3 in Table 1, the leader travels on the freeway with less frequent oscillations, where the leader will try to accelerate from 5 mph to the road speed limit, 50 mph, and then decelerate back gradually at every 2 min. Fig. 3 illustrates the speed profiles of the leader and follower, who adopts three different green driving strategies. The speeds of the leader, the speeds of the follower and the advisory speed limits are represented by blue dotted, green dotted and red solid lines, respectively. Note that the advisory speed limits in the first two scenarios are not used by the follower, who performs either none or heuristic green driving. The initial two minutes are warm-up periods when the speed limit is set at the given value (65 mph). Fig. 3(a) shows that, without green driving, the follower's speed profile is almost the same as the leader's. Fig. 3(b) shows that, with heuristic green driving, the follower's speed profile is smoother than the leader's. Fig. 3(c) shows that, with the algorithmic green driving, the follower's speed profile is much smoother than the leader's. The three figures also show that the

Table 1
Six test scenarios.

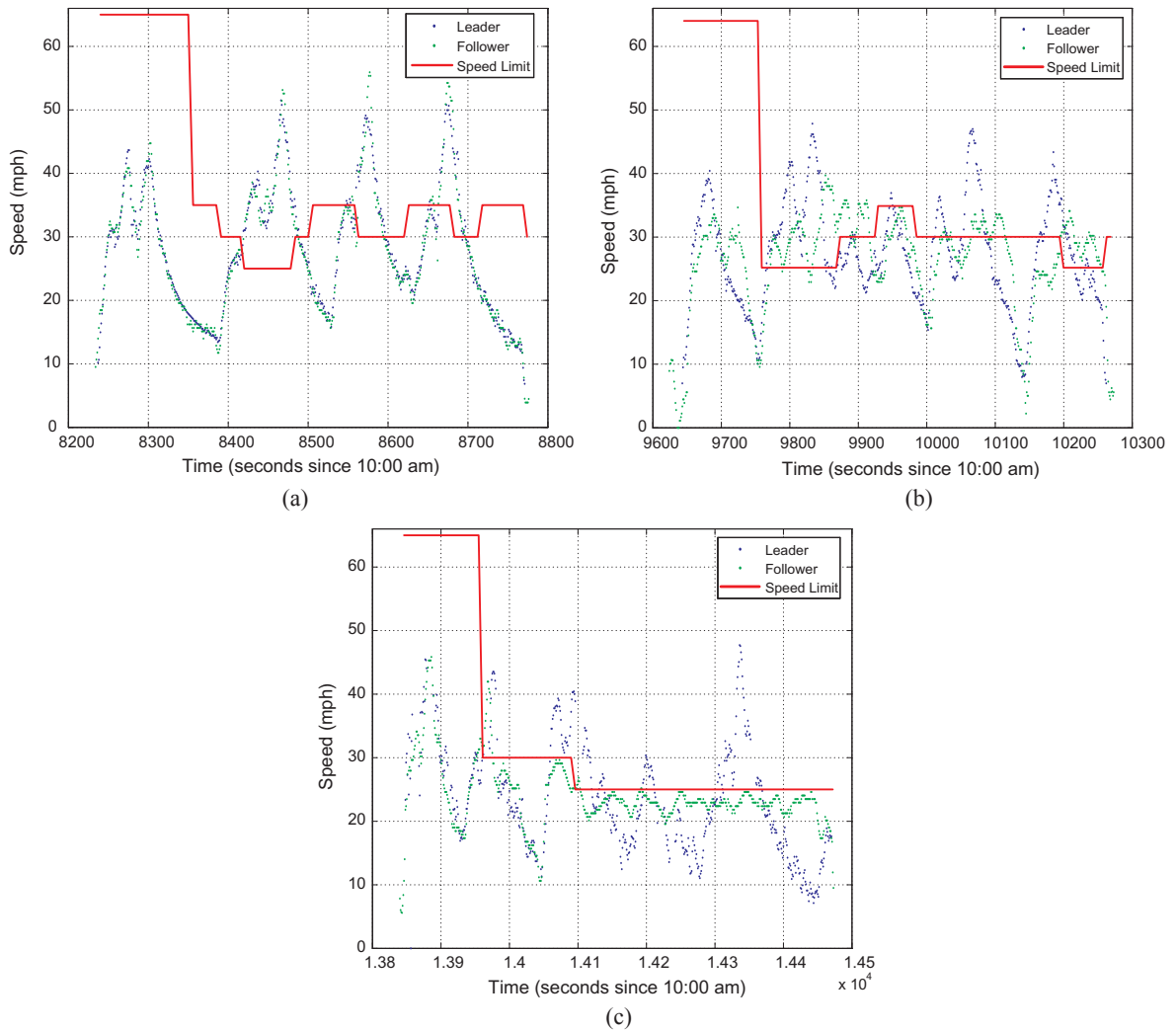| Scenario	Leader: Stop-and-go traffic	Follower: Green driving strategy
1	Slow	None
2	Slow	Heuristic
3	Slow	Algorithmic
4	Fast	None
5	Fast	Heuristic
6	Fast	Algorithmic

Fig. 3. Speeds and advisory speed limits in slow stop-and-go traffic. The follower's green driving strategy is (a) none, (b) heuristic, (c) algorithmic.

smoothness of the advisory speed limits in the three scenarios also increases from none, heuristic, to algorithmic green driving. In particular, with the algorithmic green driving, the advisory speed limit is indeed slightly larger than the follower's average speed. Note that the advisory speed limit of the following vehicle could be higher than the speed of the leader, and generally the limit is only higher than the leader's speed when the clearance between the leader and the follower is large. This is expected by the green driving strategy to make sure that the follower can catch the leader without increasing its travel time during the trip.

Fig. 4 shows the distances between the leader and the follower in the three scenarios. Fig. 4(a) shows that, without green driving, the distance is always very small (< 30 m), since the follower always follows the leader. But with heuristic and algorithmic green driving, the distances can become quite large but decrease to normal following distances periodically. Thus in both cases the follower is able to smooth its speed profiles but still follow the leader in the long run.

Note that in the first case study, the oscillation of the leader is less frequent, i.e., the period is long. In that sense, for the smoothed follower, the clearance could become very large during one period (in this run, the distance can be as high as 300 m). This is also expected by the green driving application to reduce vehicle emissions and fuel consumption. The distance is not reasonable in real roads with multiple lanes and heavy volumes. While, for one-lane roads, without over-passing of individual vehicles, the large clearance can be achievable when the application is applied. The similar conclusion can be applied for the heuristic green driving strategy, where the drivers smooth their own movements during the whole trip.

The statistical summary of the speed profiles is given in Table 2. We have the following observations: without green driving, both the average values and standard errors of the follower's speeds are almost the same as those of the leader's; with heuristic green driving, the average speeds are almost the same, but the standard error of the follower's speeds is 14% smaller than that of the leader's, since the follower's speed profile is smoother; with algorithmic green driving, the average speeds are also almost the same, but the standard error of the follower's speeds is much smaller (54%) than that of the leader's, and the follower's speed profile is much smoother.
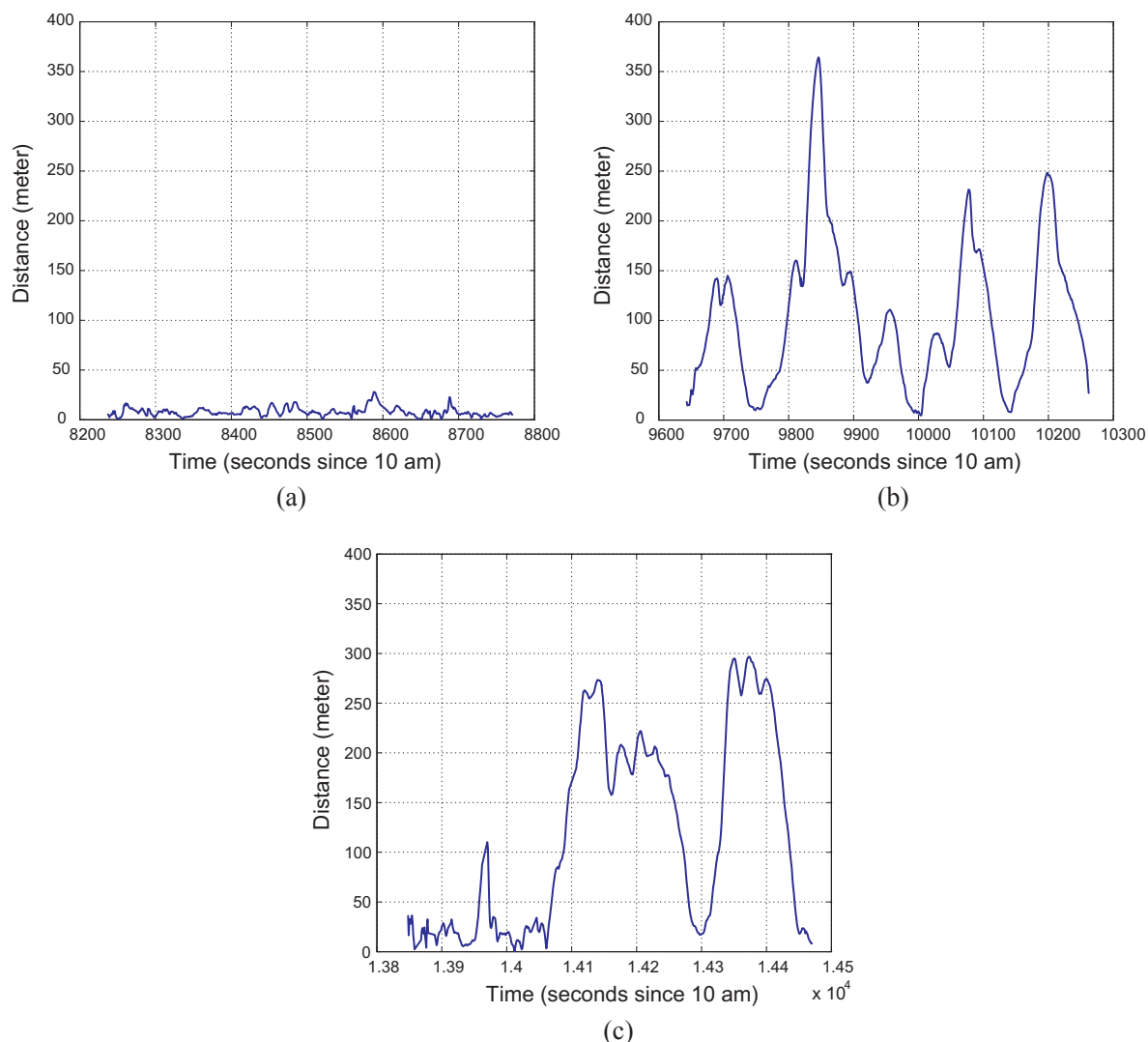
Fig. 4. Distances between the leader and the follower in slow stop-and-go traffic. The follower's green driving strategy is (a) none, (b) heuristic, (c) algorithmic.

Table 2
Statistics of speed profiles in slow stop-and-go traffic. In each cell, the first number is the average value, and the number in parentheses is the standard error.

Scenario	Leader's speeds	Follower's speeds	Difference (%)
1	7.83	7.65	−2.29
	(2.86)	(3.02)	(5.94)
2	7.78	7.50	−3.68
	(2.26)	(1.95)	(−13.77)
3	6.06	6.44	6.23
	(2.34)	(1.08)	(-53.78)

We further calculate emissions and fuel consumption with the VT-Micro emission model (Rakha et al., 2004), which uses second-by-second speed information to assess emissions and fuel consumption. The results for the three test scenarios are shown in Table 3. We have the following observations: without green driving, the emissions and fuel consumption by the leader and the follower are almost the same (the differences are less than 2%); with heuristic green driving, the follower's emissions and fuel consumption are reduced (13.47% for HC, 15.89% for CO, 8.7% for NOx, 3.36% for CO_2, and 3.70% for fuel consumption); with algorithmic green driving, the follower's emissions and fuel consumption are substantially reduced (24.55% for HC, 26.71% for CO, 25.22% for NOx, 19.73% for CO_2, and 19.88% for fuel consumption). Therefore, the effectiveness in reducing emissions and fuel consumption increases from no, heuristic, to algorithmic green driving strategies.

Table 3
Emissions and fuel consumption in slow stop-and-go traffic.

| Scenario	Emissions	Leader	Follower	Difference
1	HC (mg/mi)	3.68E+01	3.72E+01	1.18%
	CO (mg/mi)	9.05E+02	9.14E+02	0.95%
	NOx (mg/mi)	1.44E+02	1.41E+02	−2.09%
	CO_2 (mg/mi)	3.09E+05	3.11E+05	0.44%
	Fuel (l/mi)	1.34E−01	1.34E−01	0.49%
2	HC (mg/mi)	3.33E+01	2.88E+01	−13.47%
	CO (mg/mi)	7.74E+02	6.51E+02	−15.89%
	NOx (mg/mi)	1.36E+02	1.24E+02	−8.70%
	CO_2 (mg/mi)	3.07E+05	2.97E+05	−3.36%
	Fuel (l/mi)	1.32E−01	1.27E−01	−3.70%
3	HC (mg/mi)	3.56E+01	2.69E+01	−24.55%
	CO (mg/mi)	8.40E+02	6.16E+02	−26.71%
	NOx (mg/mi)	1.23E+02	9.23E+01	−25.22%
	CO_2 (mg/mi)	3.47E+05	2.79E+05	−19.73%
	Fuel (l/mi)	1.49E−01	1.20E−01	−19.88%
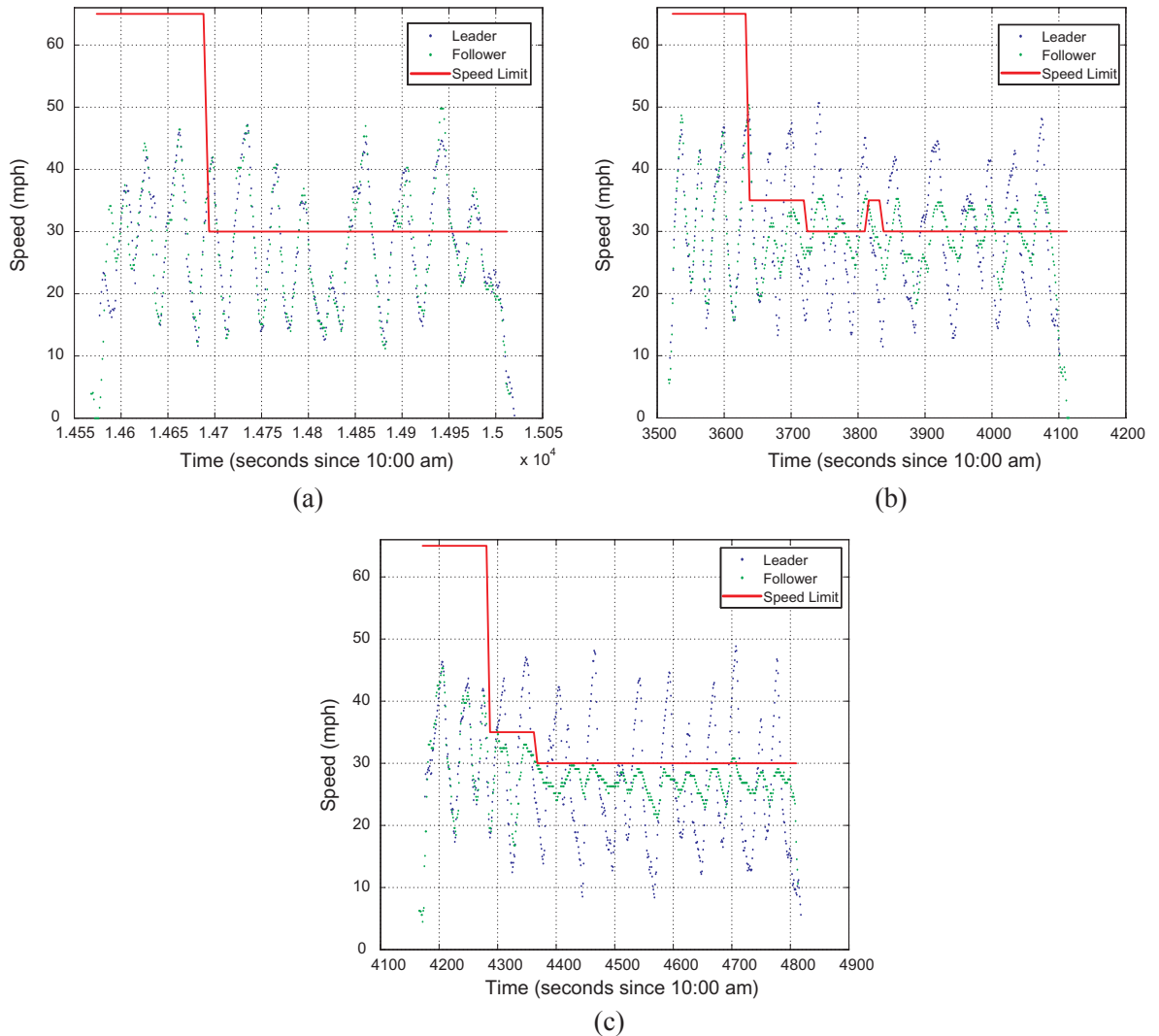
Fig. 5. Speeds and advisory speed limits in fast stop-and-go traffic. The follower's green driving strategy is (a) none, (b) heuristic, (c) algorithmic.
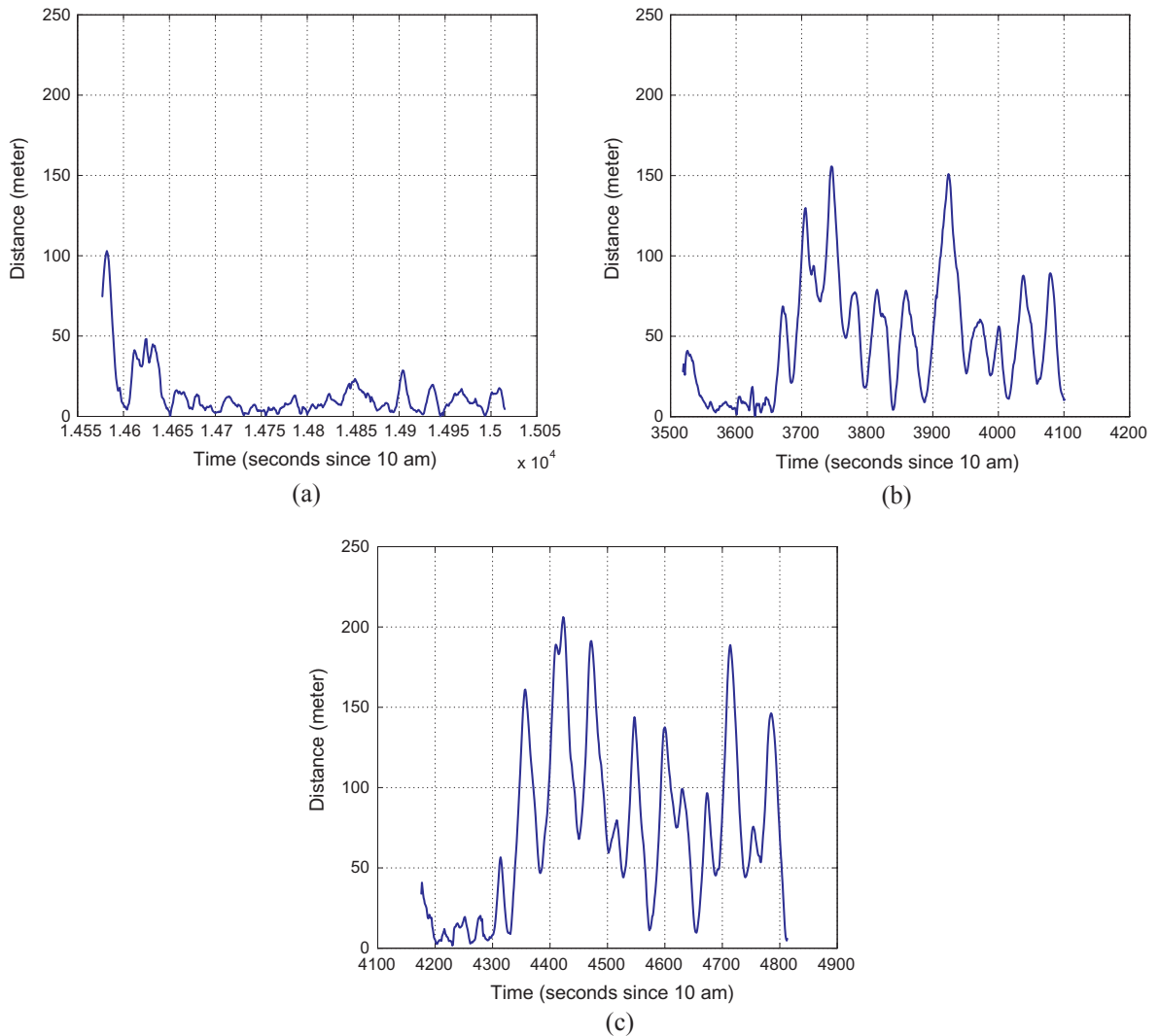
Fig. 6. Distances between the leader and the follower in fast stop-and-go traffic. The follower's green driving strategy is (a) none, (b) heuristic, (c) algorithmic.

Table 4
Statistics of speed profiles in fast stop-and-go traffic. In each cell, the first number is the average value, and the number in parentheses is the standard error.

Scenario	Leader's speeds	Follower's speeds	Difference (%)
4	7.43	7.49	0.69
	(2.72)	(2.77)	(1.71)
5	8.08	7.84	−2.97
	(2.71)	(1.64)	(−39.43)
6	7.42	7.53	1.51
	(2.89)	(0.81)	(−72.11)

Note that the results in scenario 1 indicate that if a driver applies simple car-following rules to follow its leader, the trajectory and, therefore, its emissions and fuel consumption, are almost the same as its leaders. In that sense, we can assume that a vehicle without control will have similar performance to its leader's, and compare the differences between the leader's and follower's performance in heuristic and algorithmic scenarios to evaluate the benefits of the GD application. Another issue worth mentioning is that the emissions and fuel consumption are estimated directly based on the VT-Micro emission model with the second-by-second speed information, but not directly measured with fuel consumption instruments, since each test run was only about 10 min, and the average fuel consumption for each run was less than 0.2 l. Hence, the direct fuel consumption measurements in cars might not be reliable, and the savings from the GD application might not be captured accurately.

Table 5
Emissions and fuel consumption in fast stop-and-go traffic.

Scenario	Emissions	Leader	Follower	Diff
4	HC (mg/mi)	4.08E + 01	4.85E + 01	18.76%
	CO (mg/mi)	9.90E + 02	1.24E + 03	25.33%
	NOx (mg/mi)	1.58E + 02	1.57E + 02	−0.79%
	CO_2 (mg/mi)	3.62E + 05	3.74E + 05	3.35%
	Fuel (l/mi)	1.56E − 01	1.63E − 01	4.09%
5	HC (mg/mi)	4.55E + 01	2.67E + 01	−41.30%
	CO (mg/mi)	1.11E + 03	6.03E + 02	−45.88%
	NOx (mg/mi)	1.76E + 02	1.21E + 02	−31.59%
	CO_2 (mg/mi)	3.83E + 05	2.79E + 05	−27.15%
	Fuel (l/mi)	1.65E − 01	1.20E − 01	−27.73%
6	HC (mg/mi)	4.31E + 01	2.56E + 01	−40.59%
	CO (mg/mi)	1.06E + 03	5.77E + 02	−45.32%
	NOx (mg/mi)	1.77E + 02	1.03E + 02	−41.78%
	CO_2 (mg/mi)	3.90E + 05	2.68E + 05	−31.20%
	Fuel (l/mi)	1.68E − 01	1.15E − 01	−31.52%

5.2. Fast stop-and-go traffic

When the leader is in fast stop-and-go traffic, which corresponds to scenarios 4–6 in Table 1, Fig. 5 illustrates the speed profiles of the leader and the follower, who adopts three different green driving strategies. The results are similar to those in Fig. 3, except that the period of stop-and-go is shorter at around 1 min.

Fig. 6 shows the distances between the leader and the follower. Similar to Fig. 4, without green driving, the follower always follows the leader closely; but with heuristic or algorithmic green driving, the follower is able to smooth its speed profiles but still follow the leader in the long run. Different from the scenarios with slow stop-and-go traffic, the distances are smaller due to the shorter period of the leader's oscillations.

The statistical summary of the speed profiles is given in Table 4. Similar to Table 2, the algorithmic green driving strategy has the most significant smoothing effect on the speed profiles. This is also verified by the results in emissions and fuel consumption, given in Table 5. Compared with Table 3, the leader generates more emissions and consume more fuel, as it is in fast stop-and-go traffic; however, the algorithmic green driving strategy leads to comparable emissions and fuel consumption for the follower, since the follower's speed profiles are much smoother in both slow and fast stop-and-go traffic. In this sense, the green driving strategy is much more efficient when vehicles stop and go frequently.

6. Conclusion

In this paper, we presented 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: none green driving, heuristic green driving, and the IVC-based algorithmic green driving. Results show that the heuristic green driving has better smoothing and environmental effects than none green driving, but the IVC-based algorithmic green driving outperforms both. In particular, with the algorithmic green driving strategy, the standard error in the speeds can be reduced by 54% in slow stop-and-go traffic and by 72% in fast stop-and-go traffic; the greenhouse gas emissions (CO_2) and fuel consumption are reduced by 20% and 30% respectively under the two types of traffic conditions. This study clearly demonstrates the feasibility and effectiveness of the algorithmic green driving strategy.

In the future we will be interested in extending the field tests in the following aspects. First, the driving condition is relatively ideal, as there are no other vehicles on the ring road during the field tests. We will be interested in testing the algorithmic green driving strategy on open roads, where the stop-and-go traffic patterns are determined by the surrounding traffic conditions, and other vehicles could squeeze between the leader and the follower. Second, there is only one green driving vehicle in this study. We will be interested in testing with multiple green driving vehicles, for which the fourth step in Yang and Jin (2014) will be included to calculate the advisory speed limits. For these studies, the safety measures might have to be enhanced to minimize the distraction of the smartphone application, and it is important but challenging to evaluate the effects in smoothing the speed profiles and reducing emissions and fuel consumption for surrounding vehicles. Third, in reality, it may not be easy to identify the leaders and follower on roads for the smartphone application. To overcome this problem, we plan to install distance measurement instruments in cars and connect them with the smartphone application to replace the leader application. In addition, we will install some fuel consumption

and emission measurement devices to monitor the actual amounts of vehicles during tests. Futuremore, we will study the influence of drivers' compliance rates to the advisory speed limits on the effectiveness of the strategy, and further improve the application, such as polishing the user interface, to motivate drivers to comply the suggestions from the application. Finally, we plan to design more field tests to compare the proposed green driving application with the other eco-driving systems (Carsten and Tate, 2005; Barth and Boriboonsomsin, 2008; Wu et al., 2010) in real world.

Acknowledgments

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