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Arterial Velocity Planning based on Traffic Signal Information under Light Traffic Conditions

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***Abstract*— Vehicle fuel consumption and emissions are directly related to the acceleration/deceleration patterns and the idling period. In order to reduce emissions and improve fuel economy, sharp acceleration/deceleration and idling should be avoided as much as possible. Unlike on freeways, traffic on signalized corridors suffers from increased fuel consumption and emissions due to idling and acceleration/deceleration maneuvers at traffic signals. By taking advantage of the recent developments in communication technology between vehicles and roadside infrastructure, it is possible for vehicles to receive the signal phase and timing information well in advance of approaching a signalized intersection. Based on this traffic signal information, we have developed arterial velocity planning algorithms that give dynamic speed advice to the driver so that the probability of having a green light is maximized when approaching signalized intersections. The algorithms are aimed at minimizing the acceleration/deceleration rates while ensuring that the vehicle never exceeds the speed limit, and that it will pass through intersections without coming to a stop. Using a stochastic simulation technique, the algorithms are used to generate sample vehicle velocity profiles along a 10-intersection signalized corridor. The resulting vehicle fuel consumption and emissions from these velocity profiles are calculated using a modal emissions model, and then compared with those from a typical velocity profile of vehicles without velocity planning. The energy/emission savings for vehicles with velocity planning are found to be 12-14%.**

Keywords: traffic signal; speed; algorithm; energy; emissions

I. BACKGROUND

A. Introduction

With the increasing awareness on global climate change, a lot of focus is being placed on lowering emissions and fuel consumption of motor vehicles. In order to achieve this, several researchers studied the dependence of fuel consumption and emissions of vehicles on its trajectory patterns [1, 2, 3, 4, 5]. For freeways, the relation between speed and acceleration/deceleration profiles with fuel consumption and emissions has been widely studied [6]. It was observed that in order reduce the fuel consumption and emissions, sharp accelerations/decelerations and idling time must be avoided as much as possible. Freeways are designed to have continuous traffic flow and therefore have no signals where the traffic is expected to slow down and idle on red. As a result, a vehicle on the freeway has no constraint on the time interval at which it reaches a particular point of the road. Therefore, it is relatively easy to design optimal speed algorithms (based on minimizing fuel consumption and emissions) by changing driving behavior. However, for the signalized corridor case, traffic suffers from increased delays due to idling at the traffic signals on red and increased fuel consumption and emissions due to inherent accelerations/decelerations required at the signals. Many empirical studies have shown a positive relationship between vehicle emissions and fuel consumption with the delays at traffic signals [7, 8, 9]. To date, most of the research focus has been placed on developing better traffic signal control algorithms that are both dynamic and adaptive, using information such as vehicle queue lengths.

In contrast, there has been little research on developing dynamic optimal speed advising algorithms on the vehicle side, based on traffic signal timing information. Rather than modifying the design of the signal timing controller at the traffic signals [10, 11, 12], optimal speed advice algorithms can be developed that satisfy the constraint of when a vehicle reaches the traffic signal location along with constraints to minimize the fuel consumption and emissions of the vehicle.

Several researchers have developed and studied optimal speed advising algorithms for arterial traffic (see, e.g., [7, 8, 13, 14, 15]). However, the majority are oriented towards giving optimal speed advice to the driver in order to improve *safety* by taking into consideration the current weather conditions, road grade, etc. None of these speed advice algorithms directly deal with minimizing emissions and fuel consumption while maintaining safety.

With the recent improvements in the communication between vehicles and the road infrastructure, it is now possible to get the current state and the timing of the traffic signals beforehand, prior to when it is in view of the driver. Based on this signal information, it is possible to give speed advice to the driver such that by the time the vehicle reaches a particular signal, it will be green. Along with the constraint that the driver should always see green, we can also add the constraints for reducing the fuel consumption and emissions to the algorithm and come up with optimal speed advice.

With the assistance of this algorithm, the driver doesn't have to worry about whether he/she can make it to the intersection before it turns red or not. As a result, unnecessary hard accelerations/decelerations can be avoided. Idling time at

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the intersection is also minimized, since the vehicle rarely stops. Based on the traffic signal information and the speed advice information, the driver knows what to expect ahead at the intersection. As a result there can be an increase in the safety at the intersections [15].

B. *Energy/Emissions vs. Vehicle Velocity*

It is well known that vehicle fuel consumption and emissions are strongly correlated to its modal operation, as commonly described by the instantaneous velocity and acceleration. For a signalized arterial corridor, a typical driving pattern consists of 1) a cruise mode around the speed limit while traveling down the road, 2) a deceleration mode when the vehicle may have to stop and idle at the intersection if the signal is red, and 3) an acceleration mode when a green light is given. From the perspective of reducing fuel consumption and emissions, these vehicles will be better off cruising at a speed lower than the speed limit so that they do not have to stop at the traffic lights at all. This is illustrated in Fig. 1. Using the steady-state activity data set and the methodology presented in [16], the vehicle fuel consumption in terms of grams per second is plotted against the cruising speed. For a corridor with the speed limit of 70 km/h, the time-weighted average fuel consumption between partly cruising at the speed limit and partly idling is represented by the blue dashed curve. This figure shows that a vehicle cruising at 35 km/h for 40 s consumes less fuel than the same type of vehicle cruising at 70 km/h for 20 s followed by idling for another 20 s.

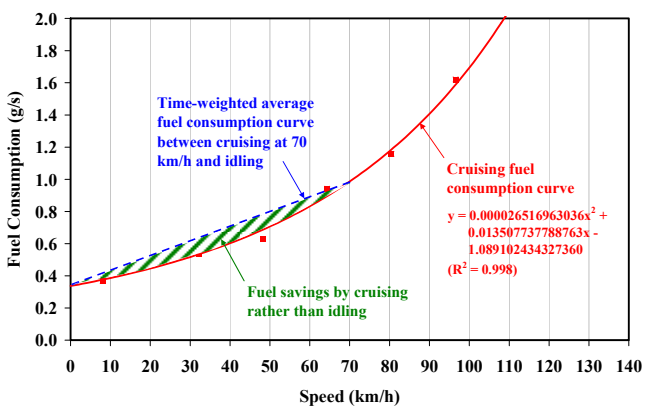

Figure 1. Fuel consumption vs. cruise speed.

II. METHODOLOGY

A. *System States*

In the development of an arterial velocity planning algorithm, we first define a system, which consists of vehicle(s), intersection(s), and traffic signal(s). At any point in time, t, the system states can be modeled with the following inputs:

- Distance to the next intersection when speed advice becomes available (D), which is typically 200-300 m if using dedicated short-range communication (DSRC) technology
- Current state of the signal (s) when the distance from a vehicle to the next intersection (d) $\leq D$; $s \in \{g, r\}$
- Vehicle velocity when first receiving speed advice (v_0)
- Time to the change of signal state (t_i) where $i \in \{g, r\}$

For simplicity, we include the amber phase of signal in the red phase. Therefore, when the vehicle first receives speed advice (i.e. $t = 0$), the current state of the traffic signal can be either red or green, as shown in Fig. 2. If the current state of the signal is red, then the next phase of the signal is green followed by red and so on (i.e. $t_g < t_r < t'_g$). If the current state of the signal is green, then the next phase of the signal is red followed by green and so on (i.e. $t_r < t_g < t'_r$).

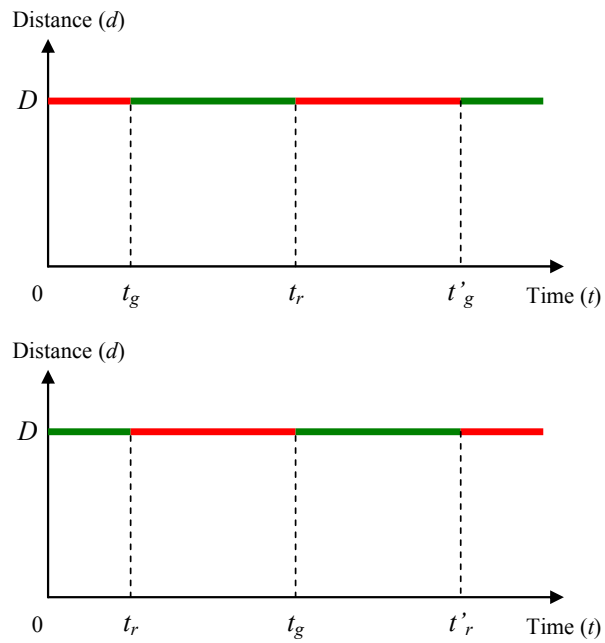

Figure 2. States of the vehicle-intersection-signal system.

B. *Algorithm Development*

The goal of the velocity planning algorithm is that a driver should always get a green signal when (s)he reaches an intersection. In order to minimize vehicle fuel consumption and emissions, this goal should be accomplished in the following manner:

- The vehicle should avoid acceleration/deceleration maneuvers as much as possible;
- The vehicle should cross an intersection as soon as possible;
- The vehicle's speed should never reach zero (i.e. no stop or idling); and
- Furthermore, it is also important that the vehicle's speed at any instant of time should never exceed the traffic speed or the roadway speed limit. Under light traffic conditions, it is reasonable to assume that the traffic speed is the same as the speed limit.

There are multiple ways that velocity planning algorithms can be developed. Three basic algorithms are presented below with increasing levels of sophistication.

1. Uniform velocity algorithm: This algorithm does not consider the initial velocity of the vehicle when receiving speed advice at time $t = 0$. It simply determines the targeted uniform velocity the vehicle should travel at by solving the optimization program below:

$$\max \quad v = \frac{D}{t_p} \text{ ; where } \begin{cases} t_p \in [t_g, t_r) \text{ or } t_p = t'_g, \text{ if } s = r \\ t_p \in (0, t_r) \text{ or } t_p = t_g, \text{ if } s = g \end{cases}$$

$$\text{s.t.} \quad v \le v_{\text{limit}}$$

Note that t_p is the time taken to reach the signalized intersection from the instant the car enters DSRC range of that intersection.

The drawback of this algorithm is that the transition from the initial velocity to the targeted uniform velocity is instantaneous, which is impractical.

2. Uniform acceleration algorithm: This algorithm is a one step improvement over the previous algorithm. It accounts for the acceleration or deceleration necessary to bring the vehicle from its initial velocity to the targeted speed, $v = v_0 + at$. Nevertheless, the disadvantage of this algorithm is that the maximum acceleration of the vehicle is set to a constant value irrespective of the velocity of the vehicle. This is also impractical considering that a vehicle can accelerate more when it is at a lower velocity than when it is at a higher velocity.

3. Power-constrained algorithm: This algorithm takes into consideration that a vehicle has the capability to accelerate more when it is at a lower velocity than when it is at a higher velocity by imposing an engine power constraint. It assumes that a vehicle cannot demand increased tractive power that is greater than the maximum possible power of the vehicle. The tractive power requirement ($P_{tractive}$) in kilowatts based on the vehicle dynamics (instantaneous velocity and acceleration) can be calculated as [17]:

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

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

C. Proposed Algorithms

As discussed earlier, when a vehicle first receives speed advice, the current state of signal could be either red or green. In each scenario, it could be that the vehicle's initial velocity is greater than the targeted speed, or vice versa. Therefore, the vehicle needs to accelerate or decelerate according to the system state at $t = 0$. If the current state of the signal is red, an appropriate acceleration or deceleration rate can be determined by solving the optimization program below:

$$\text{minimize} \quad |a|$$

$$\text{subject to: (i)} \ (v_0 t_1 + \frac{1}{2} a t_1^2) + (v_0 + a t_1)(t - t_1) = D$$

$$\text{(ii)} \ t_1 \le t$$

$$\text{(iii)} \ t_g \le t < t_r$$

$$\text{(iv)} \ \frac{P_{tractive}}{\eta_{tf}} + P_{accessories} \le P_{engine}$$

$$\text{(v)} \ v_0 + a t_1 \le v_{\text{limit}}$$

In Constraint (i), v_0 is the velocity of the vehicle at the instant it enters the DSRC range, t is the total time taken to reach the intersection, t_1 is the portion of time spent accelerating or decelerating with an acceleration or deceleration rate a, and $(t-t_1)$ is the portion of time spent traveling at an uniform velocity before reaching the intersection. Constraints (i) through (iii) ensure that the vehicle will get a green signal when arriving at the intersection. Constraint (iv) limits the acceleration to the maximum value allowed by the engine power. Constraint (v) limits the vehicle's velocity to the roadway speed limit. Once the appropriate acceleration or deceleration rate has been determined, the corresponding speed at any time t can be back-calculated and provided to the driver.

On the other hand, if the current state of the signal is green, the optimization may need to be performed twice. The first optimization will aim at guiding the vehicle through the intersection within the current green period; and thus, the constraint (iii) in the above optimization program will need to be replaced by $0 \le t < t_r$. If it fails to find a feasible solution, then the second optimization will be performed to guide the vehicle through the intersection at the first instant of the next green period. That is, the constraint (iii) will be $t = t_g$. Then, the solution can be used to back-calculate the recommended speed for the driver.

III. Stochastic Simulation

In this section, we apply the algorithms presented in Section II to generate vehicle velocity profiles of a vehicle traversing a hypothetical 10-signalized intersection corridor.

We use stochastic simulation to capture the variability of infrastructure-related parameters and the randomness of traffic-related parameters. The set up of the simulation is described below:

- Link length (L): We create a hypothetical 10-signal intersection corridor with the length of the links between two consecutive intersections being 500-600 m. The length of each link is randomly drawn from a uniform distribution.
- Speed limit (v_{limit}): The speed limit on all links is set to be 70 km/h.
- DSRC range (D): We assume that vehicles will only receive speed advice from the velocity planning when they are within the DSRC range as measured from the signal ahead. The range of current DSRC transceivers in the market is typically 200-300 m, so we set this parameter as 200-300 m. The DSRC range at each intersection is randomly drawn from a uniform distribution.
- Traffic signal: In this paper, we are only concerned with vehicles traversing the created arterial corridor. Therefore, we simply use a two-phase signal at all the intersections. Since we deal with light traffic condition in this paper, we assume an actuated signal strategy with the total green period (i.e. minimum green time + extension green time) being modeled as a uniform distribution, $t_g \sim U(\alpha, \beta)$, where α is 40 s and β is 50 s. Similarly, we assume the same distribution of the total green time for the cross street traffic. Thus, the total red time on the main arterial corridor is also modeled as $t_r \sim U(\alpha, \beta)$.
- Vehicle engine power (P_{engine}): The simulation is performed for a typical mid-sized sedan car. As discussed earlier, the engine power of the vehicle is used to determine the maximum acceleration at different speeds, given that road grade of all the links in the simulated corridor is assumed to be zero.

With these simulation settings, we run the velocity planning algorithms 30 times to determine speed advice for a vehicle traversing the corridor with various link lengths and DSRC ranges as well as under random signal phase and timing as dictated by the actuated signal control. For each run, we extract the vehicle velocity profile across the entire corridor. An example of the velocity profile and the associated acceleration/deceleration profile is shown in Fig. 3. Also shown in Fig. 3 is the distance-time diagram of the vehicle as well as the signal phase and timing at each intersection for that simulation run.

For each simulation run, we also create the vehicle velocity profile for a baseline case (i.e. for vehicles that do not have velocity planning) for comparison purposes. As shown in Fig. 4, the velocity profiles of these vehicles are different. We assume a typical driving behavior along a signalized corridor where the drivers attempt to cruise at or around the speed limit until they are visually aware of the traffic signal ahead (assumed to be at 75 m before the intersection). If the signal is green, the drivers simply keep the cruise speed while crossing the intersection. If the signal is red, the drivers slow down the vehicles to a stop and then idle. Once the signal turn green, they accelerate the vehicles back to the speed limit on the link. This driving behavior is applied at every intersection in the baseline case.

IV. Energy and Emissions Evaluation

This section presents the evaluation of the energy and emissions benefits of the velocity planning algorithms based on the generated vehicle velocity profiles. The evaluation is conducted using a state-of-the-art modal energy/emissions model described below.

A. Comprehensive Modal Energy and Emissions Model

The comprehensive modal emissions model (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 monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC), and nitrogen oxides (NO_x) based on different modal operations from 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. Each component is modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to the vehicle type, engine, emission technology, and level of deterioration [17]. 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 rigorously validated using various data sets and techniques. Backcast validation results using dependent emission data sets (those used in the development of the model) indicate satisfactory model performance [17, 20]. A forecast validation effort using independent emission measurement results (independent in both vehicles and driving cycles) also shows that the CMEM estimates are well within the range of the measurement results [21].

B. Energy and Emissions Results

The sample vehicle velocity profiles generated in the previous section are used as inputs for CMEM 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 (e.g. passenger cars) with more than 100,000 miles, and 2) LDV17, which is a Tier 1 light-duty truck with a loaded weight of 3,751-5,750 lbs (e.g. pick-ups, SUVs). These two CMEM vehicle categories represent the largest proportion in the 2005 fleet mix of southern California [22].

For comparison purposes, the energy and emissions for a baseline case (i.e. for vehicles that do not have speed advisement) are also calculated for the same vehicle categories. Table 1 shows the energy and emissions comparison results

between the vehicles without and with velocity planning for the two CMEM vehicle categories. The results for both cases are given in terms of the average value and the standard deviation of the sample set of 30 velocity profiles. According to Table 1, the vehicles with velocity planning consume about 12% less fuel and produce about 14% less CO_2 emission. These results are the same for both vehicle categories.

C. *Travel Time*

The travel time (TT) on an average is 1.06% shorter for the vehicles with velocity planning as compared to the vehicles without velocity planning. However, this difference is not statistically significant at 5% alpha.

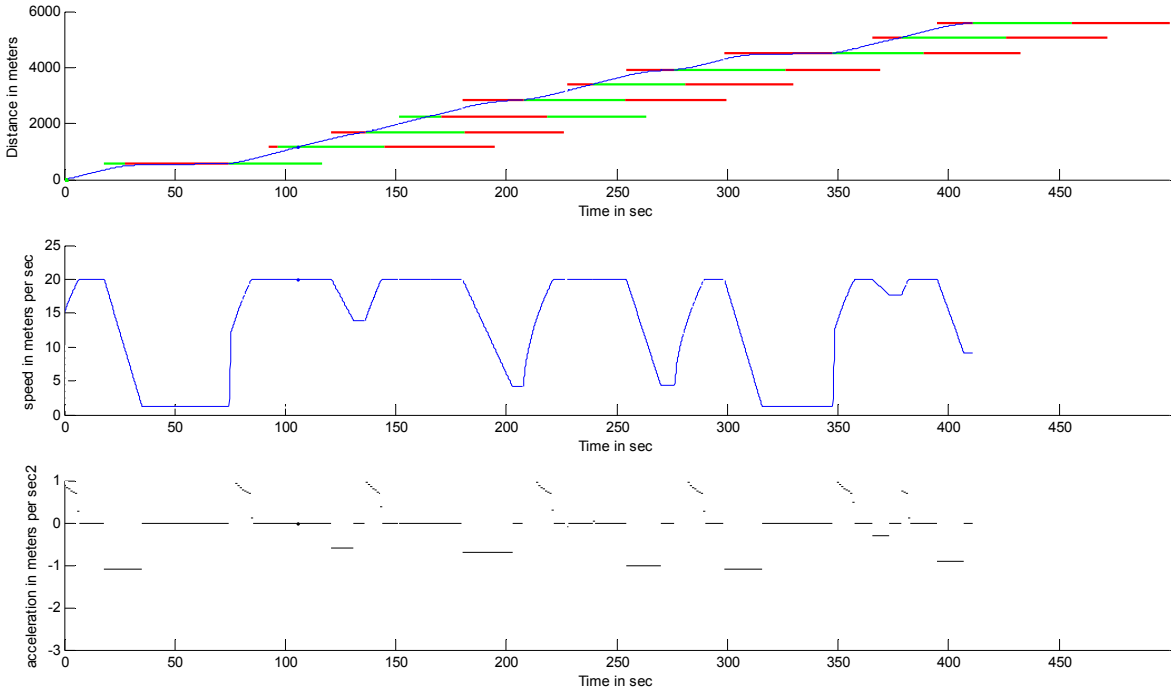

Figure 3. Sample trajectory of vehicle with velocity planning.

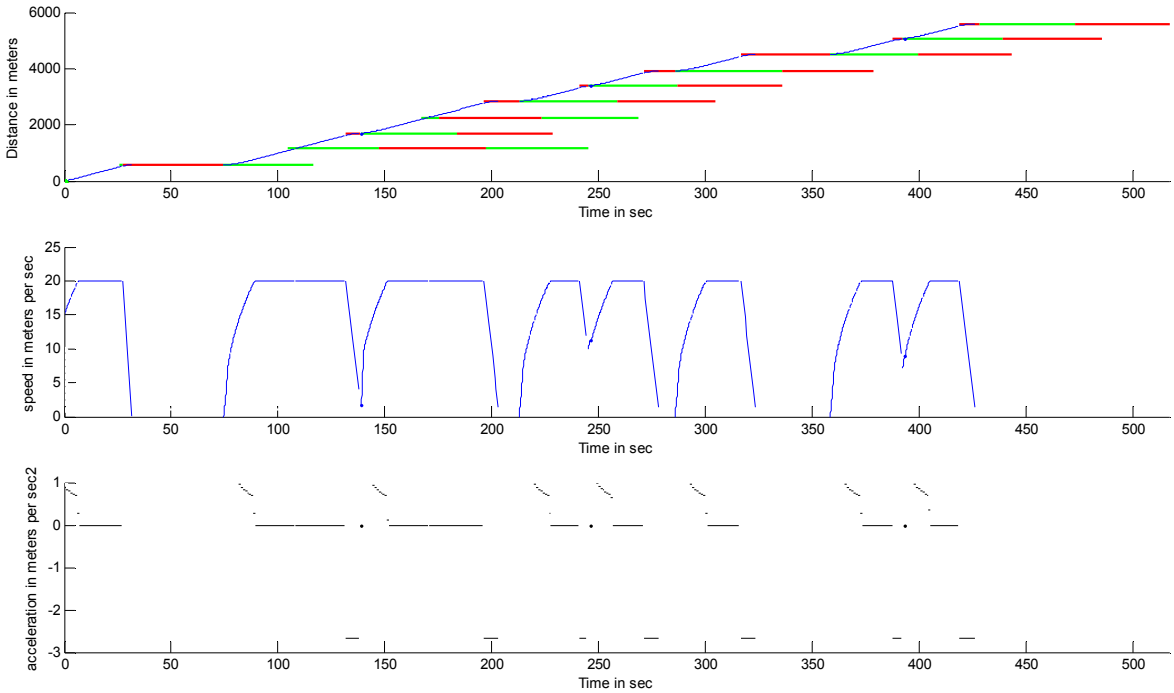

Figure 4. Sample trajectory of vehicle without velocity planning.

V. CONCLUSIONS AND FUTURE WORK

Fuel consumption and emissions are directly related to the acceleration/deceleration patterns of the vehicles traveling on the arterial and the idling period while stopped at traffic signals. In order to reduce emissions and improve fuel economy, sharp acceleration/decelerations and the idling must be avoided as much as possible. Unlike in the freeways, traffic on the signalized corridors suffers from inherent acceleration/deceleration maneuvers at the traffic signals and idling. By taking advantage of the recent developments in communication between vehicles and road infrastructure, it is possible to obtain the signal phase and timing information in situ. Based on this real-time signal information, we have initially developed an algorithm that can provide dynamic speed advice to the driver such that the driver can adjust his/her speed so that the probability of passing through a green light without stopping is maximized. In addition, the speed transitions can be made smoothly to minimize emissions from sharp accelerations/decelerations. Based on the algorithms presented in this paper, the energy/emission savings for vehicles with velocity planning are found to be 12-14%.

TABLE 1. ENERGY AND EMISSIONS COMPARISON

LDV24	**Without**		**With**		**% Diff. in Avg.**	***p*-value of *t*-test**
	Avg.	*S.D.*	*Avg.*	*S.D.*		
Fuel (g/mi)	118.3	13.2	103.8	9.3	-12.3	8.7E-06
CO_2 (g/mi)	371.0	41.2	318.8	25.3	-14.1	3.2E-07
TT (sec)	456.7	60.7	451.9	56.9	-1.06	0.635

LDV17	**Without**		**With**		**% Diff. in Avg.**	***p*-value of *t*-test**
	Avg.	*S.D.*	*Avg.*	*S.D.*		
Fuel (g/mi)	151.0	17.4	132.4	12.4	-12.3	1.6E-05
CO_2 (g/mi)	476.8	55.0	411.7	35.4	-13.7	1.5E-06
TT (sec)	456.4	60.6	448.9	61.9	-1.06	0.635

In subsequent work, it is planned to expand this research by also incorporating additional information along the corridor (e.g., traffic speed, density, and flow, as well as other vehicle travel parameters). It is expected that this improved algorithm will have better energy/emissions performance during conditions of higher traffic density. As another phase of work, the developed algorithms will be taken a step further by also providing feedback from the vehicles to the traffic controllers. The initial research phases were primarily focused on vehicles adjusting their trajectories based on known infrastructure conditions. It is expected that even further energy/emission benefits will be possible by making timing adjustments to the signal controllers that will maximize the energy and emission parameters.

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