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A STUDY ON POTENTIAL ENVIRONMENTAL BENEFITS OF GREEN DRIVING STRATEGIES WITH NGSIM DATA

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Abstract

The main purpose of this paper is to examine potential environmental benefits of green driving strategies with NGSim data on Interstate-80 near Berkeley, California. We calculate vehicles emissions before and after applying green driving strategies with the VT-Micro emission model. For each vehicle, its trajectory before applying green driving strategies is observed and given in the dataset. We assume that, with the help of green driving strategies, the vehicle could drive at a constant speed over the whole road section with the same travel distance and time as before. After examining impacts of speed-acceleration adjustment on calculated emissions and fuel consumptions, we choose 5127 out of 9951 cars and estimate potential savings in HC, CO, NOx, CO2, and fuel consumptions. With a new model of the relationships between emissions/fuel consumptions and average speeds, we can fit the data with R-squares close to or greater than 0.9 and find that green driving strategies are most effective for traffic flows with average speeds around 50 km/h and potential savings can be from 20% to 60% for different pollutants. In the future, we will continue our studies with more realistic information on vehicle types and other emission models.

Keywords: Green Driving, NGSIM Data, VT-Micro, Vehicle Emissions, Traffic Conditions

1 INTRODUCTION

Nearly one third of the greenhouse gas (GHG) emissions are from the transportation sector (*1*). Transportation is also a major source of pollutants of Hydrocarbons (HC), Carbon Monoxide (CO), Nitrogen Oxides (NOX). Although alternative fuel or electric vehicles have potential to reduce vehicle emissions significantly, their benefits cannot be felt in the near future. In contrast, we could apply technologies such as adaptive cruise control (ACC) and inter-vehicle communications (IVC) to manage traffic conditions so as to avoid stop-and-go traffic and therefore to reduce emissions and fuel consumptions. That is, we can devise "green driving" strategies to smooth traffic flow.

Previous studies have explored the potential of using technologies to smooth traffic in order to reduce vehicle emissions. Bose et al. (*2*) studied the impacts of ACC on vehicle emissions using CMEM. Ahn and Rakha (*3*) attempted to quantify the energy and environmental impacts of route choice decisions using in-field collected global positioning system (GPS) data with microscopic and macroscopic emission simulations. Their results showed that the shortest path could increase emissions although it could save driver’s travel time. Barth and Boriboonsomsin (*4*) introduced an environmental friendly dynamic eco-driving advice system which relies on real time traffic information provided by the California Freeway Performance Measurement System (PeMS). This concept was further investigated under real-world driving conditions. Their results showed that the reduction in fuel consumption and emissions for eco-driving vehicles is in the order of 10% to 20% compared to non eco-driving vehicles in this real-world experiment. El-Shawarby, Ahn and Rakha (*5*) used on board devices to measure real time energy-consumption and emissions on different levels of cruise speed and acceleration. They concluded that the optimum driving speed range is 60-90 km/h for energy-consumption and emissions. Barth and Boriboonsomsin (*6*) used collected GPS trajectory data to investigate real world carbon dioxide (CO2) emissions in southern California. Through using a microscopic emission estimation model CMEM, they proposed and compared strategies that can reduce CO_2 based on different traffic conditions. They did not discuss other emission components such as HC, CO, NOx. Treiber, Kesting and Thiemann (*7*) used NGSIM trajectory data to estimate fuel consumption with a physics fuel consumption model. They smoothed vehicle trajectory data before using them to estimate fuel consumptions. However, they did not use any available microscopic emission models.

In this paper, we propose to study potential environmental benefits of green driving strategies with NGSIM trajectory data and the VT-Micro microscopic emission model. In our study, we do not consider implementation issue of green driving strategies. Instead, we assume that all vehicles can drive at a constant speed after green driving. Compare emissions of this ideal scenario with realistic data then can give us insights on when green driving strategies are the most effective. In this study, we will carefully examine the available data sets and calculations of emissions and fuel consumptions. We decide to only choose a portion of vehicles, whose second-by-second speeds and acceleration rates are within the feasible domain of the VT-Micro model. In addition to examining potential environmental benefits for individual vehicles, we propose a new model to fit the relationships between emissions/fuel consumptions and average speeds. With the new model we can then determine the magnitude and conditions of most savings.

This paper is organized as follows. In section 2, we describe the VT-Micro model, NGSIM data, and the procedure of computing emissions. In section 3, we examine impacts of trajectory sampling and speed-acceleration adjustment on emissions. In section 4, we discuss potential environmental benefits for individual vehicles and study models for fitting the relationships between emissions/fuel consumptions and average speeds. In section 5, we summarize this paper and discuss possible directions for follow-up studies.

2 METHODOLOGY

2.1 The VT-Micro Model

Microscopic emission models estimate instantaneous emissions and fuel consumption rates for different classes of vehicles based on instantaneous speeds and acceleration rates in vehicle trajectory data. The VT-Micro model was developed from experimentation with numerous polynomial combinations of speed and acceleration levels (*8*).This model was tested using chassis dynamometer data collected from the Oak Ridge National Laboratory (ORNL). With a relatively good fit to the original data, the final regression model has a combination of linear, quadratic and cubic speed and accelerations. The ORNL data consisted of nine normal emitting vehicles which included six light-duty passenger cars and three light duty trucks.

From (*9*), the VT-Micro model can be written as

$$MOE_e(v,a) = \begin{cases} e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(L_{i,j}^{e} \times v^{i} \times a^{j})} & for\ a \geq 0 \\ e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(M_{i,j}^{e} \times v^{i} \times a^{j})} & for\ a < 0 \end{cases} \qquad (1)$$

where v and a are the instantaneous speed and acceleration rate, respectively, and MOE is the second-by-second emission rate or fuel consumption. The unit of acceleration is km/h/s, and the unit of speed is km/h. Here $L_{i,j}^{e}$ and $M_{i,j}^{e}$ are coefficients for acceleration and deceleration regimes and differ for different pollutants or fuel consumption. In our study, we consider emissions in HC $(e = 1)$, CO $(e = 2)$, NOX $(e = 3)$, CO2 $(e = 4)$, and fuel consumption $(e = 5)$. Their units are milligrams/second (mg/s) for vehicle emissions and liter/second for fuel consumption.

The VT-Micro model is only feasible for a speed-acceleration domain described by the following equations:

$$v \leq 120$$

$$a \leq -0.00002 * v^3 + 0.0031 * v^2 - 0.2558 * v + 14.4, \qquad (2)$$

$$-5 \leq a \leq 10.$$

Such a domain is shown with the solid lines in Figure 1. This domain applies to both LDV and LDT.

2.2 NGSIM Data

We use data sets collected on eastbound I-80 in the San Francisco Bay area in Emeryville, CA. There are three data sets on April 13, 2005 during three 15-minute periods: 4:00 pm to 4:15 pm, 5:00 pm to 5:15 pm, and 5:15 pm to 5:30 pm. The other data set was collected on December 3, 2003 during 2:35 pm. and 3:05 pm. In this study, we only consider passenger cars, which belong to class 2 in NGSIM data sets, since there are only very few heavy trucks, which belong to class 3, and motor-cycles, which belong to class 1. There are 4543 ‘auto’ vehicle trajectories in the data set of 2:35pm to 3:05pm. There are 1942, 1742, and 1724 ‘auto’ vehicle trajectories in the data set of 4:00 pm to 4:15 pm, 5:00 to 5:15 and 5:15 to 5:30.

In the NGSIM data sets, vehicles’ trajectories are provided every one tenth (4:00-4:15, 5:00-5:30) or one fifteenth second (2:35-3:05), but VT-Micro estimate emissions with second-by-second speeds and acceleration rates. To make the emission estimation consistent, we do not use speeds and accelerations provided by NGSIM. Instead, we used location information provided by NGSIM to calculate second-by-second speeds and accelerations. We first sample second-by-second location information from NGSIM. For a vehicle i, if its trajectory spans from $t_i(a)$ (seconds) to $t_i(b)$ (seconds), we choose the sampling time points as: $t_i(0), t_i(0)+1, \cdots, t_i(0)+T_i$, where the first sampling point $t_i(0) \in [t_i(a), t_i(a)+1]$, and T_i is the total travel time of the vehicle. Then we use this location information to calculate the average speeds and acceleration rates during $[t_i(0)+t-1, t_i(0)+t]$ for $t = 1, \cdots, T_i$ as follows

$$v_i(t) = 3600(x_i(t_i(0)+t) - x_i(t_i(0)+t-1)) \tag{3}$$

$$a_i(t) = \frac{v_i(t+1) - v_i(t-1)}{2} \tag{4}$$

where we assume that $v_i(0) = v_i(1)$ and $v_i(T_i+1) = v_i(T_i)$. Note that here the units of location, speed, and acceleration are km, km/h, and km/h/s, respectively, which are consistent with VT-Micro’s units. Thus the travel distance of the vehicle is given by

$$d_i = x_i(t_i(0)+T_i) - x_i\big(t_i(0)\big),$$

and the average speed is

$$v_i = 3600\frac{d_i}{T_i}. \tag{5}$$

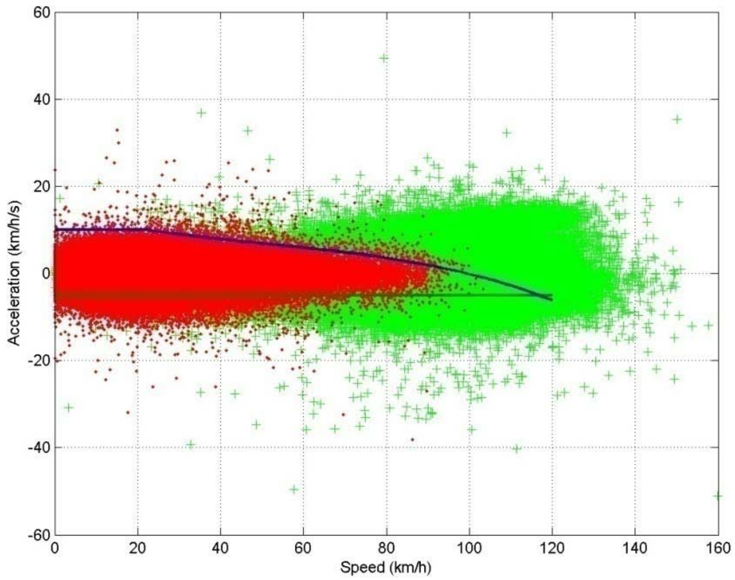

Figure 1 Relationship between speeds and acceleration rates: Red dots for cars in data sets of 4:00-4:15pm, 5:00-5:15pm, and 5:15-5:30pm; Green plus signs for cars in the data set of 2:35-3:05pm; and Solid lines are the feasible speed-acceleration domain for VT-Micro's LDV3 vehicles.

Figure 1 shows the distribution of second-by-second speeds and acceleration rates of all vehicles in the four data sets. From the figure, we can see that most speeds and acceleration rates are within the feasible domain of VT-Micro as shown in equation (1) for the later three data sets. But for the earliear data set, most of speeds and accelerations are outside of the feasible domain.

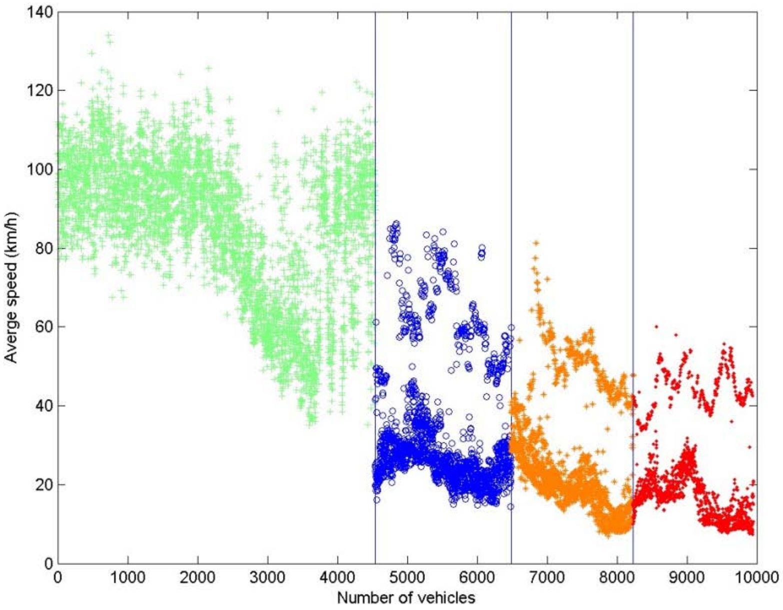

Figure 2. Average speeds of cars in different data sets: The four regions from left to right correspond to data sets of 2:35-3:05, 4:00-4:15, 5:00-5:15, and 5:15-5:30, respectively

Figure 2 shows the average speeds of cars in four data sets. From the figure we can clearly see that congestion level increases from the first to the fourth data sets, as expected. From 2:35 to 3:05, the first 2000 vehicles travel at free flow speed, and it is free flow during this time. But for the rest 2500 vehicles, the average speeds keep decreasing, and it suggests that congestion propagated on the road section. In the latter three data sets, there are two groups of average speeds, where the higher average speeds correspond to cars using the carpool lane. Therefore, these data sets can represent three important regimes of traffic: free flow, formation of congestion, and congested traffic. In real world, there is a fourth regime when congestion dissipates.

2.3 Emission Estimation Before and After Green Driving Strategies

For vehicle i, we assume that some green driving strategies can completely smooth out its trajectory on the road section. That is, after using green driving strategies, it travels at a constant speed v_i with a zero acceleration speed. With this assumption, the vehicle's travel distance and time do not change. Therefore here we ignore the impacts of green driving strategies on traffic flow itself. This assumption is quite strong, since it does not consider the interactions among vehicles. However, by comparing vehicle emissions before and after green driving strategies, we will be able to obtain some insights on their potential environmental benefits.

Before applying Equation 1 to calculate emissions for a vehicle before and after green driving strategies, we want to adjust its speeds and accelerations so that they fall in the feasible domain of the VT-Micro model. From Figure 1 we can see that only minimal adjustments are applied for congested traffic, but substantial adjustments are necessary for free flow. Since such adjustments would change our results, we need to interpret our results cautiously, in particular for free flow.

For vehicle i's speed and acceleration rate at time t, we make the following adjustments to its speed and acceleration before or after green driving,

$$\hat{v}_i(t) = \min(v_i(t), 120),$$

$$\hat{a}_i(t) = \min(a_i(t), \max(-0.00002\hat{v}_i(t)^3 + 0.0031\hat{v}_i(t)^2 - 0.2558\hat{v}_i(t) + 14.4, 0)), \quad (6)$$

$$\hat{a}_i(t) = \max(\min(\hat{a}_i(t), 10), -5) .$$

Obviously for trajectories after green driving, only the first equation above is applied, since $a_i(t) = 0$. Note that the second equation above is slightly different from Equation 2, since $-0.00002v_i\,(t)^3 + 0.0031v_i(t)^2 - 0.2558v_i(t) + 14.4 < 0$ when speed is greater than 100 km/h. In this case, we set the acceleration as 0. Again, such an adjustment does not reflect the realistic situation. The effects of such adjustment will be discussed in Section 3.

In our study we calculate the emission or fuel consumption rate for vehicle i as follows ($e = 1, \cdots, 5$)

$$E_{e,i}(\hat{\boldsymbol{v}}_i, \hat{\boldsymbol{a}}_i) = \frac{\sum_{t=t_i(0)+1}^{t_i(0)+T_i} MOE_e(\hat{v}_i(t), \hat{a}_i(t))}{d_i}, \quad (7)$$

which has the unit of mg/km and l/km for fuel consumption. We can see that, after green driving, the emission rate is

$$\bar{E}_{e,i} = \frac{\sum_{t=t_i(0)+1}^{t_i(0)+T_i} MOE_e(v_i, 0)}{d_i} = \frac{MOE_e(v_i, 0)T_i}{d_i} = 3600\frac{MOE_e(\hat{v}_i, 0)}{v_i} \quad (8)$$

Then the potential saving percentage of green driving strategy for vehicle i and pollutant e can be calculated by

$$S_{e,i} = 1 - \frac{\bar{E}_{e,i}}{E_{e,i}}. \quad (9)$$

3 PRELIMINARY RESULTS

In this section, we examine the impacts of trajectory sampling and speed-acceleration adjustment on emission calcualtions.

3.1 Sensitivity of Emissions to Trajectory Sampling Schemes

In our study, we sample locations of vehicle i every 1 second, but the original data sets provide the locations every one tenth or one fifteenth second. Thus the starting point $t_i(0)$ could have an impact on speeds, accelerations, and total travel distance. Table 1 shows the mean and standard deviation of different traffic and emission values for four vehicles from the four data sets. Here we assume that all vehicles are of LDV3 type. From the table we can see that the coefficient of variation is generally smaller than 2%. Thus emission estimation is not sensitive to the sampling scheme.

	Dataset	ID	T_i (s)	d_i (km)	v_i (km/h)	HC (mg/km)	CO (mg/km)	NOX (mg/km)	CO2 (g/km)	Fuel (l/km)
Mean (Std)	2:35-3:05	3284	50.6000 (0.5071)	0.8678 (0.0097)	61.7423 (0.2479)	16.2365 (0.1917)	349.5191 (5.7651)	74.5857 (2.8629)	119.50 (1.44)	0.0515 (0.0006)
Mean (Std)	4:00-4:15	672	29 (0)	0.4691 (0.0039)	58.2290 (0.4806)	47.7081 (0.9020)	1281.1 (45.7)	151.0042 (5.6914)	312.21 (8.37)	0.1371 (0.0034)
Mean (Std)	5:00-5:15	284	51.6000 (0.5164)	0.4702 (0.0056)	32.8060 (0.0887)	21.1447 (1.0149)	498.0905 (37.1156)	71.9498 (2.1348)	227.58 (7.23)	0.0978 (0.0033)
Mean (Std)	5:15-5:30	3	114.3000 (0.4830)	0.4766 (0.0025)	15.0109 (0.0306)	24.6502 (0.0722)	542.8825 (1.8056)	62.9381 (0.3373)	339.25 (0.42)	0.1453 (0.0002)

Table 1. Sensitivity of emissions and fuel consumption to trajectory sampling scheme

3.2 Impacts of speed-acceleration adjustment

As discussed in Section 2, the VT-Micro model only works for certain speed-acceleration domain. Also we showed that many points from the data set of 2:35-3:05 are outside of the domain. In Figure 3, we demonstrate possible impacts of speed-acceleration adjustment. Here we assume that all vehicles are of LDV3 type. In both Figure 3(a) and 3(b), the dots are CO2 emissions after green driving, and the cusp at 120 km/h in Figure 3(a) is caused by speed adjustment and can be explained with Equation 8.

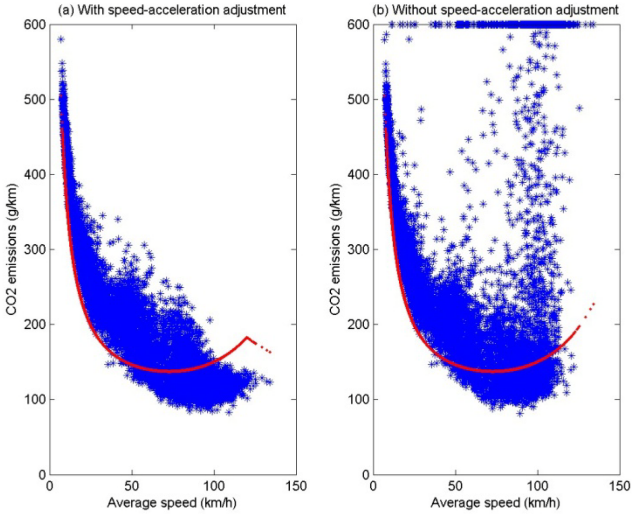

Figure 3. Impacts of speed-acceleration adjustment on CO2 emissions

In Figure 3, the asterisks are CO2 emissions before green driving. In Figure 3(b), emission values greater than 600 g/km are set to 600 g/km. Comparing both figures we can see that CO2 emissions at high speeds can be substantially impacted by speed-acceleration adjustment. In this sense, the fidelity of the VT-Micro model is low for traffic near free flows. Therefore, in later studies, we will choose vehicles for which the difference between the emissions calculated with speed-acceleration adjustment and those without adjustment is within 5%. Namely, we will choose vehicle i if for any $e = 1, \cdots, 5$

$$\frac{E_{e,i}(\boldsymbol{v}_i,\boldsymbol{a}_i)}{E_{e,i}(\hat{\boldsymbol{v}}_i,\hat{\boldsymbol{a}}_i)} \in [0.95, 1.05] \qquad (10)$$

With this criterion, we are able to choose 105 out of 4543 cars in the 2:35-3:05 data set, 1752 out of 1942 cars in the 4:00-4:15 data set, 1622 out of 1742 cars in the 5:00-5:15 data set, and 1648 out 1724 cars in the 5:15-5:30 data set. That is, more vehicles' speeds and acceleration rates are within the VT-Micro's feasible domain when traffic gets more congested.

4 ENVIRONMENTAL BENEFITS OF GREEN DRIVING STRATEGIES FOR DIFFERENT CONGESTION LEVELS

In this section, we analyze potential savings of green driving strategies for 5127 vehicles satisfying Equation 10. Hereafter, we use original speeds and acceleration rates without adjustment in Equations 7 and 8.

4.1 Potential Savings of Green Driving Strategies

Figure 4 shows emissions of four pollutants and fuel consumptions of 5127 vehicles. These vehicles' total travel time is 116.96 hours, and the total travel distance is 2448.2 km. Before green driving, the total amount of HC, CO, NOX, CO2, and fuel consumption for all vehicles are 0.0557 kg, 1.2656 kg, 0.1764 kg, 682.5 kg, and 292.5 l, respectively. After green driving, the total amount are 0.0470 kg, 1.1160 kg, 0.1224 kg, 544.7 kg, and 234.4 l, respectively. The corresponding savings in total emissions and fuel consumptions are 15.63%, 11.81%, 30.58%, 20.19%, and 19.88%. Furthermore, we can see that the average gas mileage increases from 11.95 l/100 km or 19.69 mile/gallon to 9.57 l/100 km or 24.57 mile/gallon.

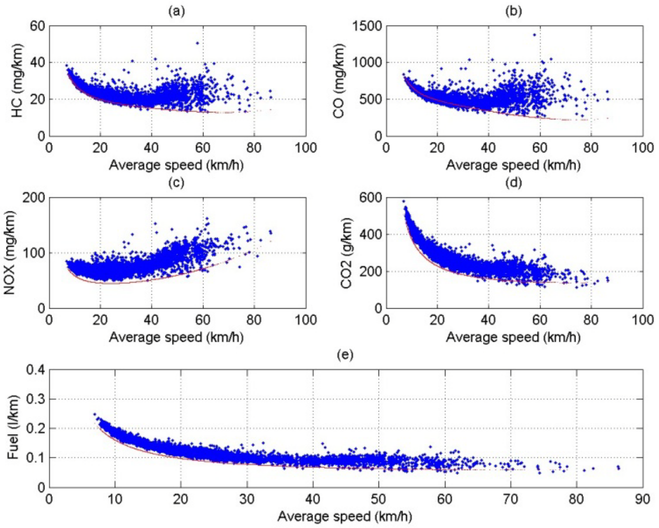

Figure 4. Emissions and fuel consumptions of vehicles before (blue asterisks) and after (red dots) green driving strategies

Figure 5 shows potential savings with green driving strategies. From both Figures 4 and 5, we can see that it is possible that the proposed green driving strategies could increase emissions and fuel consumptions. In particular, 0.86%, 31.23%, 0.23%, and 0.66% of all vehicles could increase their emissions in HC, CO, NOX, and CO2, respectively, and 0.66% could increase their fuel consumption. The ranges of average speeds for the occurrence of such increases are [10, 40] km/h for HC, [5, 40] km/h for CO, [35, 90] km/h for NOX, [35, 90] km/h for CO2, and [35, 90] km/h for fuel consumption. That is, generally green driving strategies could increase HC and CO for speeds lower than 40 km/h and NOX, CO2, and fuel consumption for speeds higher than 35 km/h.

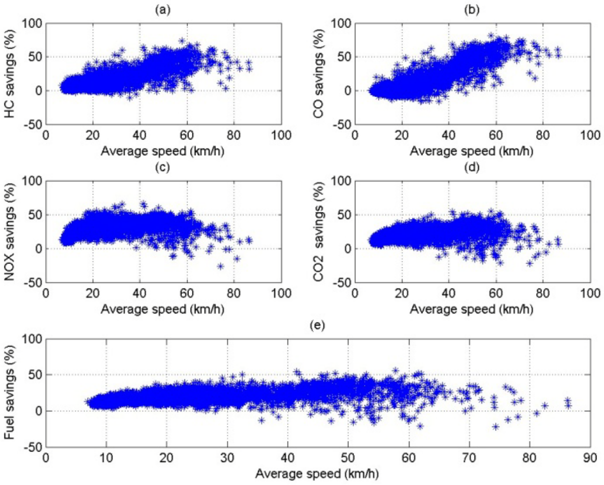

Figure 5. Potential savings in emissions and fuel consumptions with green driving strategies

Even though a significant portion of vehicles could increase their CO emissions, but from Figure 5(b) we can see that other vehicles can decrease their CO emissions by a even larger margin.

Figure 6 further shows the distribution patterns of saving percentages. This figure confirms our observations from Figures 4 and 5. From the figure we can also see that CO2 and fuel have almost the same saving profile. This means that they are highly related to each other.

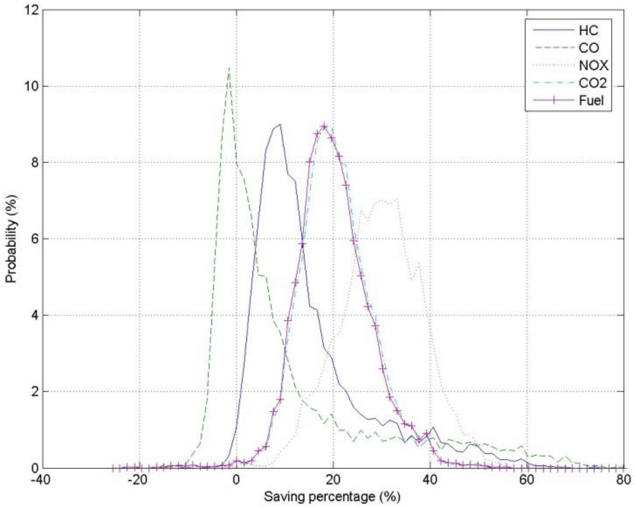

Figure 6. Distribution of saving percentages for different emissions and fuel consumption

4.2 Fitting the relationships between emissions/fuel consumptions and average speeds

As can be seen from Figures 4 and 5, we are only able to estimate potential savings for vehicles with average speeds smaller than 90 km/h. In this subsection, we attempt to fit emissions and fuel consumptions as functions of average speed and then extrapolate the resulted curves to free flow regime. Here we adopt the same functions from reference (*6*) for emissions and fuel consumptions of vehicle i before green driving

$$\ln\big(E_{e,i}(\boldsymbol{v}_i, \boldsymbol{a}_i)\big) = \beta_{e,0} + \beta_{e,1}v_i + \beta_{e,2}v_i^2 + \beta_{e,3}v_i^3 + \beta_{e,4}v_i^4 + \epsilon_{e,i} \qquad (11)$$

where $E_{e,i}(\boldsymbol{v}_i, \boldsymbol{a}_i)$ is defined in Equation 7 with second-by-second speeds $\boldsymbol{v}_i$ and acceleration rates $\boldsymbol{a}_i$, v_i is the average speed of vehicle i, $\beta_{e,j}$ $(e = 1, \cdots, 5; j = 0, \cdots, 4)$ is the coefficient for emission or fuel e, and $\epsilon_{e,i}$ is the error term. The same formula can also be used to fit emissions and fuel consumptions after green driving.

Pollutants		$\beta_{e,0}$	$\beta_{e,1}$	$\beta_{e,2}$	$\beta_{e,3}$	$\beta_{e,4}$	R^2
e=1 (HC)	Before	4.027244	-0.08204	0.002159	-2.1E-05	6.13E-08	0.6189
	After	4.011591	-0.09116	0.002683	-3.9E-05	2.06E-07	0.9978
e=2 (CO)	Before	7.111451	-0.08096	0.002174	-2.1E-05	5.84E-08	0.5110
	After	7.069401	-0.0757	0.002208	-3.5E-05	2.06E-07	0.9985
e=3 (NOX)	Before	4.703609	-0.06186	0.002251	-2.7E-05	1.11E-07	0.5958
	After	4.753301	-0.09837	0.003334	-4.3E-05	2.06E-07	0.9947
e=4 (CO2)	Before	13.7517	-0.1002	0.002564	-2.9E-05	1.17E-07	0.8777
	After	13.75014	-0.12122	0.003287	-4.2E-05	2.06E-07	0.9988
e=5 (Fuel)	Before	-0.91003	-0.1003	0.002556	-2.9E-05	1.13E-07	0.8750
	After	-0.91634	-0.12052	0.003271	-4.2E-05	2.06E-07	0.9988

Table 2. Results for fitting the relationships between emissions/fuel consumptions and average speeds with the model in Equation 11

Table 2 shows the coefficients and R-square for the relationships between four emissions and fuel consumptions and average speeds. From the table, we can see that, after green driving, the model in Equation 11 can fit the data very well with R-square>0.99. This is not coincidence. Rather, from Equations 1 and 8, we can see that

$$\ln \bar{E}_{e,i} = -\ln\frac{v_i}{3600} - \ln MOE_e(v_i, 0) = -\ln\frac{v_i}{3600} - L^e_{0,0} - L^e_{1,0}v_i - L^e_{2,0}v_i^2 - L^e_{3,0}v_i^3\ , \qquad (12)$$

which can be well approximated with Equation 11. For emissions and fuel consumptions before green driving, the model in Equation 11 can fit the data well with R-square>0.5. In particular, the model fits CO2 and fuel consumptions with R-squares greater than 0.87. However, the model in Equation 11 cannot be used to extrapolate data to free-flow regime well. This can be seen in Figure 7, which shows that emissions are unreasonably large for large average speeds after green driving.

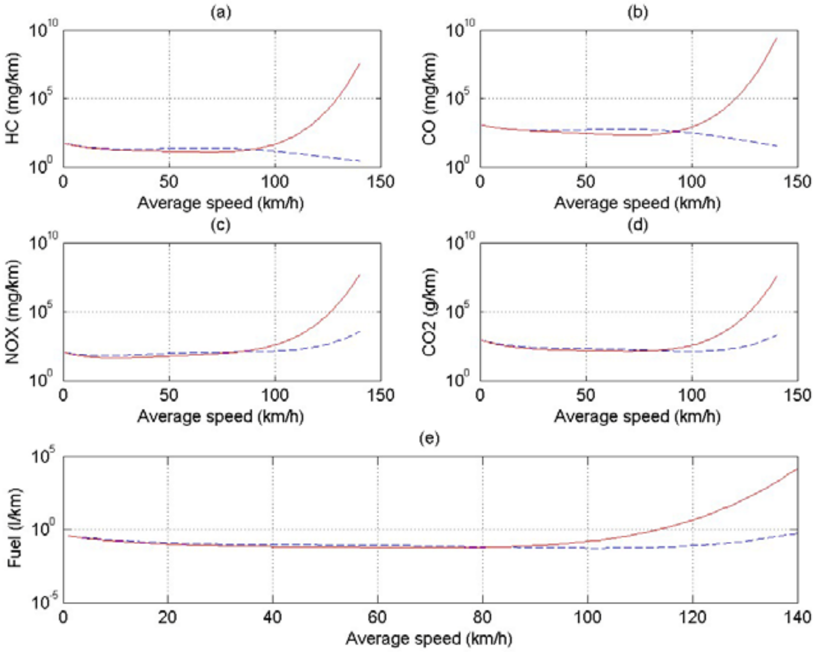

Figure 7. Fitted relationships between emissions/fuel consumptions and average speeds with Equation 11: dashed lines for relationships before green driving, solid lines for those after green driving.

Pollutants		$\beta_{e,0}$	$\beta_{e,1}$	$\beta_{e,2}$	$\beta_{e,3}$	R^2
e=1 (HC)	Before	-2.84072	0.037989	-5.7E-05	-9E-07	0.9429
	After	-3.01905	0.05401	-0.00077	4.66E-06	1
e=2 (CO)	Before	0.246721	0.038572	-1.8E-05	-1.3E-06	0.9322
	After	0.038755	0.06947	-0.00124	7.7E-06	1
e=3 (NOX)	Before	-2.22054	0.066847	-0.00039	7.48E-07	0.9654
	After	-2.27734	0.0468	-0.00011	2.23E-07	1
e=4 (CO2)	Before	6.821611	0.029429	-0.00012	-4.1E-07	0.8975
	After	6.719495	0.02395	-0.00016	8.36E-07	1
e=5 (Fuel)	Before	-7.83607	0.028707	-0.0001	-5.7E-07	0.8980
	After	-7.94699	0.02465	-0.00018	9.31E-07	1

Table 3. Results for fitting the relationships between emissions/fuel consumptions and average speeds with a new model in Equation 13

Inspired by Equation 12, we introduce a new model for the relationships:

$$\ln\big(E_{e,i}(\boldsymbol{v}_i, \boldsymbol{a}_i)\big) + \ln\frac{v_i}{3600} = \beta_{e,0} + \beta_{e,1}v_i + \beta_{e,2}v_i^2 + \beta_{e,3}v_i^3 + \epsilon_{e,i}. \tag{13}$$

Table 3 shows the coefficients and R-square for the relationships between four emissions and fuel consumptions and average speeds. Comparing results in Table 3 with those in Table 2, we can see that the new model in Equation 13 has one fewer parameter than that in Equation 11, but it fits the data very well: it is not surprising that R-squares are 1 after green driving as explained in Equation 12; even for data before green driving, R-squares are close to or larger than 0.9 for all the variables.

Figure 8 shows fitted relationships between emissions/fuel consumptions and average speeds. Compared with Figure 7, these curves look more reasonable. Therefore, we could apply Equation 13 to extrapolate for emissions and fuel consumptions in free flow regime. From Figure 8, we can see that, on average, green driving strategies may not be able help to save emissions when average speeds are greater than 90 km/h. However, it is important to note that such a conclusion is based on the assumption that Equation 13 can be extrapolated to free flow regime.

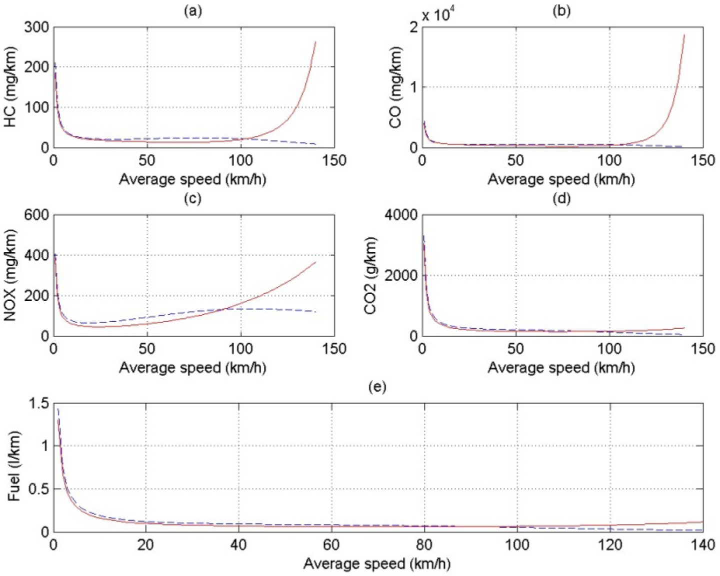

Figure 8. Fitted relationships between emissions/fuel consumptions and average speeds with Equation 13: dashed lines for relationships before green driving, solid lines for those after green driving.

Figure 9 shows saving percentages with fitted relationships in Equation 13. In the figure, all negative percentages are set to be 0. As shown in the figure, the average speeds with most savings are around 70 km/h for HC and CO, 40 km/h for NOX, and 50 km/h for CO2 and fuel consumption. Furthermore, the saving percentages can be greater than 40% for HC, 60% for CO, 30% for NOX, and 20% for CO2 and fuel consumption. Note that these observations are probably true, since Equation 13 can fit data before and green driving very well for average speeds smaller than 90 km/h.

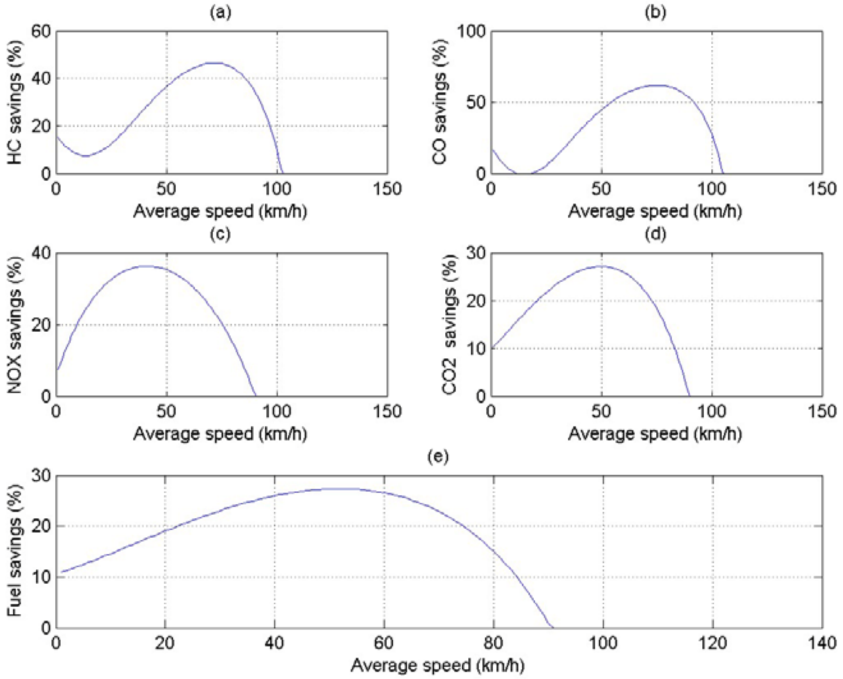

Figure 9. Saving percentages from fitted relationships between emissions/fuel consumptions and average speeds with Equation 13

5 DISCUSSION AND CONCLUSIONS

In this study with the help of NGSIM data sets and the VT-Micro model we attempted to provide some insights on potential environmental benefits of green driving strategies. We carefully discussed the sampling and calculation of vehicles' second-by-second speeds and acceleration rates and examined them against VT-Micro's feasible domain of speed and acceleration. We found that, when average speeds are higher than 90 km/h, vehicles' second-by-second speeds and acceleration rates have to be adjusted. As a result of such an adjustment, vehicle emissions and fuel consumptions can be significantly different from the original ones. Therefore we only chose 5127 out of 9951 cars in the original data sets for our further study. With the chosen vehicles, we discussed potential savings in fuel consumptions and emissions of HC, CO, NOX, and CO2. In addition, we presented a new model, Equation 13, to fit the relationships between emissions/fuel consumptions and average speeds.

In this study, we made the following contributions. First, we presented a systematic procedure to sample and calculate vehicles' second-by-second speeds and acceleration rates and estimate vehicle emissions from NGSIM data. We also demonstrated impacts of speed-acceleration adjustment when applying the VT-Micro model and presented a criterion to choose reasonable vehicle trajectories. This procedure is critical for obtaining meaning results and insights. Second, we proposed a new model, Equation 13, for the relationships between emissions/fuel consumptions and average speeds. Compared with an existing model in (6), this model has one fewer parameter, but provides significantly better fitting with R-squares near or greater than 0.9 for all five variables. The new model also provides more reasonable results for speeds higher than 90 km/h. Third, we found that, from Figure 9, the saving profiles are usually concave with respect to speeds with a unique maximum points. In addition, we found that the saving percentages can be greater than 40% for HC, 60% for CO, 30% for NOX, and 20% for CO2 and fuel consumption. Such savings are usually achieved for speeds around 50 km/h. We have a high confidence in these observations since (1) we used 5127 vehicles' trajectories and (2) the new model in Equation 13 fits the data with very high R-squares. The most important insight from this study is that green driving strategies that can help to smooth traffic flow can achieve the best effects for traffic flow with an average speed around 50 km/h.

However, this study has a number of limitations. The first limitation is in the assumption of constant driving speeds for all vehicles after using green driving strategies. In reality, this can hardly be achieved simultaneously. However, in our other study (12), it is shown that smooth driving can indeed be achieved with the help of inter-vehicle communications for small market penetration rates and reasonable communication delays. The second limitation is related to the VT-Micro model, which only works for relatively congested traffic. In the future, we will check out other models such as MOVES and CMEM. The third limitation is related to the NGSIM data, from which we cannot tell vehicle model year, engine size, or mileage. Thus we cannot determine the exact vehicle type used in VT-Micro or other emission models. In this study, we simply assume all vehicles are of LDV3 type. That said, however, we suspect that different vehicle types will not significantly impact the relative savings.

In addition to addressing the aforementioned limitations of this study, we will be interested in investigating potential environmental benefits for more traffic patterns with other NGSIM data sets. We will also investigate how to implement green driving strategies with information and communication technologies, especially IntelliDrive technologies. We will also test such green driving strategies in field in the follow-up studies.

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