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SIMULATION EVALUATION OF GREEN DRIVING STRATEGIES BASED ON INTER-VEHICLE COMMUNICATIONS

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ABSTRACT

Transportation system produces a large percentage of local pollutants including hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO2), and oxides of nitrogen (NOx), etc. Apart from switching to alternative fuels, one measure would be to apply information and communication technologies to help us drive more smoothly so as to decrease pollutants emissions. This paper studies potential benefits of two green driving strategies based on inter-vehicle communication (IVC). Here green driving strategies are similar to intelligent speed adaptation , but we assume that an IVC-equipped vehicle is able to receive detailed trajectory information from other such vehicles with the help of IVC. For the purpose of evaluation, we integrate Newell's car-following model and VT-Micro to establish a simulation platform. Market penetration rates of IVC-equipped vehicles and delivery delays of messages are two prominent features of IVC systems. We simulate stop-and-go traffic to calculate potential reductions in air pollutant emissions and fuel consumption under different market penetration rates and delivery delays. Results show that significant savings under frequent stop-and-go traffic conditions may be obtained with our strategies (HC: -88.3%, CO: -95.8%, NOx: -91.5%, CO2: -36.3%, Fuel Consumption: -71.3%) for the same travel time and almost the same overall travel distance. It is also shown that relatively large savings can be achieved even for a market penetration rate as low as 1% and communication delays larger than 2 minutes. In the future we will investigate environmental benefits of green driving strategies for more traffic scenarios and realistic communication scenarios.

Keywords: Green Driving, Emissions, Fuel Consumption, VT-micro Emission Model, Newell Car-following Model, Intelligent Adaptation System, Inter-vehicle Communication

1 INTRODUCTION

According to the Energy Information Administration, the transportation sector in the U.S. is responsible for one third of CO2 emissions, over one half of NO2 emissions, and over three quarters of CO emissions. Globally, the situation is worsening with the rapid development of motor vehicle transportation in developing countries. It is well known that excessive speed (defined as exceeding the posted speed limit or driving too fast for ambient conditions [1]) and stop-and-go traffic on road can significantly increase fuel consumption and vehicle emissions [2]. Many strategies have been proposed to address this problem. In [3], effects of speed bumps on road were investigated to control speed. In [4], effects of police enforcement were studied to monitor speed in road. However, both of these two traditional methods have proven to have only moderate effects on controlling excessive speed [2].

In the past few years, many telecommunications and information technologies have been adopted by drivers to improve their daily driving experience. For example, the sales of global positioning systems (GPS) units are up 488% during the holiday season of 2008 [5], and adaptive cruise control systems have helped drivers reduce their workload and its associated stress [6]. In the near future, with the development of IntelliDrive technologies, especially inter-vehicle communications (IVC), including vehicle-to-vehicle and vehicle-to-infrastructure communications, will be available to relay time-critical and location-based traffic information between vehicles so that people can drive more smoothly and more safely. As the number of cars equipped with these technologies increases, we expect that drivers will adapt their behaviors accordingly [7]. Such collective behavior changes will result in different traffic flow characteristics, transportation systems performance, and environmental impacts. Therefore instead of using alternative fuels[8] and traditional methods, new technologies, such as IVC and cooperative autonomous cruise control (CACC) can also be used to improve traffic flow, fuel consumption economy, and reduce emissions.

Inter-vehicle Communications (IVC) can help establish self-organized, decentralized, real-time traffic information systems. Many studies are underway to investigate IVC based on mobile ad hoc networking technology as a mean of developing the ”internet on the road” [9, 10]. In [11, 12, 13], researchers describe potential applications and properties of Autonet, including connectivity, adthe impacts of market penetration rate (MPR), and delivery delay, and the effect of IVC on vehicle travel time. However, there have been no systematic studies of potential environmental benefits of IVC.

In the literature there have been studies on intelligent speed adaptation (ISA) strategies to smooth traffic. ISA systems use aggregate-level road congestion information to adjust speed limits of vehicles on specific road sections [2]. Moreover, ISA systems monitor vehicle speeds and current traffic conditions, and, based on these, they provide corrective actions or optimal process for drivers. The information collected for ISA is usually obtained from loop-detectors or on-board sensors. In ISA systems, there are three basic methods to adjust speed limits [14, 2]: fixed, variable and dynamic. Such speed limits could be implemented in advisory, voluntary, or mandatory fashions [14, 2].

Recently, a lot of energy has been devoted to testing the impacts of ISA systems, including on road injuries, the release of air pollutants and fuel consumption. These studies have shown that ISA can effectively improve safety and reduce traffic congestion. In [2], a set of speed limits and corrective actions are communicated to drivers. In addition, ISA has potential to mitigate congestion by smoothing the dynamics of congested traffic. ISA equipped vehicle has a much smoother trajectory (with smaller speed variation), which leads to fuel savings and emission reductions. Results show that ISA can reduce fuel consumption up to 70 percent, and cut emissions of CO, HC and NOx by 93 percent, 90 percent and 86 percent respectively. Even for realistic traffic adjustment, fuel consumption can decrease by 13 percent. But it was shown that ISA systems could increase travel time by a small percentage (6 percent). In addition, many field implementations of ISA systems have been done to test the influence of ISA on traffic safety and the environment. ISA experiments in Tilburg (Netherlands) show that with speed limits control, driving is much safer

[15, 16, 17]. Road injuries are reduced by 15 to 20 percent, and carbon dioxide emissions are reduced by approximately 11 percent. Moreover, in [18], with optimal speed limits adjustment, freeway traffic conditions are more stable, which also benefits to driving safety and reduces air pollutants emissions. Another concern with ISA systems is that they may worsen road congestion. However, in [19, 20], Liu and Tate show that under very congested levels, ISA does not change traffic conditions.

In this paper, we will study green driving strategies based on IVC and, in particular, their effects in emission reductions and fuel consumption savings in different traffic conditions. We assume that IVC-equipped vehicles share their trajectories with each other. With detailed information of vehicles' trajectories, we propose two green driving strategies to maximize energy efficiency of vehicles in road. These green driving strategies are similar to ISA schemes, but, with the help of IVC, vehicles can get information from other vehicles directly. One advantage of such IVC-based green driving strategies is that vehicles can get more relevant information. But such strategies could be restricted by limited market penetration rates of IVC devices and communication delays. To evaluate the potential benefits of such green driving strategies, Newell's car-following model [21] and the VT-Micro emission model [22] are integrated into a simulation platform.. Newell's model is a trajectory translation model, which is based on vehicle locations. The model is simple and straightforward to describe vehicle movement in traffic streams. Moreover, studies in [23] show that Newell's model matches realistic vehicle trajectories very well. So, with proper parameter values, using Newell model can lead to well description of traffic streams. Moreover, we can change the desired speed of individual drivers based on green driving strategies. With the integrated simulation model we then study environmental benefits of green driving strategies for different market penetration rates and communication delays.

This paper is organized as follows. In Section 2, We first describe green driving strategies to smooth traffic streams. In Section 3, we combine a microscopic traffic model with an emission model to study green driving strategies. In Section 4, we summarize results from our simulations that study strategies described in Section 2. Section 5 presents concluding remarks.

2 GREEN DRIVING STRATEGIES BASED ON INTER-VEHICLE COMMUNICATIONS

In this section, we first present two IVC-based green-driving strategies and then introduce communication delays to the strategies.

2.1 Two Green Driving Strategies

With IVC-based green driving strategies, speed limits of allIVC-equipped vehicles are set based the information they gather from other IVC-equipped vehicles. In this study we propose to set an IVC-equipped vehicle's desired speed to the average speed calculated from other IVC-equipped vehicles.

Suppose that N vehicles run in a selected region of one traffic network and market penetration rate of IVC equipped vehicles is p, the number of IVC-equipped vehicles is n (where expected value of n is Np). For all vehicles with new technologies, we have two methods to set the speed limits under global and sectional traffic information. Then, based on messages broadcasted among vehicles, speed limits are modeled in the following ways. Suppose that spacing of all IVC-equipped vehicles are $s_1^{IVC}(t), s_2^{IVC}(t), , s_n^{IVC}(t)$, and their speeds at time t are $v_1^{IVC}(t), v_2^{IVC}(t), , v_n^{IVC}(t)$, then dynamic speed limits at time t can be modeled in the following two models. The first model is based on average value of speeds collected by IVC-equipped vehicles.

$$v_{lk}(t) = \frac{\sum_{i=1}^{n} v_i^{IVC}(t)}{n} \tag{1}$$

where $v_{lk}(t)$ is the speed limit set for equipped vehicle k at time t. The second model is based on desired average speed of all IVC-equipped vehicles. The speed limit of equipped vehicle i is set as following equation.

$$v_{lk}(t) = \frac{\sum_{i=1}^{n}(s_i^{IVC}(t) - d_j)}{\sum_{i=1}^{n}\tau_i} \tag{2}$$

Both of the two strategies have their own advantages. For average speed adjustment, only speed information is necessary to be delivered, and speed can be obtained directly from vehicle engines or GPS devices. While for desired speed adjustment, we need more information, including time gap and jam spacing, which are only available when distance sensors are installed. However, the first model only considers global information, and the second strategy also incorporates local information. Therefore theoretically the second strategy should be more robust.

Additionally, with different considerations of network scales, speed limit adjustments are different because of various numbers of equipped vehicles. In this paper, we set two different levels of network scales: *whole network (global), downstream section (sectional).* When we study the whole network, all equipped vehicles in transportation system communicate with each other. They share traffic information to improve the entire network conditions. The more advanced strategy is identifying dynamic speed limits for individual vehicles. The settings are based on downstream flow for a given vehicle. All IVC-equipped vehicles in selected region deliver information to the chosen vehicle and speed limits for this individual vehicle are calculated based on this information. Those two adjustments work under the two different network scales (global and sectional) and satisfy different planning targets.

2.2 Communication Delays

Using information provided by IVC, many interesting and useful applications have recently been studied, such as information warning system, traffic control, or cooperative assistance systems [24]. The most general platforms to apply IVC systems are cellular networks and mobile wireless networks. Different applications of ICC depend differently on properties of the vehicular network. For example, communication delays affect the quality of message delivery. For cellular networks, the accuracy of traffic system delay, caused by communication is treated as constant value [25]. By contrast, for mobile ad hoc wireless network, communication delays dependent on routing protocols and vehicle distributions [26]. . In [12], it was shown that delivery delay is highly related to routing protocols, flow-rates, and market penetration rates. The conclusion of delay for IVC system is that $delay = 1/(flowrate * IVC(\%))$. For environmental applications, delay is an important consideration because the amount of pollutants released is sensitive to vehicles speed and acceleration, which may change a lot during a non-trivial delay. Green driving strategies in this paper process delay as a key parameter.

In this study, we consider two types of delays: constant delays, and delays linearly proportional to distances between vehicles. The first type of delays could occur when IVC are enabled with cellular networks, where communication delays are not sensitive to distance in a relatively small region for applying green driving strategies. The second type of delays could occur when IVC are enabled with instantaneous or delay-tolerant multi-hop ad hoc communications.

If we denote $D_{i\to k}(t)$ as the delay of the information from vehicle i to vehicle k at t, then the two green driving strategies can be written as

$$
\begin{aligned}
v_{lk}^{(1)}(t) &= \frac{\sum_{i=1}^{n} v_i^{IVC}(t - D_{i\to k}(t))}{n}, \qquad (3)\\
v_{lk}^{(2)}(t) &= \frac{\sum_{i=1}^{n} (s_i^{IVC}(t - D_{i\to k}(t)) - d_i)}{\sum_{i=1}^{n} \tau_i}. \qquad (4)
\end{aligned}
$$

For constant delays, $D_i = D, i = 1, 2, \cdots, n$. For delays linearly proportional to the distance,

$$
D_{i\to k}(t) = \delta \cdot |x_i^{IVC}(t) - x_k^{IVC}(t)| \;\; \forall i = 1, 2, \cdots, n \qquad (5)
$$

where δ is the coefficient of delay with distance between two equipped vehicles.

3 AN INTEGRATED SIMULATION MODEL

3.1 Traffic Flow Model

Newell's car-following model [21] is the simplest car-following model as it focuses on predicting vehicle trajectories. It assumes that a following vehicle tries to minimize its distance from its leading vehicle in congested traffic. And in free traffic, vehicle always keeps the free flow speed. **Equation** 6 describes this driving rule in congested and free traffic. We set the speed limit as v_{li} for vehicle i, then from [27], we get Newell-Daganzo Car-following Model.

$$x_i(t+\tau_i) = \ min\ \{x_{i-1}(t)-d_i,\ x_i(t)+v_{li}\cdot\tau_i\} \tag{6}$$

where, vehicle $i-1$ is the leader of vehicle i.

3.2 Emission Model

In 2004, Rakha *et al* [22] presented the Virginia Tech Microscopic energy and emission model (VT-Micro), which was developed to predict the emissions of different air pollutants for different vehicle classes using statistical models that relay on speed and acceleration. Their typical model, which was estimated via linear regression, linked the logarithm of a emission rate (or a fuel consumption rate) with a simple polynomial that contains vehicle speed and acceleration.

$$\log MOE_e = \sum_{i=0}^{3}\sum_{j=0}^{3}(K_{ij}^{e}u^{i}a^{j}) \tag{7}$$

where MOE is an instantaneous fuel consumption or emission rate (mg/s), K_{ij}^{e}'s are regression coefficients, u is a vehicle's instantaneous speed (km/h), and a is its instantaneous acceleration rate (km/h/s).

3.3 Integrated Model

In this subsection, one integrated model with traffic flow and emissions models is described. Since both Newell model and VT-Micro emission model are microscopic models, the connection between these two models are straightforward. **Figure** 1 describes the flow chart of applying Newell model and VT-Micro emission model to estimate emissions and fuel consumption under different green driving strategies.

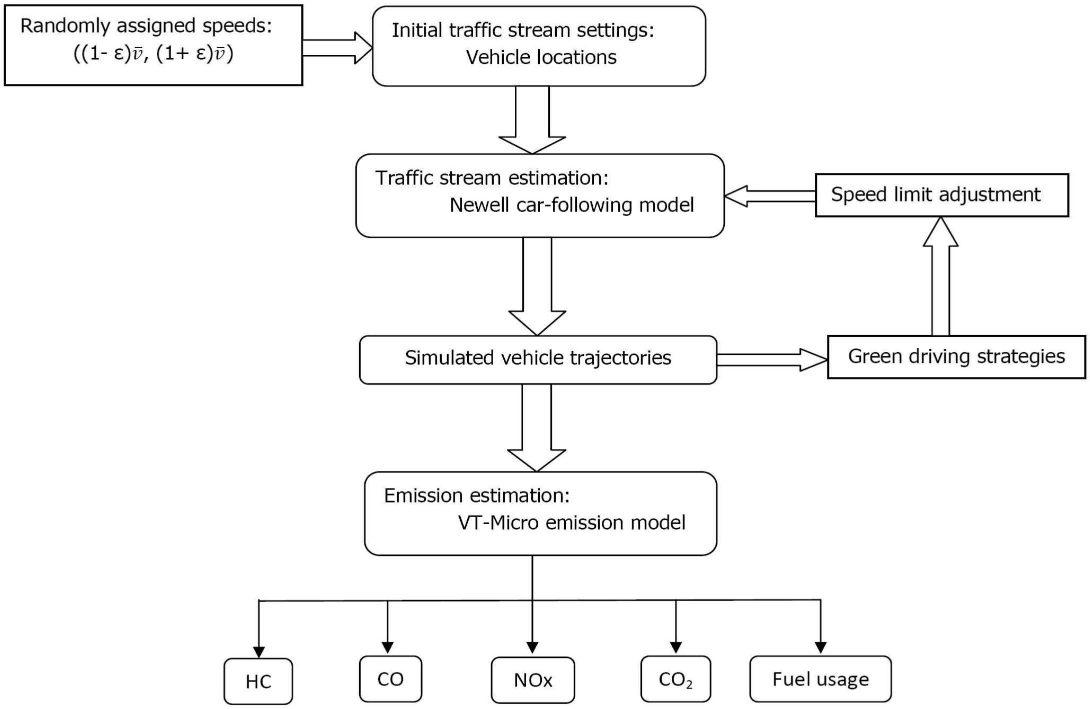

Figure 1: Flow Chart of Integrating Newell Model and VT-Micro Emission Model

The integrated model has four basic components: Initial traffic stream setting, traffic stream simulation, speed limit adjustment with green driving strategies and emission estimation. In initial traffic stream setting, distribution of initial vehicle speeds is arbitrarily provided, which is applied to set the initial vehicle locations in road. Secondly, for traffic stream simulation, all vehicle trajectories are simulated with proper parameter settings (e.g. time gap, jam spacing, speed limit, etc). In the third components, historical trajectories are packed to be communicated between informed vehicles, which are used to adjust speed limits based on the strategies described in section 2. Finally, with well adjusted vehicle trajectories, VT-Micro emission model helps to estimate emissions and fuel consumption. With different green driving strategies, we compare emissions and fuel usage to study effects of these new technologies.

4 SIMULATION

Table 1 Simulation Settings

Parameters	Value
Road Length	20 miles
Section Length	2.5 mile
Vehicle Number	1600
Simulation Period	30 minutes
Market Penetration Rate	{0.01,0.02, …,1}
Free Flow Speed	65 mph
Jam Spacing	29.33 ft
Time Gap	1.55 seconds

In this study, we simulate traffic on a one-lane ring road with settings in **Table 1**. In our simulation, we set boundary of initial speed for all vehicles. All initial speed are randomly distributed in the region of $[1-\varepsilon, 1+\varepsilon] * \bar{v}_{desired}$ (where $\bar{v}_{desired}$ is the average speed calculated from overall vehicle density in road). This initial setting is applied to make the traffic scenarios more reasonable and reduce extreme accelerations. In the simulation runs, $\varepsilon = 0.5$. In addition, we assume that all IVC-equipped vehicles rigorously comply with suggested speed limits through green driving strategies.

4.1 Effect of Different Strategies and Network Scales

In section 2, we proposed two different strategies to maintain speed limits. These two strategies make the speed variation smaller than that in non-Green Driving system. **Figure** 2 shows the speed trajectory of one vehicle during half hour. In this figure, velocity trajectory of Green Driving system applying desired speed (red) is much smoother than that of normal non-Green Driving system. Moreover, the actual average speeds of both scenarios are approximately same (Green Driving: $31.0 km/hr$, non-Green Driving: $31.1 km/hr$).

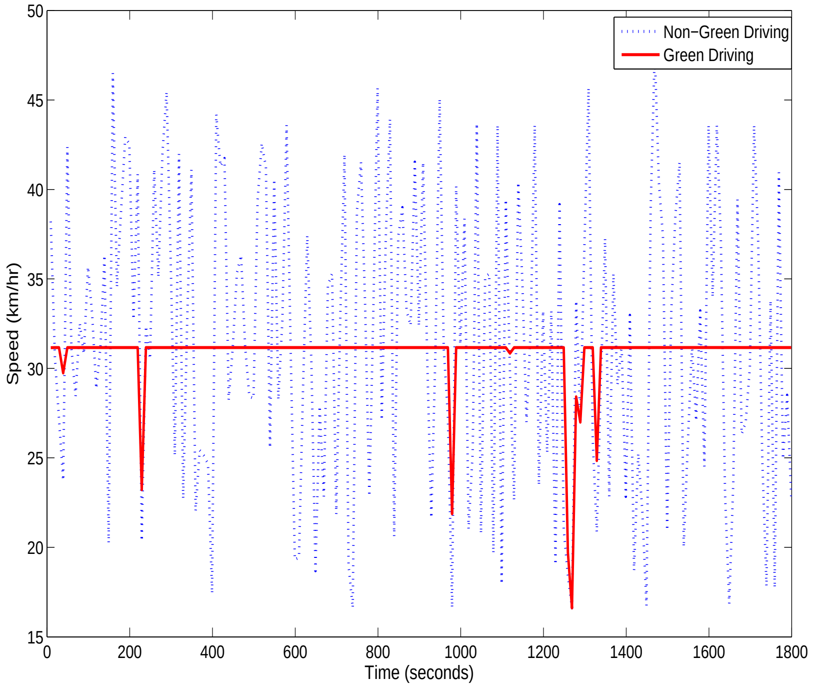

Figure 2: Speed trajectories of non-Green Driving system (blue) and Green Driving system (red)

Furthermore, **Table 2** lists the emissions and fuel consumption savings from these strategies. The table indicates that applying green driving strategies, definitely, emissions and fuel consumption are reduced. In this example, all vehicles are IVC-equipped. We find that savings for different types of emissions: HC: 87.90% - 88.33%, CO: 93.08% - 95.79%, NOx: 88.92% - 91.52%, CO2: 28.66% - 36.32%, FUEL USE: 68.47% - 71.31%. With random initial traffic, emission and fuel consumption savings are large and green driving strategies are all efficient.

Table 2 Emissions and Fuel Consumption Obtained from Non-delay System with 100% MPR

MPR (%)	scale	strategies	HC (mg /km)	CO (mg/km)	Nox (mg/km)	CO2 (g/km)	Fuel Use (liter/km)	VDT (km)
0			952.48	29939.97	1078.81	286.36	0.36	24922.10
100	Global	Average speed ajustment	113.97 (-88.03%)	1261.13 (-95.79%)	91.54 (-91.51%)	204.26 (-28.67%)	0.11 (-68.48%)	19310.30 (-22.52%)
		Desired speed adjustment	114.98 (-87.93%)	1800.23 (-93.99%)	109.23 (-89.88%)	183.80 (-35.82%)	0.10 (-70.99%)	24758.50 (-0.66%)
	Sectional	Average speed ajustment	113.90 (-88.04%)	1260.23 (-95.79%)	91.60 (-91.51%)	204.21 (-28.69%)	0.11 (-68.48%)	19313.60 (-22.50%)
		Desired speed adjustment	111.12 (-88.33%)	1684.88 (-94.37%)	103.44 (-90.41%)	182.35 (-36.32%)	0.10 (-71.31%)	24816.90 (-0.42%)

Moreover, considering total vehicle distance traveled, desired speed adjustment has much better performance than that of average speed adjustment. Under average speed adjustment, total distance traveled decreases more than 22%; while for desired speed adjustment, it is less than 0.7%. This difference comes from the properties of the strategy. As we explained in section 3, average speed adjustment can leads large gap ahead of IVC-equipped vehicles. **Figure** 3 shows several trajectories picked from our simulation. In **Figure** 3(a), when global average speed adjustment is applied, in front of IVC-equipped vehicles, large gap exists, but it does not accelerate to approach its leader due to its lower speed limit. This gap does not appear on the second graph. Since traveling speed takes an important role in transportation study, people will not accept any new strategies if they reduce traveling speed significantly. So, we claim that using desired speed adjustment has better effect on transportation system.

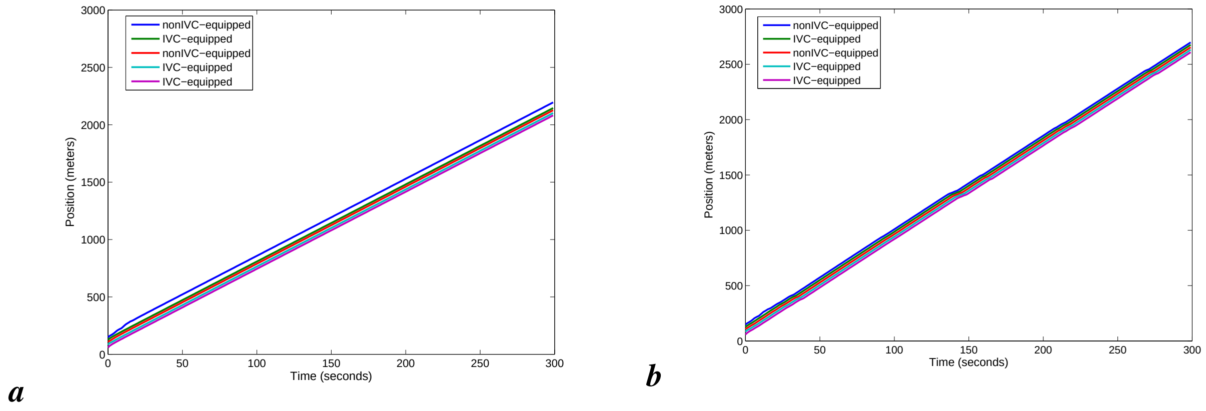

Figure 3: Vehicle Trajectories (a) Global Average Speed Adjustment, (b) Global Desired Speed Adjustment

4.2 Effect of MPR

In this subsection, the same initial traffic condition is set, but different market penetration rates are proposed. Traffic scenarios based on global desired speed adjustment are simulated. **Figure** 4 shows speed and acceleration histograms of all vehicles during half hour. **Figure** 4(a) comes from non-Green Driving system, while **Figure** 4(b) describes Green Driving system with 50% of IVC-equipped vehicles. Comparing these two graphs, speed concentrates on a narrow region after using global desired speed adjustment. It seems that the speed control scheme really works for traffic stream.

Results of emission and fuel consumption savings are shown in **Figure** 5. As expected, emission savings can gradually increase when we apply green driving strategy with global desired speed adjustment. For HC, its reduction increases from 63.45% at 1% MPR to 89.0% at 100% MPR; for CO, it increases from 67.32% to 94.0%; for NOx, it is from 60.60% to 89.9%; for CO2, it is from

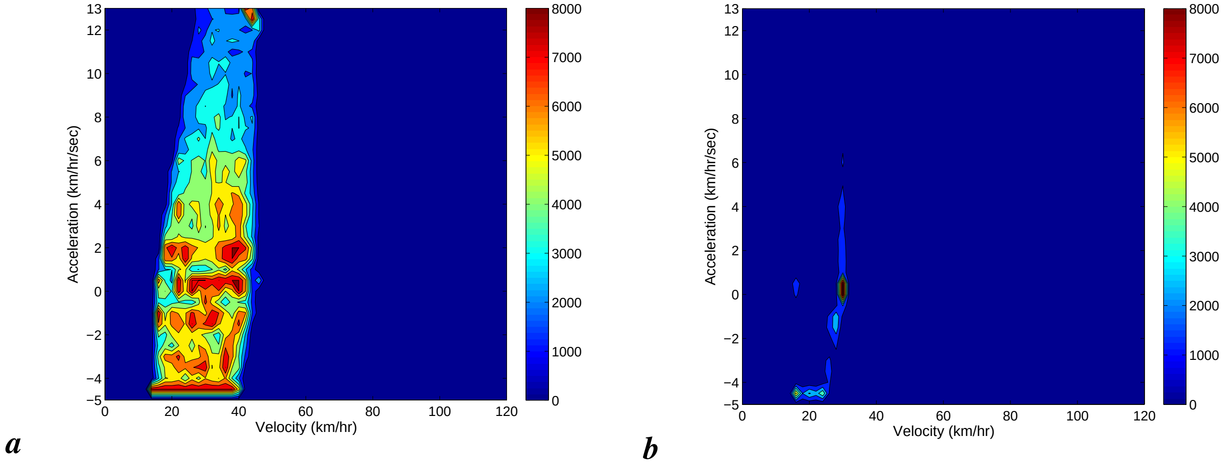

Figure 4: Speed-Acceleration Histograms (a) non-Green Driving system, (b) Green Driving system with 50% MPR

20.18% to 35.8%; and for fuel consumption, it is from 51.78% to 71.0%. All these reduction are huge, but the improvements of reduction with MPR are not significant when MPR is greater than 20%. The cause of this observation is that we only apply car-following behaviors in our simulation, which leads to the situation that one IVC-equipped vehicle not only adjusts its own driving behavior, but also affects its followers in road. After a while, location trajectories of both equipped vehicle and its followers are all smoothed due to green driving strategies and car-following rule. An important observation is that, even with an MPR as low as 1%, savings of emission and fuel consumption can still be huge. We expect that, in real world, due to lane-changing and other activities, savings at MPR's may not be as high as 60%. But reasonable savings are still possible due to car-following behaviors.

4.3 Effect of Communication Delay

In this subsection, MPR of IVC-equipped vehicles is 50% and constant delivery delay are assigned for all vehicles. Considering delay, when larger delay in the communication system exists, the

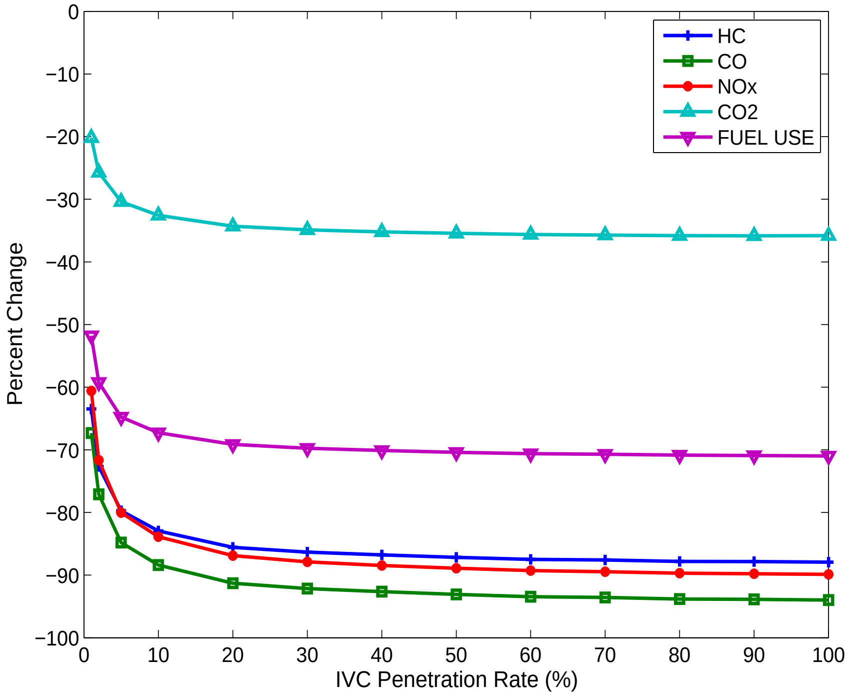

Figure 5: Emission/Fuel Consumption Reductions at different MPR with Global Desired Speed Adjustment

information vehicles receive is older and less useful for current speed limit adjustment. So, it is straightforward to predict that high delay can reduce the effect of green driving strategies. In these simulations, various delivery delays are assigned, and their effects on emission and fuel consumption reductions are studied. **Figure** 6 verifies our prediction. With higher delivery delay, all emissions and fuel consumption savings are increasing (approximately 3-5% for 150 seconds delay).

Besides of effect of constant delay, linear delivery delay is another reasonable assumption. In section 3, we assume a simple linear relationship between delay and distance (**Equation** 5). It is obvious that higher delay causes less emissions and fuel consumption reductions. We expect that with larger coefficient δ, savings under sectional desired speed adjustment is smaller, because

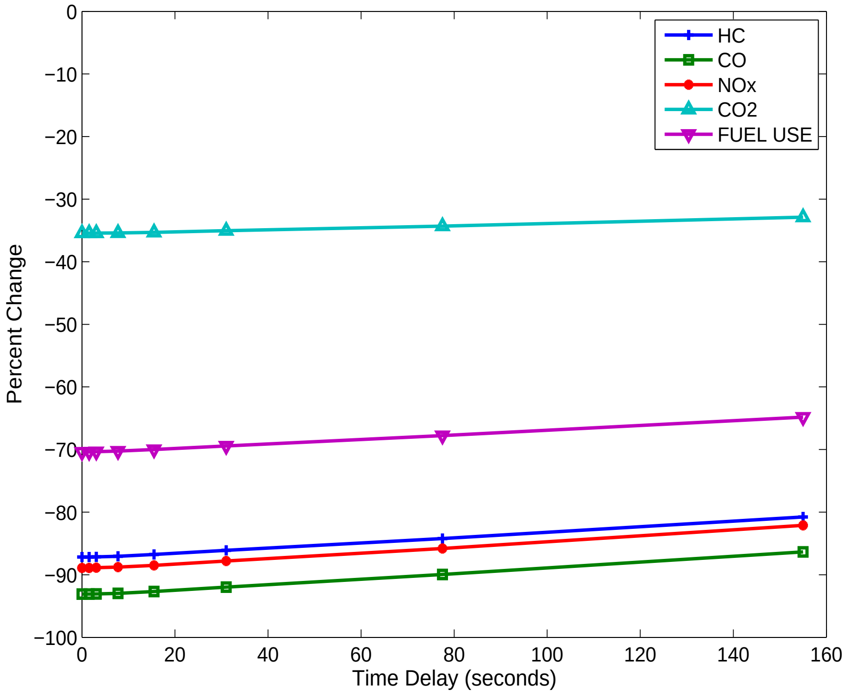

Figure 6: Emission/Fuel Consumption Reductions at different MPR with Global Desired Speed Adjustment

higher coefficient value leads higher delay for all IVC-equipped vehicles. In simulations, various δ values are set: $\{0, 0.005, 0.01, 0.02, 0.05\}$ $second/meter$, and savings of all fives emissions and fuel consumption are calculated. From **Figure** 7, we observe the decreasing trend of reductions with coefficient. Combining with constant delay analysis, we claim that larger delay actually makes the reduction smaller.

5 CONCLUSION

In this paper, we investigated the effect of green driving strategies based on inter-vehicle communication system. Two important factors of IVC systems, market penetration rate and communication

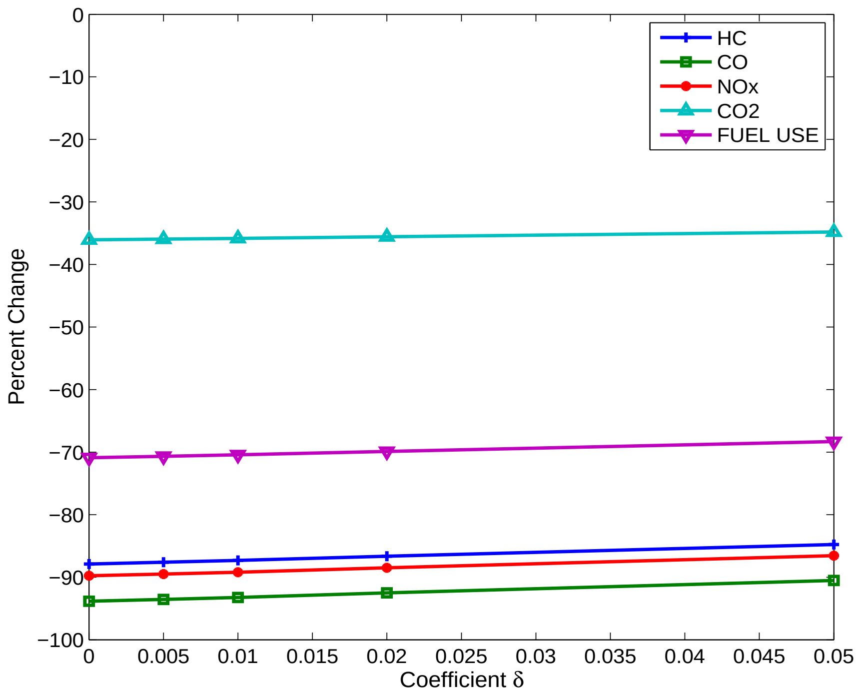

Figure 7: Emissions/Fuel Consumption Reduction at Different Coefficients with Sectional Desired Speed Adjustment

delay, were studied. We made two major conclusions from this work. Firstly, with higher market penetration rate (MPR) of IVC-equipped vehicles, reduction of emissions and fuel consumption were larger. This conclusion was reasonable, since higher MPR leaded to more communication and large amount of information, which could help us to find even more accurate and optimal adjustment of speed limits to achieve less emissions and fuel consumption. The second conclusion was that with the effect of communication delay, savings of emissions and fuel consumption were reduced. Larger delay made more information useless. Then, speed adjustment would not be accurate enough, and this leaded to less smoother traffic, which was equivalent to less reduction of emissions and fuel consumption.

But the more important insight with the impacts of market penetration rates and communication delays is that, even with a very low market penetration rate (1%) and a large communication delay (>2min), we can still achieve significant savings for frequent stop-and-go traffic. This feature is very promising, since it means that such green driving strategies can work even with a small adoption rate. This is different from traditional approaches, e.g., with alternative fuels, which require high market penetration rate to achieve significant savings.

In the future, we will investigate the potential benefits of such green driving strategies for different traffic conditions. In this study, as shown in **Figure** 2, the frequency of stop-and-go traffic is very high, but in reality it is usually smaller. We will investigate impacts of the frequencies on emission savings in future studies. In this paper, homogeneous traffic is modeled. We want to extend our strategies to non-homogeneous traffic and evaluate savings of emission and fuel consumption. And, also when we apply ISA system, 100% acceptance rate are assigned to equipped vehicles, which is not obtainable in realistic world. So, in future, we can simulate the traffic and communication system with reasonable acceptance rate. Furthermore, since only arbitrary communication properties are assigned in this paper, the result may not match to realistic situation. So, it is important to simulate transportation system with some reasonable communication settings. Finally, the application of these green driving strategies should be tested in real world situation.

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