A CONTROL THEORETIC FORMULATION OF GREEN DRIVING STRATEGY BASED ON INTER-VEHICLE COMMUNICATIONS

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ABSTRACT

The transportation sector generates a large percentage of local pollutants including hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO2), and oxides of nitrogen (NOx). Apart from switching to alternative fuels, various green driving strategies that smooth traffic flow and reduce congestion can be implemented to lower pollutant emissions and fuel consumption. In this paper, we study constant and dynamic green driving strategies based on inter-vehicle communications. With Newell's car-following model, a theoretical analysis demonstrates that optimal smoothing effects can be achieved when the constant speed limit is close to but not smaller than the average speed of traffic, which can guarantee a vehicle's speed profile be smooth while still following its leader during a relative long time period. Then we consider a dynamic strategy in which, through inter-vehicle communication, controlled vehicles share their location and speed information. By simulations with Newell's car-following model and CMEM emission model for different market penetration rates of IVC-equipped vehicles and communication delays, we can see that the proposed dynamic green driving strategy can significantly reduce emissions and fuel consumption without reducing average speed of traffic in a stop-and-go traffic stream. In the future, we will investigate traffic and environmental benefits of green driving strategies for more realistic traffic and communication scenarios.

Keywords: green driving, speed control, smooth traffic flow, emissions, fuel consumption, Newell's car-following model, CMEM, inter-vehicle communication, market penetration rate, communication delay

1 INTRODUCTION

According to Intergovernmental Panel on Climate Change, the transportation sector in the U.S. was responsible for one third of greenhouse emissions in 2004, of which 80% was from passenger cars and freight trucks on the roadway systems [1]. Globally, the situation was worsening with the rapid development of motor vehicle transportation in developing countries [2]. Traffic oscillation, known as stop-and-to wave, is one major cause of greenhouse emission in transportation systems [3]. The frequent accelerations associated with stop-and-go states in traffic leaded to higher greenhouse emissions [4]. Moveover, when vehicle traveled at the speed over 65 mph, i.e., excessive speed, emissions and fuel consumption would increase significantly [3].

Speed control can offer a direct and effective way to control traffic and improve on-road performance [5]. Some traditional speed control methods, such as speed bumps [6] and police enforcement [7], have been studied to control excessive speed and smooth traffic oscillations, but they showed moderate effects on speed control. Recently, advanced technologies are introduced to develop variable speed limit and realize speed control in transportation systems. Variable speed sign is one method in which, advisory speed signals is displayed on road for driver to improve traffic flow and safety. In [8], Smulders established a control strategy based on the mean of speed on freeway, which showed significant improvement of the stability of the traffic stream. In [9], Kuhne proposed a speed control scheme in which standard deviation of speed was regarded as one decision variable to determine speed limit. Moreover, Papageorgiou implemented variable speed limit in freeway to improve traffic flow efficiency [10].

Another method of speed limit control is applying telecommunication and information technologies to design in-car speed limiter [11]. Different from variable speed signs which provide signals to all vehicles on roads, in-car speed limiter is able to enforce speed limit to individual vehicle directly. Intelligent Speed Adaptation (ISA) is one common used advanced technology for developing in-car speed limier [12]. In the literature, there have been numerous studies on ISA to smooth traffic. ISA systems used road congestion information provided by loop detectors through wireless communication to adjust speed limits of individual vehicles on specific road sections [13]. In [13, 14], a set of speed limits and appropriate actions, such as not accelerating quickly, were provided to drivers through ISA systems. Experiments showed that ISA had potential to mitigate congestion by smoothing the dynamics of congested traffic. ISA equipped vehicle had a much smoother trajectory (with smaller speed variation), which leaded to low fuel consumption and pollutant emissions. In addition, many field implementations of ISA systems had been done to measure the influence of ISA on traffic safety and environment. ISA experiments in Tilburg (Netherlands) showed that with speed limit control, driving behavior was much safer and more environmentally friendly [15, 16, 17]. Moreover, in [5], with optimal speed limits adjustment, freeway traffic conditions were more stable, which also benefited to driving safety and reduced air pollutant emissions.

However, since ISA systems obtained aggregate traffic information from loop detectors, the implementation was limited by the distribution of the detectors. Moreover, due to data processing and internet access, the traffic information was delivered to the drivers for more than 30-second delay [13], which might reduce the effect of green driving implementation. Recently, inter-vehicle communication (IVC) technologies, which exchanges individual vehicle information through wireless communication between vehicles, are investigated to develop advanced vehicle control system [18]. A number of effort, such as CarTalk [19] and FleetNet [20], are underway to investigate inter-vehicle communication based on mobile ad hoc network technology as a means of developing "Internet on the road". Studies indicates that IVC systems could provide valuable, real-time traffic information with smaller delay (< 0.1 second [21]) to the drivers than ISA systems. Applying IVC systems, people can drive more smoothly and safely with appropriate speed limit settings. As the number of cars equipped with these technologies increases, we expect that drivers will adapt their behaviors more accordingly [18, 22, 23]. Such collective behavior changes will result in different traffic flow characteristics, transportation systems performance, and environmental impacts. Therefore, IVC has even better potential to improve traffic flow, fuel consumption economy, and reduce emissions. However, there have not been any systematic studies of potential environmental effect of IVC system.

In this paper, we construct green driving strategies based on a feedback control system, with which a set of appropriate speed limits is provided to individual vehicles to smooth stop-and-go waves and decrease emissions and fuel consumption. In the study, vehicles equipped with IVC systems share their individual traffic information. Based on these, we theoretically analyze effect of a constant green driving strategy on microscopic car-following behaviors. We also propose one dynamic green driving strategy to reduce traffic oscillations. The influence of characteristics of IVC systems, such as market penetration rate (MPR) of equipped vehicles, communication delay, on the strategy is investigated. To evaluate the potential benefits of such green driving strategies, Newells car-following model [24] and Comprehensive Modal Emission Model (CMEM) [25] are integrated into a simulation platform. Comparing with other car-following models, such as Gipps's model [26] and General Motor model [27], Newell's model is simple and straightforward to describe vehicle movement in traffic streams and is easy to be cooperated with speed limit control. With the integrated simulation model we then study environmental benefits of green driving strategies under various traffic conditions.

The rest of the paper is organized as follows. In section 2, we will describe Newell's car-following model, CMEM emission model and a control scheme. In section 3, we will theoretically analyze constant green driving strategy. Section 4 presents a dynamic green driving strategy and its effect on environment. Conclusions and future work will be presented in section 5.

2 Model Description

2.1 Newell's Car-following Model

In an open road, if vehicle n follows an (n-1)-th vehicle, the trajectory of the n-th vehicle $x_n(t)$ depends on $x_{n-1}(t)$ of the (n-1)-th vehicle. This also indicates that the trajectory $x_{n+1}(t)$ of a following (n+1)-th vehicle has no effect of determining trajectory of $x_n(t)$. In Newell's model, if vehicle n is able to advance its location where it keeps minimum distance (jam spacing or spacing displacement) s_j away from vehicle n-1 without exceeding speed limit (or free flow speed) v_f, then after a certain time gap (or time displacement) τ, vehicle n will arrive at $x_{n-1}(t) - s_j$. If vehicle n cannot run to that location, then it will run with free flow speed. The two possible locations are combined to be Newell's car-following model.

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

We assume that a sampling interval of Newell's model is $\triangle t = \tau$ and $t = i\triangle t$. Then, the discrete-time expression of Newell's car-following model is obtained.

$$x_n(i+1) = \min\{x_{n-1}(i) - s_j, x_n(i) + v_f\tau\} \tag{2}$$

Equation 2 also implies that, treveling with Newell's car-following model, one vehicle always takes the most advanced position possible, limited by free flow speed and the position of its leader. Once a vehicle catches up with the car it follows, the two trajectories become translationally symmetric with time and space displacement τ, s_j [28].

Moreover, Newell's car-following model is a stable model, with which the following vehicle will not have an amplified response of a change in the motion of the leading vehicle. Suppose that spacing between vehicle n and n-1 is constant for all $n = 1, 2, \cdots, N$, i.e., $s(t) = x_{n-1}(t) - x_n(t) = s$, where $s < v_f\tau$, which indicates that the traffic is congested. From **Equation** 1, the relationship of speed between the leader and its follower in congestion is

$$v_n(t+\tau) = v_{n-1}(t). \tag{3}$$

We add a speed disturbance $y(t)$, which is generated by acceleration or deceleration, to the leading vehicle at time t [29]. Assume that the disturbance $y(t)$ is very small, so that traffic is still congested. From **Equation** 3, we know that the disturbance $y(t)$ is preserved and translated to the follower. It indicates that disturbance $y(t)$ will not be amplified in the following vehicle by Newell's car-following model. But this also implies that without control of driving behavior, the disturbance cannot be released with Newell's car-following model. Study in [30] also shows that traffic oscillation will propagate from downstream to upstream without smoothing. Therefore, we have to set control strategies to smooth the disturbances and satisfy our purpose of smoothing traffic.

2.2 Emission Model

In August 1995, the College of Engineering-Center for Environmental Research and Technology (CE-CERT) at the University of California, Riverside began a four-year research project to develop a Comprehensive Modal Emissions Model (CMEM). This project was aimed to develop and verify a modal emissions model that accurately reflects Light-Duty Vehicles emissions. In the developing of CMEM, both engine-out and tailpipe emissions of over 300 vehicles, including more than 30 high emitters, were measured at a second-by-second level. CMEM can predict second-by-second emissions and fuel consumption of individual vehicle or aggregated vehicles [25].

The CMEM is developed from a parameterized physical approach which breaks the entire emission process into two components: vehicle operation and emission production. Input of CMEM contains two parts: 1) vehicle and operation variables, such as speed, acceleration, and road grade; 2) model calibrated parameters, such as cold start coefficients, engine friction factor. Output of CMEM is either second-by-second or summarized emissions (HC, CO, CO2, NOx) and fuel consumption [25, 4].

2.3 Feedback Control

Feedback control is a control mechanism that uses information from measurements to manipulate a variable to achieve the desired result [31]. In a feedback control system, information about system performance is measured and that information is used to correct how the system performs. There are three basic components in a feedback control system: sensor, controller and plant. Sensor is used to measure the system performance, controller reacts to information from sensor and applies corrective action to a plant, and the plant will response to the action. Feedback control systems vary in complexity, but generally fall into four categories: on-off, proportional (P), proportional plus intergral (PI), proportional plus integral plus derivative (PID). The block diagram of feedback control is illustrated in **Figure** 1

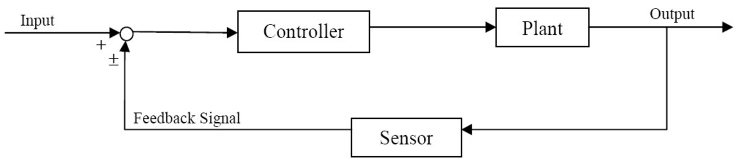


Figure 1: Block diagram of feedback control system

Feedback control system has potential on improving the robustness of system of reaction to disturbance or noise. Therefore, introducing feedback control in green driving is able to smooth traffic. In the implementation of feedback control on green driving, Newell's car-following model is chosen as the plant, and green driving strategy is designed as the controller. The goal of green driving is smoothing traffic oscillations, i.e., stop-and-go traffic, and reducing emissions and fuel consumption without decreasing the average speed. Therefore, the performance index in this control system is chosen as the standard deviation of speed [3, 4]. The control scheme is used in section 4 to design a dynamic green driving strategy.

3 Analysis of Simple Green Driving Strategies

In this section, we will analyze some simple green driving strategies. In our study, we introduce IVC technology in transportation system. One vehicle equipped with IVC system collects its own traffic information, including location, spacing, velocity, acceleration, etc, from GPS device or smartphone. It is also able to communicate with other vehicles equipped with IVC system either from DSRC (Dedicated short range communication) [21] or from 3G network using smartphone [32]. Hence, vehicles in transportation system can share their information, and based on these information, drivers can decide their driving behaviors to smooth traffic.

From Newell's car-following model (**Equation** 1), we see that vehicle trajectories can be controlled by speed limit (free flow speed) v_f. So, we will try to set an appropriate speed limit for vehicles to control speed and smooth traffic. Our goal of designing this speed limit is smoothing vehicle trajectories, i.e., reducing standard deviation of velocities of the vehicles without decreasing the average speed.

Suppose that there are N vehicles traveling on a homogeneous road. We donate location, spacing, and velocity of vehicle n at time t by $x_n(t), s_n(t), v_n(t)$. Let the set of IVC equipped vehicles applying green driving strategy by $\mathscr{G}$, which is a subset of $\{1, 2, \cdots, N\}$. We donate the number of green driving vehicles by G. v_f, s_j represent the free flow speed and the jam spacing.

3.1 Failure of Two Green Driving Strategies

With the information shared by IVC equipped vehicles, one of the most straightforward thinking of designing speed limit is using average speed. In [13, 14, 3], average speed of a road section is introduced as one major factor to set speed limit. Here, the first green driving strategy is

$$U_g(t) = U(t) = \frac{\sum_{g \in \mathscr{G}} v_g(t)}{G}. \tag{4}$$

Discretizing $U_g(t)$ as $U_g(i)$. Then, discrete Newell's car-following model (**Equation** 2) is modified.

$$x_g(i+1) = \min\{x_{g-1}(i) - s_j, x_g(i) + U_g(i)\tau\} \tag{5}$$

This strategy does not work in some traffic scenarios. For example, in one extreme solution, all controlled vehicles are stopped, i.e., $v_g(t) = 0$. Then, $U_g(t) = 0$. From **Equation** 5, $x_g(i+1) = x_g(i)$, and $v_g(i+1) = 0$. This is a steady-state solution of the control problem. It indicates that controlled vehicles will not move even the other vehicles is moving, i.e., the controlled vehicles fail to follow their leaders. From **Equation** 4 and **Equation** 5, we can get multiple steady-state solutions if and only if $U_g(i)$ is smaller than the average speed of the leading vehicles.

Another green driving strategy is using predicted average speed of the controlled vehicles.

$$U_g(i) = U(i) = \frac{\sum_{g \in \mathscr{G}} x_{g-1}(i) - x_g(i) - s_j}{\tau G} \tag{6}$$

If the traffic is congested, **Equation** 6 is equivalent to

$$U_g(i) = U(i) = \frac{\sum_{g \in \mathscr{G}} v_g(i+1)}{G}. \tag{7}$$

Equation 7 is a predictive version of **Equation** 4. With **Equation** 7, the controlled vehicles would be able to follow the leading vehicles. But, the resulting trajectories may not be smoother. For example, if $\mathscr{G} = \{2\}$, i.e., only vehicle 2 is under control. Then,

$$U_2(i) = \frac{x_1(i) - x_2(i) - s_j}{\tau}. \tag{8}$$

Equation 5 becomes

$$x_2(i+1) = x_1(i) - s_j.$$

In this case, the following vehicle's trajectory is not smoother than that of the leading vehicle. Also the follower could have speed larger than v_f, if the spacing is too large.

3.2 Analysis of Constant Green Driving Strategy

From the analysis in the preceding section, we see that a successful green driving strategy should (1) enable the following vehicles to follow their leading vehicles, and (2) smooth the trajectories.

Theoretically, for the periodic stop-and-go traffic, if we set speed limit as the average speed, the controlled vehicles would have very smooth trajectories after a finite time and enable to track the leading vehicles on average; i.e.,

$$||x_g(i) - x_0(i)|| \rightarrow constant.$$

Then, we will theoretically analyze effect of a constant speed limit on smoothing traffic. Firstly, average $\bar{v}_g$ and standard deviation σ_g of speed of controlled vehicle g are set as the measurements of smoothness.

$$\bar{v}_g = \frac{1}{T} \int_{t=0}^{T} v_g(t) dt = \frac{\sum_{i=1}^{K} v_g(i)}{T} \tag{9}$$

$$\sigma_g = \sqrt{\frac{1}{T}\int_{t=0}^{T}(v_g(t)-\bar{v_g})^2 dt} = \sqrt{\frac{\sum_{i=1}^{K}(v_g(i)-\bar{v_g})^2}{k-1}} \tag{10}$$

Here, T is the trajectory period of stop-and-go traffic, and $K = T/\tau$. Since standard deviation measures the dispersion of speed, with larger σ_g, there are larger speed variation, and the traffic is less smoother.

Assume that a vehicle n follows a vehicle n-1, and vehicle n is IVC equipped vehicle. Speed limit of vehicle n is set as the average speed of its leader, vehicle n-1, i.e., $U_n = \bar{v}_{n-1}$. However, in reality, it is difficult for the following vehicle to estimate accurate value of the average speed of its leader. So, we put an additional term ε in the speed limit.

$$U_n = \bar{v}_{n-1} + \varepsilon$$

Considering safety issues, we let $0 \leq U_n \leq v_f$. We donate speed of vehicle n-1 by $v_{n-1}(t)$, and initially, the road is congested. In [33], Li *et al* measured oscillation of traffic patterns and concluded that most trajectories were periodic with period from 2 to 4 minutes. So, We assume that $v_{n-1}(t)$ is a sine function with period T.

$$v_{n-1}(t) = \frac{v_f(1+\sin(\frac{2\pi t}{T}))}{2} \tag{11}$$

We let $x_{n-1}(0) = 0$. Trajectory of vehicle n-1 is

$$x_{n-1}(t) = \int_{\xi=0}^{t}\frac{v_f(1+\sin(\frac{2\pi\xi}{T}))}{2}d\xi = \frac{v_f}{2}(t+\frac{T}{2\pi}-\frac{T}{2\pi}\cos(\frac{2\pi}{T})). \tag{12}$$

Average speed of vehicle n-1 is $\bar{v}_{n-1} = v_f/2$. Initially, vehicle n stays at $x_n(0) = -\frac{v_f\tau}{2} - s_j$. With the constant speed limit adjustment, Newell's car-following model is revised below.

$$x_n(t+\tau) = \min\{x_{n-1}(t)-s_j, x_n(t)+U_n\tau\} \tag{13}$$

This indicates that if $x_{n-1}(t)-x_n(t)-(s_j+U_n\tau) < 0$, $x_n(t+\tau) = x_{n-1}(t)-s_j$; otherwise, $x_n(t+$

$\tau) = x_n(t) + U_n\tau$. Using this statement, we estimate position of vehicle n with constant green driving strategy. Then, without losing generality, we analyze effect of the strategy on smoothing trajectory in one period.

1. $\varepsilon \leq 0$, i.e., $U_n \leq \bar{v}_{n-1}$.

   In this scenario, the initial spacing of vehicle n is $x_{n-1}(0) - x_n(0) = \frac{v_f\tau}{2} + s_j \geq U_n\tau + s_j$. From **Equation** 13, we know that $x_n(\tau) = x_n(0) + U_n\tau$, i.e., $v_n(t) = U_n, \forall t \in [0,\tau)$. It indicates that vehicle n runs in free flow traffic and does not follow its leader. Assume that after $t = \tau$, there is a point at $t = t_1$ when vehicle n starts to run in congested traffic (**Equation** 14), so that vehicle n follows its leader.

$$x_{n-1}(t) - x_n(t) < s_j + U_n\tau \tag{14}$$

   During $[\tau, t_1)$, vehicle n runs with speed limit U_n. So, $x_n(t) = x_n(\tau) + U_n(t-\tau) = x_n(0) + U_n t, \forall t < t_1$. Subtitling $x_n(t)$ and **Equation** 12 into the left side of **Equation** 14 lead to

$$\frac{v_f}{2}(t + \frac{T}{2\pi} - \frac{T}{2\pi}\cos(\frac{2\pi t}{T})) - (x_n(0) + U_n t) = (s_j + U_n\tau) - \varepsilon t + \frac{v_f}{2}(\frac{T}{2\pi} - \frac{T}{2\pi}\cos(\frac{2\pi t}{T})) \geq s_j + U_n\tau$$

   It implies that there is no solution for t_1 in this scenario, and vehicle n always runs with the adjusted speed limit U_n, i.e.,

$$x_n(t) = x_n(0) + U_n t, \forall t \geq 0 \tag{15}$$

   Speed of vehicle n is obvious.

$$v_n(t) = x_n'(t) = U_n, \forall t \geq 0 \tag{16}$$

   Figure 2 shows speed solution of vehicle n under conditions: $\varepsilon < 0$ (purple dashed line with speed limit $U_{\varepsilon<0} = \bar{v}_{n-1} + \varepsilon$), $\varepsilon = 0$ (yellow dashed line with speed limit $U_{\varepsilon=0} = \bar{v}_{n-1}$). Hence, we obtain standard deviation of vehicle n's speed.

$$s.d.(v_n(t)) = 0$$

When $\varepsilon < 0$, $v_n(t) = U_n < \bar{v}_{n-1}$, which indicates that during one period, average speed of the controlled vehicle is smaller than that of the leading vehicle. While since with Newell's model, the leader's speed is translated to the follower, the average speed of an uncontrolled follower in one period is the same to that of the leader. Hence, $\varepsilon < 0$ is not acceptable in green driving strategies, since it reduces the average speed of the controlled vehicle.

2. $\varepsilon > 0$, i.e., $U_n > \bar{v}_{n-1}$.

Under this condition, initially, spacing of vehicle n is smaller than or equal to $s_j + U_n\tau$, i.e., vehicle n travels in congested traffic. $x_n(\tau) = x_{n-1}(0) - s_j = x_n(0) + \frac{v_f}{2}\tau$. After time $t = \tau$, vehicle n will follow its leader until its spacing is larger than or equal to $s_j + U_n\tau$. Assume that at $t = t_1$,

$$x_{n-1}(t_1) - x_n(t_1) = s_j + U_n\tau \tag{17}$$

From **Equation** 13, vehicle n travels in free flow traffic with the speed limit U_n after $t = t_1 + \tau$. Vehicle n will not follow its leader until its spacing is smaller than $s_j + U_n\tau$ again. So, we get

$$x_{n-1}(t_2) - x_n(t_2) = s_j + U_n\tau, \tag{18}$$

where $t_2 > t_1$. $t_1 + \tau$ is the starting time that vehicle n fails to follow its leader, and $t_2 + \tau$ is the time that vehicle n follows its leader again after $t_1 + \tau$. From **Equation** 17 and **Equation** 18, there exists

$$x_{n-1}(t_2) - x_{n-1}(t_1) = x_n(t_2) - x_n(t_1) \tag{19}$$

Equation 19 indicates that if a green driving vehicle wants to follow its leader, the distance it travels with the designed speed limit should be equal to that the leader travels in the same period. **Equation** 19 is equivalent to

$$\int_{t_1}^{t_2} \frac{v_f(1+\sin(\frac{2\pi t}{T}))}{2} dt = U_n(t_2 - t_1). \tag{20}$$

After $t = t_2 + \tau$, vehicle n will follow its leader again. The situation is similar to that of $t < t_1$. Solving **Equation** 17 and **Equation** 20, we can get $t_1 = \frac{T}{2\pi}\arcsin(\frac{2\varepsilon}{vf})$, but there is no close form for t_2. If ε tends to 0, cosine and sine function can be linearlized: $\lim_{\delta\to 0}\sin(\delta) = \delta, \lim_{\delta\to 0}\cos(\delta) = 1 - 2\delta^2$. Subtitling these linearlizations into **Equation** 18 and **Equation** 20, we solve t_1 and t_2.

$$t_1 = \frac{\varepsilon T}{\pi v_f} = aT \tag{21}$$

$$t_2 = T + \frac{\varepsilon T}{2\pi v_f} - \sqrt{\frac{\varepsilon T^2}{\pi v_f} + \frac{\varepsilon^2 T^2}{4\pi^2 v_f^2}} = bT \tag{22}$$

where, $a = \frac{\varepsilon}{\pi v_f}, b = 1 + \frac{\varepsilon}{2\pi v_f} - \sqrt{\frac{\varepsilon}{\pi v_f} + \frac{\varepsilon^2}{4\pi^2 v_f^2}}$. From the preceding analysis, we conclude that

$$x_n(t+\tau) = \begin{cases} x_{n-1}(t_1) - s_j + U_n(t - t_1) & t_1 \le t < t_2 \\ x_{n-1}(t) - s_j & t_2 \le t < T + t_1 \end{cases}. \tag{23}$$

Controlled velocity of vehicle n is

$$v_n(t+\tau) = x_n'(t+\tau) = \begin{cases} U_n & t_1 \le t < t_2 \\ \frac{v_f(1+\sin(\frac{2\pi t}{T}))}{2} & t_2 \le t < T + t_1 \end{cases}. \tag{24}$$

Figure 2 shows the solution of the velocity in this scenario (green dashed line with speed limit $U_{\varepsilon>0} = \bar{v}_{n-1} + \varepsilon$). And standard deviation of the velocity is obtained below.

$$\begin{aligned} s.d.(v_n) &= \sqrt{\frac{1}{T}\int_{t_1}^{t_1+T}(v_n(t+\tau) - \bar{v}_n)^2 dt} \\ &= \sqrt{\frac{\varepsilon^2(t_2-t_1) + \frac{v_f^2}{4}\{t_1 + T - t_2 + \frac{T}{4\pi}[\sin(\frac{4\pi t_2}{T}) - \sin(\frac{4\pi t_1}{T})]\}}{T}} \end{aligned} \tag{25}$$

We derive that $s.d.(v_n) = \sqrt{\varepsilon^2(b-a) + \frac{v_f^2}{4}\{a+1-b+\frac{1}{4\pi}[\sin(4\pi b) - \sin(4\pi a)]\}}$ when ε is very small. This indicates that the standard deviation of speed is not related to the period T. **Figure** 3 shows the relationship between standard deviation of the velocity and ε with $T =$ 200 seconds and $v_f = 65$ mph. It indicates that when ε becomes larger, standard deviation of velocity tends to be larger. In order to smooth traffic without reducing average speed, the speed limit should be larger than but close to the average speed of uncontrolled traffic.

From previous analysis of constant green driving strategy, we obtain several tips of setting speed limit for green driving vehicles.

1. Speed limit should not be smaller than the average speed of the traffic; otherwise, it will increase travel time;

2. Speed limit could be set close to but larger than the average speed of the traffic, which can smooth traffic waves with small standard deviation of speed.

In reality, the average speed of the traffic cannot be predicted precisely due to the complicate traffic conditions and noises. Hence, constant green driving strategies are not sufficient to smooth traffic well. We will investigate a dynamic green driving strategy in section 4.

4 Development and Evaluation of a Dynamic Green Driving Strategy

In section 3, we have theoretically analyzed the underlying mechanism that the constant green driving strategy adjusted vehicle speed to smooth traffic. However, in reality, period of traffic oscillation and average speed cannot be measured accurately [33]. Moreover, the average speed of the traffic is not constant in real transportation system. For example, when a shock wave occurs, the average speed of the traffic will decrease significantly. Hence, in real world, the constant green driving strategy is not sufficient to obtain a better control of traffic. Targeting on processing green

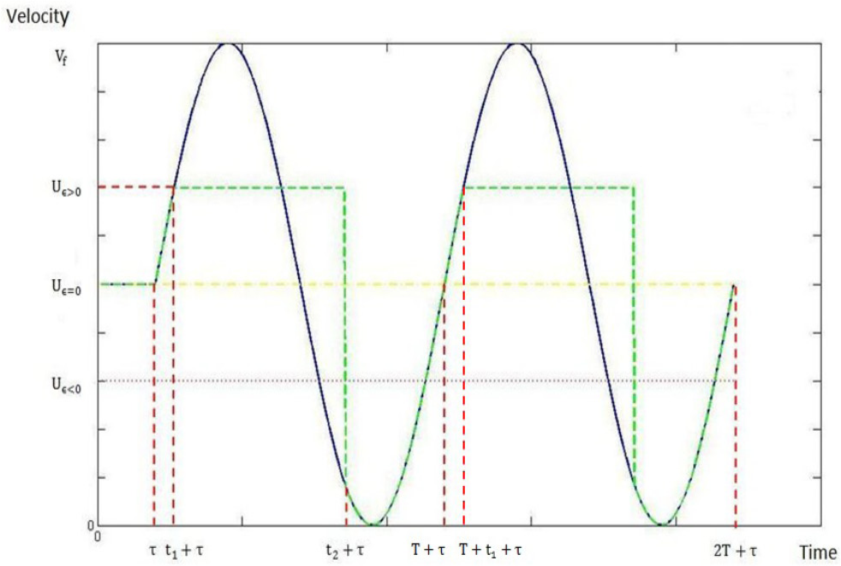


Figure 2: Controlled speed with different speed limits: $\varepsilon < 0$ (dotted), $\varepsilon = 0$ (dashdot), $\varepsilon > 0$ (dashed)

driving problem in reality, we propose one dynamic green driving strategy based on feedback control. In this section, we will firstly describe the dynamic green driving strategy. Then, effect of this strategy, including traffic smoothness and emission savings, is evaluated under various market penetration rates and communication delays by simulations.

4.1 Model Description

In this part, we present a dynamic green driving strategy based on feedback control system. Design of dynamic speed limit should satisfy the goals and requirements of green driving.

1. Vehicle doing green driving should travel smoother without too much excessive speed and quick accelerations;
2. Average speed of controlled vehicles should not decrease;
3. The strategy should work even only one vehicle is doing green driving;

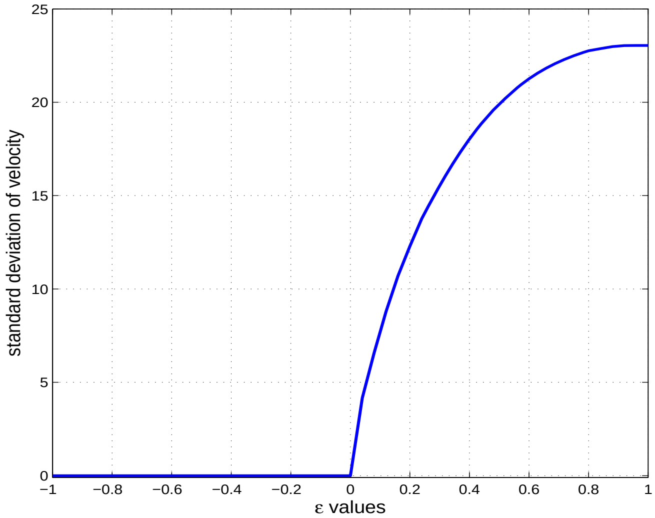


Figure 3: Standard deviation of controlled speed with different ε values (T=200 seconds, v_f=65 mph)

4. More vehicles doing green driving would smooth traffic better.

In that sense, we use mean and standard deviation of speed as the control objective. A PI control is applied in the feedback control system to realize green driving. The PI control components integrated with a processor is designed for a dynamic green driving strategy to set speed limits. The control system is illustrated in **Figure** 4.

Here, we introduce a dynamic control variable $U_g(t)$ as the speed limit for green driving vehicle $g(g \in \mathscr{G})$ at time t. This speed limit is only applied when it is safe, since we cannot control vehicle's speed directly without considering safety. In a traffic stream, we can apply the same dynamic speed limit for all controlled vehicles, i.e., $U_g(i) = U(i)$, where $U_g(i)$ is discretization of $U_g(t)$. In this case, communications among vehicles are necessary to share related information, including vehicle location $x(t)$, speed $v(t)$ and spacing $s(t)$. Once the strategy is applied, variance of the speed should tend to zero, and controlled vehicle g should follow its leading vehicle when its spacing is the smallest during a time period T_1. That is, for any i, there exists $k \in \{i - T_1 + 1, \cdots, i\}$,

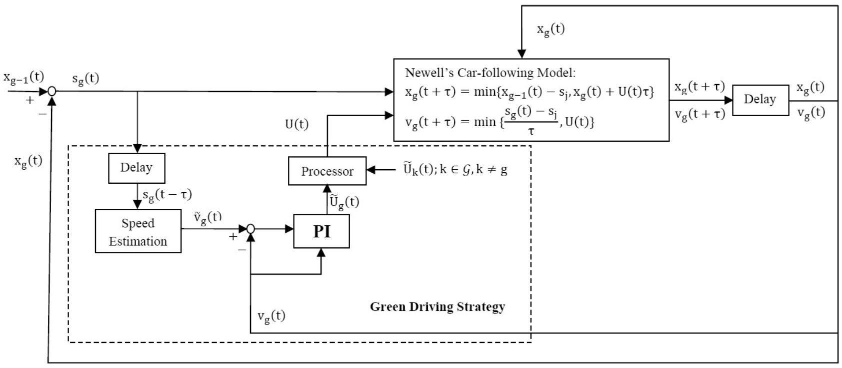


Figure 4: Block diagram of a dynamic green driving Strategy

such that

$$v_g(k) = \frac{x_{g-1}(k-1) - x_g(k-1) - s_j}{\tau}.$$

Here, T_1 should be larger than half of the period of the leading trajectory. From **Equation** 2, $v_g(k) \leq \frac{x_{g-1}(k-1)-x_g(k-1)-s_j}{\tau} = \tilde{v}_g(k), \forall k$, where $\tilde{v}_g(k)$ is predictive speed of vehicle g at time k, which is calculated by speed estimator. Based on these, we use a PI control to design a intermediate speed limti of vehicle g at time i, i.e., $\tilde{U}_g(i)$. Speed of vehicle g and the error between actual speed v_g and estimated speed $\tilde{v}_g$ are used in PI control.

$$\tilde{U}_g(i) = \frac{\sum_{k=i-T_1+1}^{i} v_g(k)}{T_1} + K_p \cdot \min_{k=i-T_1+1}^{i} \{ \frac{x_{g-1}(k-1) - x_g(k-1) - s_j}{\tau} - v_g(k) \} \tag{26}$$

As we know that when speed limit is closer to average speed of the traffic, controlled vehicle can travel much smoother. So, the first term $\frac{\sum_{k=i-T_1+1}^{i} v_g(k)}{T_1}$ is added in the speed control strategy. This term is designed to smooth traffic. The second term $\min_{k=i-T_1+1}^{i}\{\frac{x_{g-1}(k-1)-x_g(k-1)-s_j}{\tau} - v_g(k)\}$ is introduced to guarantee that the controlled vehicles can follow its leader.

IVC systems provide both historical and other vehicles' information, which could be implemented to make the strategy more robust and efficient. Therefore, a processor is introduced to apply these information to design speed limit $U(i)$. Intuitively, the most recent information are more useful in determining the speed limits. We set different weights for historical information and get

$$U_g(i) = w_1 \cdot \frac{\sum_{k=T_1-1}^{i-T_1} \tilde{U}_g(k)}{i-2(T_1-1)} + w_2 \cdot \frac{\sum_{k=i-T_1+1}^{i} \tilde{U}_g(k)}{T_1}. \tag{27}$$

Here, $w_1 + w_2 = 1$. w_2 is the weight of the most recent traffic information, so we set w_2 be larger than w_1. Then thinking about information from the other IVC equipped vehicles, we set speed limit for all equipped vehicles as

$$U(i) = \frac{\sum_{g \in \mathcal{G}} U_g(i)}{G}. \tag{28}$$

Considering communication delay in IVC system, the strategy should be modified. Since with communication delay, different equipped vehicles can receive different traffic information, the speed limits of different vehicles will be different. Assume that the communication delays are the same and constant for all equipped vehicles. We donate the communicate delay by D. Hence, speed limit of one equipped vehicle g at time i is

$$U_g^D(i) = \frac{U_g(i) + \sum_{k \neq g, k \in \mathcal{G}} U_k(i-D)}{G}. \tag{29}$$

Here, we start to apply the green driving strategy at $2(T_1-1)+D$, so that there is sufficient information to obtain speed limits. $U_g^D(i)$ is donated as the speed limit of vehicle g with delay.

4.2 Effect of Dynamic Green Driving Strategy

In this part, one freeway traffic scenario is analyzed with MATLAB simulation. As a starting point, a straight open roadway section is considered. On this road section, several vehicles runs in the same lane without lane-changing. The trajectory of the leading vehicle is provided, and several following vehicles are controlled with dynamic green driving strategy. Smoothness of traffic is compared between controlled traffic and unadjusted traffic to estimate effect of the green driving strategy. Moreover, CMEM emission model is implemented to measure the total emission and fuel consumption savings.

Table 1 Setting of Simulation and Green Driving Strategy

Parameters	**Values**
Free flow speed v_f	65 mph
Jam spacing s_j	23.83 ft
Time gap τ	1 sec
Trajectory Period I T_{p1}	50 sec
Trajectory Period II T_{p2}	150 sec
Trajectory Period III T_{p3}	300 sec
Duration T_1	2.5 min
K_p	0.01
w_1	0.25

Assume there are only two vehicles $\{1,2\}$ running with Newell's car-following model on the road. The speed of the leading vehicle 1 is known.

$$v_1(t) = v_f(\frac{1+\sin(\frac{2\pi t}{T_{p1}})}{6} + \frac{1+\sin(\frac{2\pi t}{T_{p2}})}{6} + \frac{1+\sin(\frac{2\pi t}{T_{p3}})}{6}), t \geq 0 \tag{30}$$

where, T_{p1}, T_{p2}, T_{p3} are the trajectory periods varying from 50 to 150 seconds. **Table 1** gives the settings of this simulation. The result is shown in **Figure** 5. The solid line shows speed of vehicle 2 without applying green driving strategy; while the dashed line indicates the speed of vehicle 2 applying green driving strategy. In both scenarios, trajectory of the leading vehicle 1 is the same. The two velocities have the approximately the same average values, but vehicle applying the dynamic green driving strategy has a much smoother speed trajectory. This will also result in lower emissions and fuel consumption. **Table 2** lists the statistical comparison of the two simulated speeds of vehicle 2 when the green driving strategy is used. We further use CMEM to estimate emissions and fuel consumption of these two trajectories. **Table 3** lists the total emissions, fuel consumption and relative savings. It implies that there exist significant savings of emissions and fuel consumption, and at the same time, the average speed does not change too much.

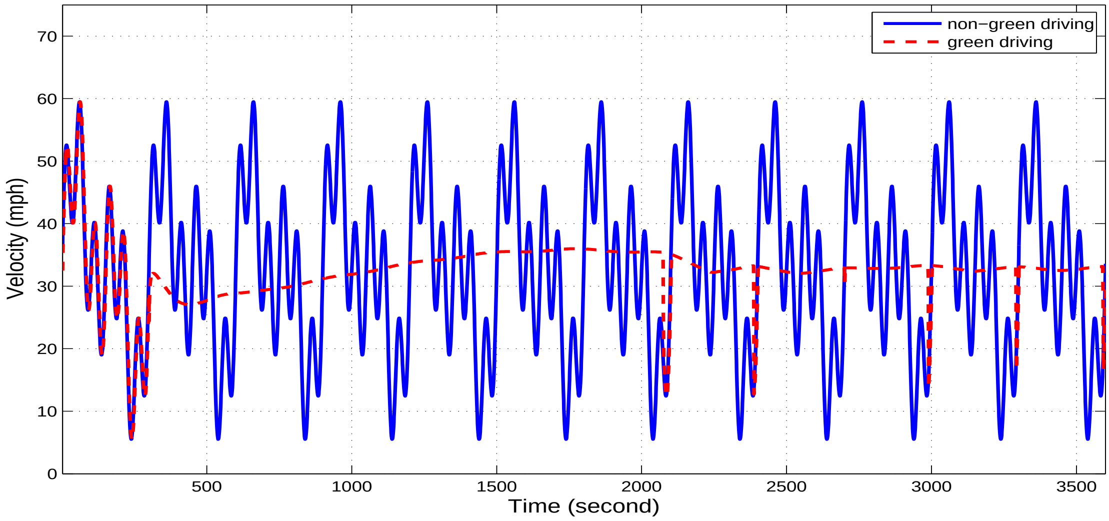


Figure 5: Speed comparison of green driving and non-green driving traffic

Table 2 Statistics of Velocity

Velocity	Non-green driving	Green driving	Difference (%)
Min (mph)	5.49	12.41	125.87
Max (mph)	59.51	36.00	-39.51
Mean (mph)	32.50	32.50	0
std. dev. (mph)	13.27	2.95	-77.80

4.3 Effect of Market Penetration rates of IVC Equipped Vehicles and Communication Delay on Traffic and Emissions

In order to investigate the effect of the characters of IVC systems on smoothing traffic and reducing emissions and fuel consumption, we simulate traffic in an one way ring road with length $L = 1.3$ miles, where $N = 100$ vehicles are traveling in the same direction. The initial locations of all vehicles are set in **Equation** 31.

$$x_n(0) = \sum_{k=1}^{n} (L/N - s_j)(\sin(\frac{2\pi k}{N}) + 1) + s_j, \forall n = 1, 2, \cdots, N \tag{31}$$

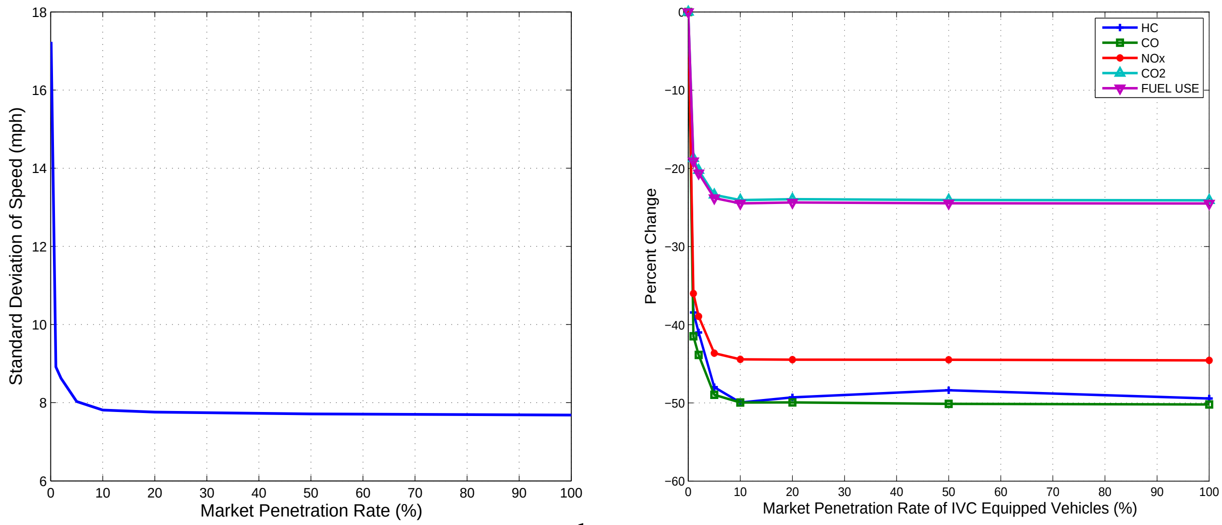
Table 3 Emissions and Fuel Consumption of Two Sample Speed Trajectories

	Non-green driving	Green driving	Difference (%)
CO2 (g/mi)	276.897	210.693	-23.91
CO (g/mi)	3.053	1.373	-55.03
HC (g/mi)	0.141	0.060	-57.45
NOx (g/mi)	0.420	0.086	-79.52
Fuel Use (g/mi)	88.948	67.160	-24.50

In the simulation, the duration time T_1 is set as 1 minutes,and the total simulation time is 10 minutes. All the other parameters are the same to section 4.2.

Considering Newell's car-following model in a ring road, we see that even only one vehicle is applying the green driving strategy, traffic can still be smoothed, since the green driving vehicle will affect the driving behaviors of its followers and make their trajectories smoother. Moreover, with higher MPR of IVC equipped vehicles, more vehicles will exchange information, which is helpful on smoothing traffic and reducing emissions. Therefore, it is expected that higher MPR's of IVC equipped vehicles lead to higher savings of emission and fuel consumption, and this saving is significant even fewer vehicles are equipped. To determine the effectiveness of MPR of IVC equipped vehicles on emissions and fuel consumption, one simulation was constructed to implement the dynamic green driving strategy under different MPR's. **Figure** 6 shows the results. The results indicates that the savings increase gradually and the standard deviation of speed decrease with MPR's. For HC, its reduction increases from 38.4% at 1% MPR to 49.4% at 100% MPR; for CO, it increases from 41.5% to 50.2%; for NOx, it is from 36.0% to 44.6%; for CO2, it is from 18.7% to 24.1%; and for fuel consumption, it is from 19.1% to 24.5%. Moreover, the reduction of speed limit is smaller than 1.5% for any market penetration rates. Another observation is that when MPR is smaller than 10%, the influence of MPR on saving emission and smoothing traffic is also very significant, i.e., the dynamic green driving strategy works for smaller IVC equipped vehicles.

Another issue is studying the effect of communication delay on the dynamic green driving strategy. When communication delay is larger, the traffic information exchanged between IVC



a. b.

Figure 6: Effect of the dynamic green driving strategy under different market penetration rates of IVC equipped vehicles: a. standard deviation of speed; b. emission and fuel consumption reductions.

equipped vehicles are less useful to determine the speed limits. It implies that communication delay will decrease the effect of the green driving strategy. Since the strategy can work for small market penetration rate, we arbitrarily set MPR be 10% to investigate the effect of communication delay. In the simulation, communication delay varies from 0 to 60 seconds. **Figure** 7 verifies our prediction that with higher communication delay, savings of emissions and fuel consumption are smaller and traffic is less smooth, i.e., standard deviation of speed tends to be larger. However, this reduction is not significant when communication delay is smaller than 10 seconds.

5 Conclusion and Future Work

In this paper, we developed a set of green driving strategies through a feedback control system. The green driving strategies were implemented via eliminating the stop-and-go waves to reduce the number and severity of individual accelerations and decelerations, and result in lower emissions and fuel consumption. We first investigated the failure of two green driving strategy using

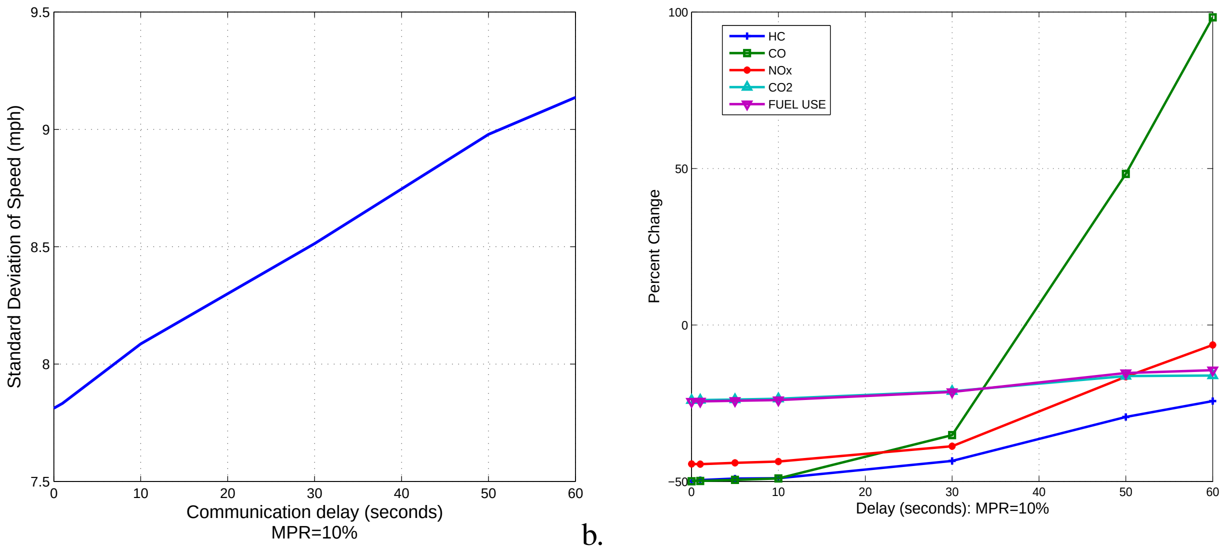


Figure 7: Effect of the dynamic green driving strategy under different communication delays of IVC equipped vehicles: a. standard deviation of speed; b. emission and fuel consumption reductions.

the average speed and the predictive average speed as speed limits theoretically. The limitation existed in these two strategies was that they might reduce the average speed of the traffic. We then theoretically analyzed effect of one constant green driving strategy on smoothing traffic and investigated the effect of a dynamic strategy.

One important contribution of this paper was that a significant insight was obtained through theoretical discussions on a constant green driving strategies: a better and executable green driving strategy was setting speed limit close to the average speed of the traffic, but it should not be smaller than the average value. The larger the speed limit, the less smoother the traffic. The principle of a successful green driving strategy was that the distance that a controlled vehicle traveled with designed speed limit to follow its leader should be equal to that the leader traveled during the same period without control.

Another contribution of this paper was that a robust dynamic green driving strategy was proposed with consideration of smoothing traffic flow and guaranteeing that a following vehicle followed its leader during a certain long period, i.e., reducing speed variation without decreasing the average speed of the traffic. The strategy was built from a feedback control system with PI control, and provided dynamic speed limits to IVC equipped vehicles. With experiment, this strategy could reduce standard deviation of speed as much as 77.8% with smaller reduction of the average speed. Emissions and fuel consumption were reduced significantly without decreasing the average speed of the traffic even only one vehicle was controlled. Moreover, market penetration rates of IVC equipped vehicles and communication delay were investigated to show their influences on the dynamic green driving strategy. Results indicated that higher MPR could lead to higher emissions and fuel consumption savings, and this savings were significant even MPR was smaller than 10%. Communication delay could reduce the effect of the green driving strategy. With larger communication delay, emissions and fuel consumption savings were smaller and the traffic was less smooth.

In the future, the dynamic green driving strategy will be further developed and applied in non-homogeneous traffic and evaluated using simulation modeling tools. Properties of communication, such as dynamic communication delays, communication connectivity [18, 23], will be in consideration. Further, real world experiments would be helpful for future studies on the effect of dynamic green driving strategy for various traffic scenarios.

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