Traffic Energy and Emission Reductions at Signalized Intersections: A Study of the Benefits of Advanced Driver Information

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Motor vehicles are one of the major contributors to greenhouse gas emission inventories. Previous studies have revealed that unnecessary acceleration and hard braking in response to sudden changes of traffic signals cause a significant amount of wasted energy and increased emissions. Altering a driver's behavior can potentially contribute to the reductions of vehicle energy/emissions. This paper proposes an advanced driving alert system that provides traffic signal status information to help drivers avoid hard braking at intersections, defines a method for evaluating vehicle energy consumption and emissions at intersections, and investigates the potential benefits of such system.

Keywords: arterials, traffic information, wireless communication, energy, emissions

1. Introduction

Reducing fuel consumption and associated greenhouse gas (GHG) emissions—particularly carbon dioxide (CO_2)—from motor vehicles has been one of the important goals for a variety of sustainable transportation programs. In order to achieve this goal, vehicle manufacturers are looking to produce more energy-efficient vehicles by: 1) using lighter and stronger materials, while maintaining safety; 2) increasing overall power train efficiency; and 3) developing alternative technologies such as hybrid and fuel-cell vehicles. Further, transportation policy makers are pushing to increase the use of carbon-neutral alternative fuels (see e.g. [1]). Many carbon-neutral options exist such as biofuels (e.g. ethanol, biodiesel) and synthetic fuels (coupled with carbon capture and storage).

In addition, vehicle fuel consumption and CO_2 emissions can be lowered by improving *traffic operations* through the use of various intelligent transportation system (ITS) technologies. ITS technology generally aims at improving traffic safety and/or reducing travel delays. However, there can be profound energy and environmental benefits by introducing different ITS technologies; especially those that help reduce traffic congestion while at the same time smooth traffic flow. For freeway traffic, example applications include: 1) ramp metering, which prevents flow breakdown in mainline as a result of the surge from merging traffic; 2) variable speed limits, which advises optimal speed limit to drivers when traffic is congested; and 3) advanced traveler information systems (e.g.

variable message signs), which divert traffic from a congested route to alternative routes. For surface street traffic, there are a variety of other strategies such as signal progression and adaptive signal control, which are designed primarily for the reduction of delays at signalized intersections. This paper focuses on providing drivers with advanced signal status information specifically for energy and emissions reduction.

1.1. Background

Unlike freeway traffic, surface street traffic suffers from increased travel delays, wasted fuel, and increased emissions at traffic signals where vehicles have to decelerate to a full stop, idle, and then accelerate back to a desired speed. Many empirical studies have shown positive relationships between vehicle energy/emissions and delays caused by traffic signal controls, e.g. [2, 3]. Therefore, past research has focused on improving signal timing and coordination of signalized intersections in corridors, and evaluating their impact on vehicle delays, fuel consumption, and emissions [4]. For example, several studies have been conducted that investigate the design of signal timing plans at isolated intersections to minimize fuel consumption and carbon dioxide emission rather than vehicle delays [5, 6]. Alternatively, Li et al. [7] define a performance index function that combines vehicle delay, fuel consumption, and emissions, and use this function in the optimization of signal timing design. Additional reductions of vehicle delay, fuel consumption, and emissions at signalized intersections may potentially be obtained through the use of advanced applications

such as real-time adaptive signal control [8] and coordinated actuated signal control systems [9].

In addition to the aforementioned technologies that target the traffic stream in general, there are also several in-vehicle technologies, such as environmentally-friendly navigation [10] and dynamic eco-driving systems [11], which can assist individual drivers in further reducing fuel consumption and emissions from their trips. These in-vehicle technologies generally provide the drivers with information (e.g. route, recommended speed, etc.) customized to the characteristics and situations of the individual vehicle. Such technologies have been shown to be effective and readily accepted by the public since they allow drivers to be more involved in reducing their own environmental footprint (for instance, fuel economy feedback in hybrid-electric vehicles is very popular).

With new communication capabilities between vehicles and roadside infrastructure enabled by Vehicle Infrastructure Integration (VII) technologies, additional information may be provided to drivers in order to improve their travel quality. One valuable data stream is traffic signal status (TSS) information from traffic signal controllers. In one specific application, TSS information can alert drivers to slow down some distance away from an intersection when there is little or no chance of passing through the intersection before the signal turns to red. This can prevent the drivers from unnecessary cruising/accelerating while approaching the intersection and having to apply hard braking near the stop line. Therefore, it can reduce fuel consumption and emissions.

1.2. Benefits of Driving Alert Based on Real-Time Traffic Signal Status Information

At signalized intersections, a driver sometimes has to make a decision on whether to proceed or stop at the yellow onset based on the estimated time-to-arrival at the intersection. Often, the driver finds that he/she will not be able to get through an intersection before the signal turns to red and has to apply hard braking. Driver behavior in this so called "dilemma zone" has significant safety implications and has received considerable attention in traffic safety research, e.g. [12, 13]. One approach for improving safety related to the dilemma zone is referred to as "dilemma control". The main idea of such a control is to switch off the green phase when there is no vehicle in the dilemma zone [14].

It can be argued that the application of unnecessary hard braking is essentially a rapid release of energy that was built up by accelerating and maintaining a constant cruise speed prior to the braking event. In other words, it is a waste of the vehicle's kinetic energy, transformed into heat through braking. We consider this maneuver as Case 1, with the velocity trajectory illustrated in Figure 1.

On the other hand, if the driver has TSS information in advance, and realizes that the residual time of the current signal phase will not allow for passage through the intersection, the driver would most likely release the throttle and let the vehicle slowly cruise to a stop. We consider this maneuver as Case 2. These two speed trajectories will result in small differences in energy consumption and emissions, simply because the driver in Case 1 maintains their cruise speed for a longer period of time before the sudden braking. Although the energy/emissions savings in Case 2 may be small for each occurrence of individual vehicles at each signal cycle, the cumulative savings of a number of occurrences can be large for multiple vehicles over multiple cycles.
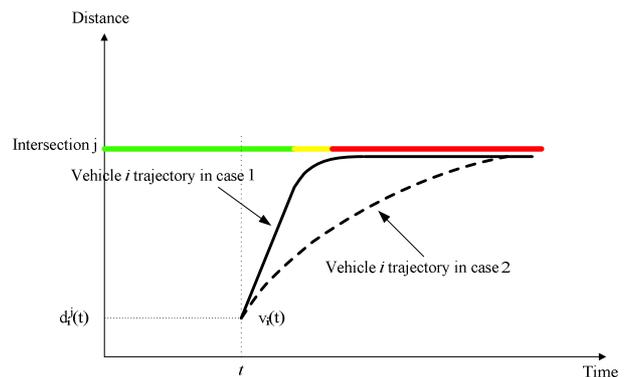

Figure 1. Vehicle trajectories with and without TSS information

In addition to the benefits of reducing vehicle fuel consumption and emissions, the TSS information may be able to provide safety co-benefits by reducing the likelihood of red light running (RLR, see [15]). In the United States, RLR causes more than 200,000 crashes per year, causing 940 deaths and 188,000 injuries. RLR crashes account for approximately 30% of all fatal crashes and 20% of all injury crashes at signalized intersections [15]. Further, it was found that a large percentage of drivers facing the yellow signal are caught in a dilemma zone due to high approaching speeds and exercise aggressive behavior [12]. The TSS information, if designed conservatively enough, can warn the driver of the unlikelihood of passing through the intersection with an allowable safe speed prior to entering a dilemma zone, thereby reducing the chances of the vehicle running the red light.

2. Advanced Driving Alert System (ADAS)

When the TSS information becomes available to instrumented vehicles through communications enabled by VII, the predicted red onset warning can be processed in conjunction with the vehicle's estimated travel time to intersections. An advisory alert can be given to drivers to inform them that they are unlikely to be able to pass safely through the intersection under normal conditions. This information allows drivers to release the throttle earlier and decelerate to the stop bar or to the back of a

queue with a gentler deceleration. Note that although not all vehicles will receive this information, the following vehicles will likely have to decelerate in a similar manner as the leading vehicles. Thus, larger benefits of emissions reductions and safety can be achieved even when a relatively small percentage of vehicles are instrumented to receive the TSS information.

Conceptually, the advanced driver information system uses a signal's time-to-red information (*TTR*) and the estimated travel time to an intersection as the basis for the advisory decisions. *TTR* is communicated to all instrumented vehicles as soon as the signal turns to green. The on-board vehicle system compares the signal's *TTR* with the estimated travel time to intersection and decides whether to issue the alert. Assume that the vehicle is at distance *d* to the far end of the intersection traveling at speed *v*. We define the followings:

$v_k(t)$ is the instantaneous speed of vehicle *k*, at time step *t*;

$d_k^j(t)$ represents the distance to intersection *j* for vehicle *k*, at time step *t*;

$tt_k^j(t)$ is the estimated travel time to intersection *j* for vehicle *k* at time step *t*;

γ is the threshold value indicating the probability of vehicle not being able to pass through the intersection;

$TTR^j(t)$ is the time-to-red for intersection *j* at time step *t*.

In order to simplify the problem, we focus on the instances when vehicles are traveling at approximately the speed limit. The estimated travel time to intersection *j* is modeled by:

$$tt_k^j(t) = \frac{d_k^j(t)}{v_k(t) + \omega}$$

where we assume that the vehicle population traveling between two intersections predominantly travels at a constant speed $v_k(t)$ with variance ω which is caused by mild acceleration/decelerations. We also assume that the variance ω follows a normal distribution, i.e. $\omega \sim N(0, \sigma^2)$ or $v_k(t) + \omega \sim N(v_k(t), \sigma^2)$. Theoretically, ω can be time varying, i.e. $\omega(t) \sim N(0, \sigma(t)^2)$, because drivers' awareness/responses to signals vary when they are approaching intersections.

Given the normally distributed variance on speed and the current speed and distance to the downstream intersection, the probability of a vehicle being able to travel through intersection *j* before red is:

$$P\left(0 \leq tt_k^j(t) \leq TTR^j(t)\right) = P\left(0 \leq \frac{d_k^j(t)}{v_k(t) + \omega} \leq TTR^j(t)\right)$$

$$= P\left(\omega \geq \frac{d_k^j(t)}{TTR^j(t)} - v_k(t)\right)$$

$$= \frac{1}{\sqrt{2\pi}\sigma} \int_X^{+\infty} exp\left(-\frac{x^2}{2\sigma^2}\right) dx$$

$$= \frac{1}{\sqrt{\pi}} \int_Y^{+\infty} e^{-y^2} dy$$

where: $X = d_k^j(t)/TTR^j(t) - v_k(t)$ and $Y = [d_k^j(t)/TTR^j(t) - v_k(t)]/\sqrt{2}\sigma$

When $1 - P\left(0 \leq tt_k^j(t) \leq TTR^j(t)\right)$ is greater than a threshold γ, the vehicle is determined not able to travel through the intersection. Therefore, the driver will be given an alert to prepare for a stop due to the expected red signal downstream. The threshold γ will be selected to be high enough to minimize the number of false alerts. This is important for gaining the driver's confidence in the system. The threshold can also be designed to be adaptive so that if a driver intends to use the TSS information to beat the signal, γ will be further increased to guarantee that the driver will not be able to go through the intersection even if he/she accelerates or the advisory system is turned off.

3. Comprehensive Modal Emission Model

In order to accurately assess the energy and emissions impact, we make use of the Comprehensive Modal Emissions Model (CMEM) [16, 17]. CMEM is a microscopic emissions model that has been developed at the University of California, Riverside. It is capable of predicting second-by-second fuel consumption and tailpipe emissions of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) based on different modal operations from an in-use vehicle fleet. In the modeling approach of CMEM, the entire fuel consumption and emissions process is broken down into components that correspond to physical phenomena associated with vehicle operation and emissions production, as briefly described below.

It is well known that speed and acceleration have a large impact on a vehicle's fuel economy and tailpipe emissions (both pollutant and GHG emissions). In turn, speed and acceleration are the primary variables that determine the power requirements necessary for specific driving maneuvers. Generally, the total tractive power requirement (in kilowatts) placed on a vehicle (at the wheels) is given in simplest form as [16, 17]:

$$P_{tractive} = \frac{M}{1000} \cdot V(a + g \cdot sin\theta) + (M \cdot g \cdot C_r + \frac{\rho}{2} \cdot V^2 \cdot A \cdot C_a) \cdot \frac{V}{1000}$$

where M is the vehicle mass (kg), V is the vehicle velocity (meters/second), a is the vehicle acceleration (meters/s^2), g is the gravitational constant (9.81 meters/s^2), θ is the road grade angle, C_r is the rolling resistance coefficient, ρ is the mass density of air (1.225 kg/meter^3, depending on temperature and altitude), A is the vehicle cross sectional area (meter^2), and C_a is the aerodynamic drag coefficient. To translate this tractive power requirement to a demanded engine power requirement, the following simple relationship can be used as a first order approximation:

$$P_{engine} = \frac{P_{tractive}}{\eta_{tf}} + P_{accessories}$$

where η_{tf} is the combined efficiency of the transmission and final drive, and $P_{accessories}$ is the engine power demand associated with the operation of accessories, such as air conditioning, power steering and brakes, and electrical loads. In the final model, $P_{accessories}$ may be modeled as a function of engine speed, and η_{tf} can be modeled in terms of engine speed and $P_{tractive}$. The power requirement on the engine P_{engine} is directly related to fuel consumption rate:

$$\frac{dF}{dt} \approx \lambda(k \cdot N \cdot D + \frac{P_{engine}}{\eta_{engine}})$$

where k is the engine friction factor (it represents the fuel energy used at zero power output to overcome engine friction per engine revolution and unit of engine displacement), N is engine speed, D is engine displacement, and η_{engine} is a measure of indicated engine efficiency. This equation is simple but fairly accurate in determining the fuel use rate (in kilowatts).

Based on the power requirement and related fuel consumption, tailpipe emissions of CO_2, CO, HC, and NO_x can be estimated as:

$$Emissions_{tailpipe} = FR \cdot \frac{g_{emission}}{g_{fuel}} \cdot CPF$$

where FR is fuel use rate in grams/s. The middle term is the engine-out emission index in grams of engine-out emissions per gram of fuel consumed. CPF is the catalyst pass fraction, which is defined as the ratio of tailpipe to engine-out emissions. CPF usually is primarily a function of fuel/air ratio and engine-out emissions.

Each component of CMEM is modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to vehicle type, engine, emission control technology, and level of deterioration. The initial versions of CMEM contain a model database for 23 light-duty vehicle/technology categories. With the constant additions of new vehicle/technology categories into the model database [18, 19], the current version of CMEM includes 28 light-duty vehicle/technology categories and three heavy-duty vehicle/technology categories.

CMEM has been developed primarily for microscale transportation models that typically produce second-by-second vehicle trajectories (location, velocity, and acceleration). These vehicle trajectories can be applied directly to the model, resulting in both individual and aggregate energy/emissions estimates. Alternatively, CMEM has also been integrated with the state-of-the-art traffic simulation model PARAMICS through the use of an Application Programming Interface (API). The integrated modeling tool has been used in a variety of ITS and transportation control measure evaluations [20, 21], and is used in the analyses described in Sections 5 and 6.

4. Energy/Emissions at Intersections

A generic method to analyze the effect of intersection influence on vehicle energy and emissions is essential for evaluating or optimizing the effectiveness of traffic signal control systems or driver information systems at intersections. To date, such a method does not exist.

In order to quantify the intersection influence, we first identify the boundary of the influenced area, i.e., the entry and exit. When traffic is under-saturated, decelerate-idle-accelerate and decelerate-accelerate (no idle) sequences would be expected to occur in the vicinity of intersections when the traffic signal is red. On the other hand, a quasi-steady cruise operation would be expected through "green light" intersections and in between intersections. When traffic is over-saturated, the influenced area could stretch to the entire link between intersections, where vehicles might experience stop-and-go conditions all the time.

TSS warning information will likely have its largest benefit during under-saturated traffic conditions. During these conditions, we further categorize the driving behaviors prior to the intersection into the following three basic scenarios, which are also depicted in Figure 2:

1. *Scenario 1*: The vehicle receives a green light and travels through the intersection at a constant cruising speed, shown as vehicle 1 in Figure 2. This scenario is equivalent to the vehicle cruising along a corridor without traffic signal controls.
2. *Scenario 2*: The vehicle travels at cruising speed when entering the dilemma zone. Without a warning, the driver applies hard braking in order to stop at the intersection, shown as vehicle 2 in Figure 2.
3. *Scenario 3*: The vehicle, which is equipped with the advanced driving alert system, receives a TSS warning well in advance of entering the dilemma

zone. The driver takes his/her foot off the pedal and lets the vehicle decelerate gently to a complete stop, shown as vehicle 3 in Figure 2.
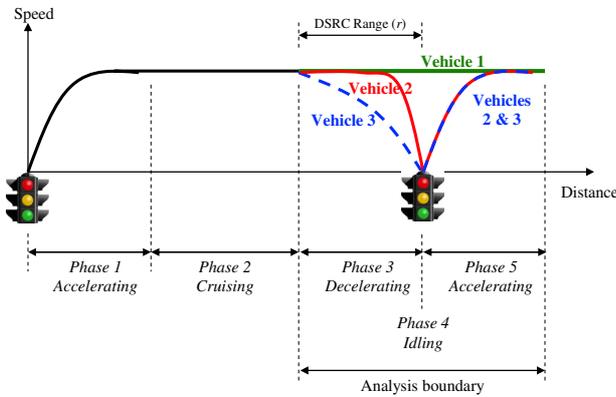

Figure 2. Driving behaviors prior to a signalized intersection

In order to analyze the vehicle energy/emissions associated with the traffic signal at the downstream intersection for these three basic scenarios, we simply define the analysis boundary as the distance from the maximum range of VII communication (*r*) on the approach link to the point where the vehicles successfully accelerate back to a desirable cruise speed on the departure link. This is shown in Figure 2. It is expected that the vehicle energy/emissions for the three scenarios will be different. Certainly, vehicle 1 will consume the least amount of energy and produce the least amount of emissions as it does not have to stop and idle at the intersection. In comparison with vehicles 3, vehicle 2 is likely to consume more fuel and produce more emissions.

As described by the CMEM model, instantaneous speed and acceleration are the two major dynamic factors that contribute to the energy/emission rates for a given vehicle in a particular driving circumstance. In the real world, vehicle driving patterns may not be as simple as what is illustrated in Figure 2, and the analysis boundary for these vehicles will likely be variable. Thus, a microscopic method has been set up to identify the intersection influence. This method sets a hybrid time boundary of instantaneous speed v_t and acceleration rate a_t, as shown below:

$$t_{entry} = t, if \begin{cases} v_{t-T} > V_{cruise}^- \ and \ a_{t-T} < A^+ \\ v_t \leq V_{cruise}^- \ or \ a_t \geq A^+ \end{cases}$$

$$t_{exit} = t, if \begin{cases} v_{t-T} > V_{cruise}^+ \ or \ a_{t-T} < A^- \\ v_t \geq V_{cruise}^+ \ and \ a_t \leq A^- \end{cases}$$

where: t_{entry} and t_{exit} are the entry and exit times for the intersection influenced area; T is the time gap between two vehicle data updates (e.g., 1 second or 5 seconds); V_{cruise}^- and V_{cruise}^+ are the lower and upper

bounds of the cruising speed; and A^- and A^+ are the lower and upper bounds of the acceleration rate.

The intersection-influenced energy/emissions should be made relative to a base scenario (i.e., vehicle 1 in Figure 2), which expects vehicles to cruise through intersections under green-light conditions. In the microscopic method presented above, the entry and exit times are dynamic terms. In other words, the intersection-influenced distances are different among vehicles. Therefore, EE_j^i, the intersection-influenced energy/emissions for vehicle j at intersection i, is the cumulative energy/emissions from the entry point to the exit point excluding $EE_{j,i}^{cruise} \cdot \int_{t_{entry}}^{t_{exit}} d(t)dt$, which is the energy/emissions for cruising only from t_{entry} to t_{exit}, such as vehicle 1 in Figure 2.

$$EE_j^i = \int_{t_{entry}}^{t_{exit}} ee_j^i(t)dt - EE_{j,i}^{cruise} \cdot \int_{t_{entry}}^{t_{exit}} d(t)dt$$

5. Parametric Evaluation

To quantify the energy/emission differences, we create a series of hypothetical vehicle trajectories (i.e. second-by-second speed profiles) corresponding to each of the three scenarios described earlier. The space-time diagram of these vehicle trajectories is shown in Figure 3. Given that the distance of the analysis boundary is approximately 585 meters, vehicle 1 spends 33 seconds to cruise over such distance with a speed of 64 km/h. Because both vehicles 2 and 3 have to stop on red at the intersection, they spend the same amount of time (i.e. 120 seconds) to travel across the analysis boundary. However, vehicle 2 reaches the intersection earlier; and thus, spends longer time idling at the intersection (i.e. 75 seconds vs. 70 seconds). Because constant speed and acceleration rate are considered in the hypothetical case, t_{entry} and t_{exit} are simply the speed differential points as shown in Figure 3.
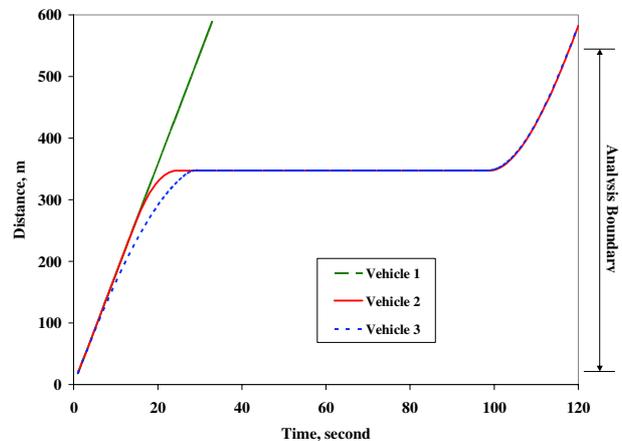

Figure 3. Space-time diagram of vehicle trajectories

All three trajectories are used as inputs for the CMEM model to calculate the associated energy/emissions. The calculation is performed for two vehicle categories in CMEM: 1) LDV24, which is a tier 1 light-duty vehicle (LDV) with mileage more than 100,000 (e.g. passenger cars), and 2) LDV17, which is a tier 1 light-duty truck with a loaded vehicle weight of 3,751-5,750 lbs (e.g. pick-ups, sport utility vehicles). These two CMEM vehicle categories represent the largest proportion in the 2005 fleet mix of Riverside County, California [21].

The calculated energy/emissions are summarized in Table 1. Two types of comparisons are presented. The first one is the differences in energy/emissions between vehicles 2 and 3 (i.e. the row "% 3 vs. 2"). The second one is the relative differences in energy/emissions between vehicles 2 and 3 after subtracting energy/emissions for vehicle 1 (i.e. the row "% (3-1) vs. (2-1)"). This approach of comparison corresponds to the method to evaluate the intersection-influenced energy/emissions EE_j^i discussed in Section 4.

According to Table 1, the ADAS can help reduce intersection-influenced fuel consumption by 14% for LDV24 and 12% for LDV17. It can also help reduce intersection-influenced CO_2 emissions by the same order. These amounts of energy/emission reductions can be regarded as an upper bound for this analysis boundary as the driver of the vehicle equipped with ADAS takes his/her foot off the pedal as soon as entering the DSRC range. In cases where an alert is issued seconds after the vehicle has entered the DSRC range depending on the signal status, the energy/emission reductions will be lower. It is also important to note that the energy/emission reductions shown in Table 1 are based on the specific vehicle trajectories used in the evaluation. The energy/emission estimates will vary for different vehicle trajectories and different vehicle categories.

Table 1. Summary of energy/emissions results (grams)

	LDV24		LDV17	
	Fuel	**CO_2**	**Fuel**	**CO_2**
Vehicle 1	27.8	87.5	35.0	110.7
Vehicle 2	70.6	222.4	93.2	294.8
Vehicle 3	64.5	203.1	86.0	272.0
% 3 vs 2	*-8.7*	*-8.7*	*-7.7*	*-7.7*
(2-1)	42.9	134.9	58.2	184.0
(3-1)	36.7	115.6	51.0	161.3
% (3-1) vs (2-1)	*-14.3*	*-14.3*	*-12.4*	*-12.4*

6. Simulation Evaluation

In the previous section, we have shown that the advanced driving alert system can provide significant vehicle energy/emissions reductions for a hypothetical vehicle at an intersection. In this section, we present the evaluation of the "traffic" energy/emission reductions of the ADAS in a simulation environment. Under this setting, a group of vehicles can be simultaneously simulated so that the impact of the ADAS on multiple vehicles can be evaluated. The following setup is used in our simulation:

- *Software*: We use PARAMICS, which is high-fidelity microscopic traffic simulation software [22]. One of the key advantages of PARAMICS is that it has an open architecture for integrating plug-in modules to perform specific simulation functions through an API. A plug-in for the ADAS is created and used to adjust vehicle trajectories. We also use the CMEM plug-in for the energy/emissions calculations.

- *Network*: The simulation network contains two successive signalized intersections as shown in Figure 4. The length of the approach link for the first intersection is about 1,900 meters. The length of the link between the two intersections is about 2,000 meters. The length of the departure link for the last intersection is 600 meters. Each of the links has three lanes. The approach links include two through lanes plus one shared lane.

- *Traffic signal*: The traffic signal is a fixed-time control with the cycle length of 120 seconds. The offset between the first and the second traffic signals is 30 seconds. The amber time is 3 seconds along the main street.

- *Vehicle demand*: We perform simulation runs with six levels of vehicle demand, as determined based on volume-to-capacity (v/c) ratio. The six v/c ratios include 0.25, 0.5, 0.6, 0.7, 0.8, and 0.85.

- *Vehicle fleet mix*: In order to be consistent with Section 5, we use only two types of vehicles in the simulation, i.e. LDV24 and LDV17, with a 50:50 split.

- *Dynamic parameters*: The speed limit on all links is set to 60 km/h, and the crawl speed (without stepping on the pedal) is assumed to be 8.1 km/h. For simplicity, we also assume that vehicles decelerate at the rate of 0.224 m/s^2 when the pedal is released, and 4.5 m/s^2 when applying hard braking (maximum deceleration of those two types of vehicles in PARAMICS). t_{entry} and t_{exit} for each vehicle can be calculated based on its instant velocity and acceleration.
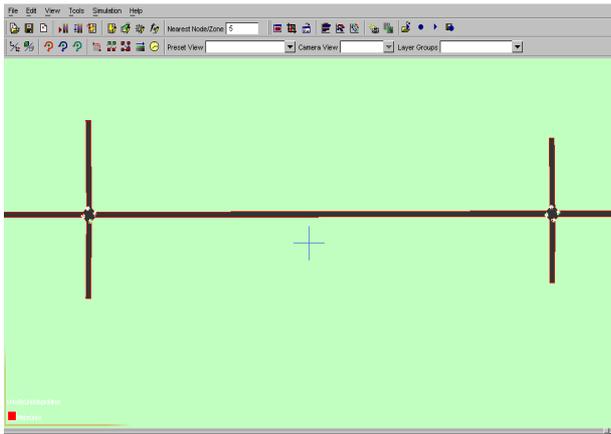
Figure 4. Simulation network in PARAMICS

In the simulation study, we set the maximum range of the VII communication (*r*) to be 300 meters, which is a typical range found for current dedicated short-range communication (DSRC) transmitters. This means that vehicles with the ADAS will only receive TSS information within 300 meters range of an intersection. It is expected that a longer DSRC range would allow drivers to adjust their driving behaviors sooner, which might result in even higher energy/emissions benefits. Further research can be done by varying such range and evaluating the associated benefits accordingly.

Once a vehicle is within the range of DSRC, the stopping probability for red signal is calculated using the formula in section 2. When the stopping probability is higher than a threshold γ, an ADAS alert will be sent to the vehicle. A set of threshold vales have been chosen for pre-test. 0.7 is selected for the rest of simulation runs due to better energy/emission results.

Only one direction of traffic is simulated. For each level of vehicle demand, the vehicles are released evenly across the first four 15-minute intervals of a one and a half hour simulation period. All vehicles are allowed to complete their trips along the simulated corridor and their corresponding fuel consumption and pollutant emissions are calculated for each link.

Two scenarios are simulated: 1) assume that all vehicles do not have the ADAS, and 2) assume that all vehicles have the ADAS (i.e. 100% technology penetration rate). For each scenario, the energy/emissions of each vehicle is calculated and aggregated over the DSRC range of the second approach link and then normalized by the number of vehicles. To be consistent with the evaluation method in Section 4, the results summarized in Table 2 are obtained by subtracting the emissions of the baseline trip, i.e. none stop trip (vehicle 1 in Figure 2.). It is noted that we did a few simplifications in the simulation study. First, we calculated the energy/emissions over the intersection-influenced range of the approach link without considering the energy/emissions along the departure link. Second, we simplified how drivers respond and

behave after receiving alerts in scenario 2 and assigned all vehicles to respond and apply a constant deceleration at the time when TSS is issued. On the other hand, the benefits of TSS can extend to the vehicles following the ADAS-instrumented vehicles even if they are not instrumented with ADAS, as the following vehicles will have to adjust their speeds according to those of the ADAS-instrumented vehicles.

According to Table 2, the vehicles with ADAS consume less energy and produce less CO_2 emissions at all levels of congestion. Figure 5 plots the percent reductions in fuel consumption and CO_2 emissions under different levels of vehicle demand. As shown in the figure, when the vehicle demand is low, e.g. v/c = 0.25, the fuel consumption and CO_2 emissions per vehicle can be reduced by about 1% and 4%, respectively. As the vehicle demand increases, fuel consumption can be saved by as much as 8% per trip, and CO_2 emissions can be reduced by about 7% in the case of v/c = 0.7, which is the peak for both energy and CO_2 emission reductions. This suggests that as traffic volume increases, more and more vehicles benefit from the ADAS. However, when the traffic volume is approaching the roadway capacity, vehicle queues start to form and propagate. These queues take up the space in the intersection-influenced areas; and thus, even the non-instrumented vehicles will have to slow down earlier. Therefore, the benefits of energy savings and emission reductions are compromised. However, it is noted that microscopic simulation software might not be able to accurately simulate the driver behaviors when traffic is close to or over saturation.
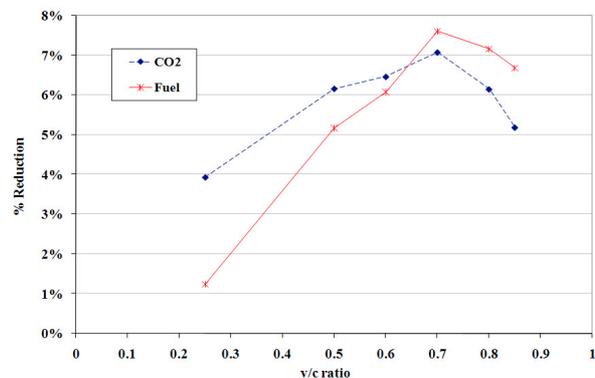

Figure 5. Reductions in energy/CO_2 emissions under different levels of vehicle demand

Table 2. Summary of normalized traffic energy/emissions results within DSRC range (grams/veh)

Scenario	Without alert system		With alert system	
v/c	Fuel	CO_2	Fuel	CO_2
0.25	19.6	58.8	19.4	56.5
0.50	28.2	80.5	26.7	75.6
0.60	31.0	87.6	29.1	82.0
0.70	33.1	93.2	30.6	86.6
0.80	35.0	98.1	32.5	92.0
0.85	36.0	101.0	33.6	95.7

7. Conclusions and Future Research

This paper proposes a new approach to influence driver behaviors through the provision of advanced information on traffic signal status for the benefits of vehicle energy/emission reductions at signalized intersections. In this study, the concept of this advisory system is modeled such that drivers are alerted to release their throttle earlier and decelerate gently for the purposes of reducing fuel consumption and emissions. According to the preliminary simulation study, the savings on fuel consumption can be as much as 8% and the reduction of CO_2 emissions can be around 7% for each vehicle when traffic is in medium congestion (v/c ratio of 0.7) under the current settings.

The paper also proposes a method of evaluating emissions at intersections using vehicle cruising trajectory as a baseline. Through both parametric and simulation evaluations, we have demonstrated that the potential benefits are significant and measurable for emissions and energy consumption by making traffic signal status information available to drivers. In addition, the safety co-benefits of this approach have also been briefly discussed.

Several future research tasks are being planned. First, the simulation evaluation will be extended to a longer corridor with multiple intersections. Also both directions of traffic at intersections will be simulated and the network-wide benefits will be determined. Second, a sensitivity analysis will be performed with respect to the communication range, and threshold for giving the driving alert, etc. Also, more complex algorithms of providing a recommended set of driving speeds rather than a simple alert will be explored. Third, the energy/emission benefits of the dilemma control at intersections will be evaluated and compared with those of the advanced driving alert system presented herein. Lastly, field experiments will be conducted and the field observation data will be analyzed to validate the benefits of the proposed concept.

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9. References

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