

Research Article

Dynamic Eco-Driving on Signalized Arterial Corridors during the Green Phase for the Connected Vehicles

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Inappropriate driving behaviours can result in additional fuel consumption and emissions. Drivers can be informed of the accurate signal phase and timing (SPaT) and distance information of the current intersection and downstream intersections via vehicle-to-everything (V2X) communications. The real-time information has been utilized to assist drivers in taking reasonable manoeuvres and gain lots of benefits on fuel consumption and emissions in some existing studies. In order to cooperatively address the optimization problem on the signalized arterial corridors, this paper presents an eco-driving optimization model considering preceding SPaT and position information. This model can be applied to pass two successive traffic signals cooperatively during green phase. In this study, a multi-stage optimal approach is proposed to minimize the fuel consumption. Field experiments are carried out for comparative analysis between the connected vehicle with speed advisory and the uninformed vehicle without speed advisory. The results indicate that the fuel saving of the connected vehicle guided by the dynamic optimization algorithm shows significant improvement. In addition, the rolling optimization among three signalized intersections is conducted and the results show that a considerable improvement can be obtained compared with the one-by-one optimization.

1. Introduction

In the urban road environment, intersections with traffic signals play a vital role that make significant impacts on the traffic flow. In general, making full use of the green time and passing the intersection within the green time as much as possible are considered as promising methods to improve the road throughput. Therefore, signal optimization at intersection and speed advisory for the vehicles have appealed much attention since 1950s. By adjusting the signal timing, the vehicles have larger probability to arriving the intersection during green time, and when applying to the road network, signal timing depends on the traffic demands to reach user equilibrium (UE) or system optimal (SO). In the other hand, based on the fixed signal timing, altering the speed of approaching vehicles can increase the utilization of green time, alleviate the stop-and-go wave thus reduce the time delay at intersections.

There have been majority of studies that dedicated to coordinated signal control under the urban road network [1, 2] to mitigate the traffic congestion. MAXBAND [3] and MULTIBAND [4] are regarded as two efficient methods to establish the green wave band for vehicles to reduce the delay and numbers of stops on arterials signalized intersections. Later, the design and control of coordinated signals at urban network level have grown up considering the demand assignment [5–10]. The research findings can provide efficient measure for the traffic planning and management department to assign the signal timing under urban road.

Although it is an interesting area to smooth the traffic flow in the term of roadside infrastructure, the control of in-vehicle system is also attractive to explore the widely used approach to improve the traffic conditions. Hence, many scholars have conducted lots of researches on speed guidance models and route choice models for drivers accounting for the traffic

security. The route choice based on the macroscopic traffic status on the network level has appealed much concern for drivers to get to the destination effectively [11, 12]. When it comes to the microscopic traffic flow, the hard acceleration, deceleration and unnecessary idling have been indicated to make a negative influence on the traffic efficiency, which can lead to additional fuel consumption and exhaust emissions [13–15]. In urban traffic system, due to blurred vision or distracting attention, drivers could not acquire the accurate signal phase and timing (SPaT) and distance information, which will generally lead to inappropriate driving behaviors, thus cause extra fuel consumption. Fortunately, vehicle-to-everything (V2X) communications have been widely applied to the analysis and construction of urban traffic scenarios [16–18]. It is entirely possible to receive the SPaT and distance information from hundreds of meters away the traffic signals relying on the reliable communication technology, which is beneficial for drivers to make more accurate decisions.

Early researchers focused on sending SPaT information to the upcoming vehicles through variable message sign (VMS). Tang et al. [19] presented an extended car-following model with consideration of remaining green time and then evaluated the fuel consumption and emissions at a signalized intersection. Sanchez et al. [20] proposed a modified intelligent driver model that provides the lead car with an optimized trajectory based on known traffic signal status. Stevanovic et al. [21] assessed the fuel consumption and emissions via adjusting signal timing. Wu et al. [22] alerted the drivers using the real-time traffic signal status information and improved the fuel consumption economy. Mahler and Vahidi [23] proposed a probabilistic predictive algorithm to predict the upcoming SPaT information to reduce the idling at red time. Suzuki and Horiuchi [24] adjusted signal control parameters and minimized CO₂ emissions or delay time. Chen et al. [25] presented a dynamic speed and dynamic signal strategy to provide drivers with speed guidance and adjust the signal timing to ensure that the vehicles travel through the intersection without stops. These researches studied that the vehicles pass an intersection during the green light considering signal timing information via VMS.

Some scholars dedicated to providing optimal speed advice with less stops or acceleration/deceleration at signalized intersections. Traford et al. [26, 27] developed an advisory speed sign system, which can instruct drivers to go through traffic signals with less stops on arterial corridors and gain the fuel benefits. Malakorn [28] explored a new method that combines the CACC technology and SPaT information with the target function of reducing acceleration and idle time. Asadi and Vahidi [29] proposed a predictive cruise control model and an optimization-based control algorithm with traffic signal information, but the control targets include the deviation from the target velocity and the use of brake force. In these studies, acceleration, deceleration or idling time are regarded as the optimization objectives, but these factors can not directly reflect the fuel consumption and emissions.

With the presentation of some fuel consumption model, researchers have paid attention to addressing the problems based on cost function of the fuel consumption. Rakha and Kamalanathsharma [30] developed a framework to refine fuel economy of both the upstream and downstream of individual signalized intersection using V2I communication. Mensing

et al. [31] studied longitudinal driving behavior considering traffic constraints and optimized velocity trajectory with minimal fuel. Kamalanathsharma [32] presented a practical multi-stage dynamic optimization with the objective function of minimizing fuel consumption at a signalized intersection. Rakha and Kamalanathsharma [33] developed an application called eco-cooperative adaptive cruise control (ECACC), which can receive the SPaT information using V2I communication to optimize speed trajectory for single vehicle. These researches studied speed guidance by minimizing fuel consumption or emissions only at isolated intersection.

Only a few researchers have focused on dynamic speed advisory strategy in real time at signalized arterial corridors during recent years. Abu-Lebdeh et al. [34–36] used dynamic speed control at signalized arterial to give drivers speed guidance and moderate traffic congestion. But they did not consider the fuel efficiency and emissions directly. Sun et al. [37] proposed a robust eco-driving control considering random red light duration. Tang et al. [38] proposed a speed guidance strategy based on car-following model to study the driving behavior and fuel consumption on multiple signal lights. Giovanni et al. [39] proposed velocity pruning algorithm to identify the feasible region and discretizing the region to find shortest routing as the fuel-optimal profiles. Mandava et al. [40] developed a dynamic velocity planning algorithms considering traffic signal information via V2I communication. Haitao et al. [41] presented a dynamic velocity planning algorithm and predefined the trigonometric velocity profiles. Wu et al. [42] proposed a dynamic speed advisory model for a platoon and the findings show that cooperative optimization of all vehicles in the platoon can get better benefits.

From the literature review, we can observe that the research on speed advisory went from VMS display to on-board display at isolated intersection then to arterial corridors. However, most studies just presented speed planning algorithm by building some rules and then evaluating the fuel/emissions efficiency, other than formulated a relationship between the speed trajectory and fuel consumption directly. Moreover, though some efforts on speed advisory at arterial corridors are made to guide the vehicles to pass more than two traffic lights, the cooperative of two continuous intersection hasn't been considered yet, which can avoid that the vehicles fails to pass the subsequent intersection after passing the current intersection.

The optimization-based speed advisory could provide a more accurate, reliable and scientific guidance. Thus, the contribution of this paper is presenting a dynamic speed optimization approach via minimizing the fuel consumption to instruct the vehicles to go through two adjacent intersections cooperatively under the fixed signal timing. Another novelty of this paper is the rolling optimization of every two-intersection group, which can be applied to the signalized arterial corridors with number of intersections iteratively.

In the next section, the methodology including the system architecture, traffic scene analysis and optimization process are introduced. Then we build an eco-driving optimization model in the third section. In the fourth section, we propose the speed profile optimization algorithm. In fifth section, experiments and simulations are conducted to verify the validity of the proposed dynamic optimization algorithm. In Section 6, conclusions and further research focus are included.

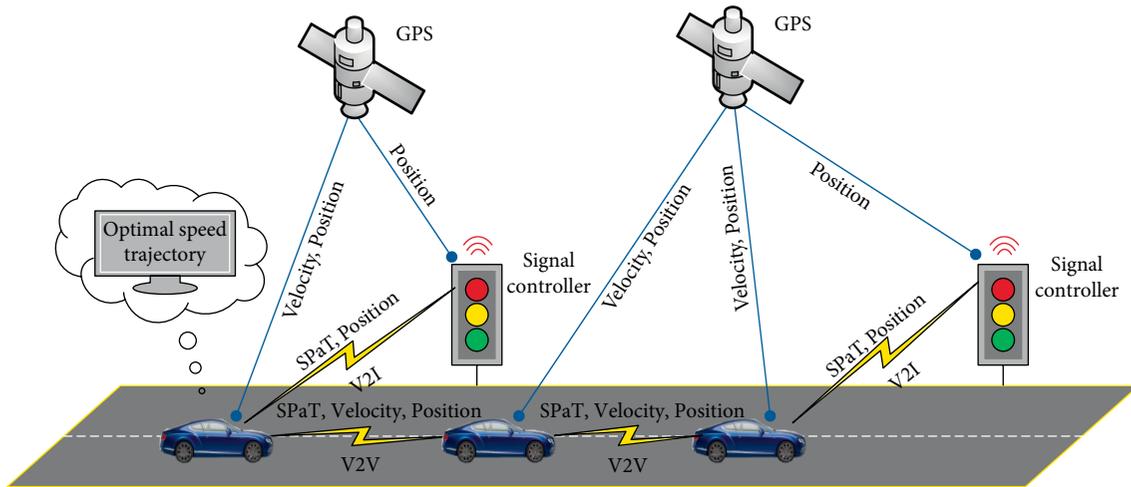


FIGURE 1: Communication layout of the trip.

2. Methodology

2.1. System Architecture. The real-time SPaT and distance information is essential for the connected vehicles to traverse the signalized arterial corridors on the urban road. With the development Internet of Vehicles technology, the connected vehicles can receive relative information from other vehicles (via vehicle-to-vehicle, V2V communication) and roadside infrastructures, such as signal controller (via vehicle-to-infrastructure, V2I communication). When the connected vehicles travel into the communication range of dedicated short range communications (DSRC), the signal controller can deliver the SPaT information of two intersections to the connected vehicles. As for the connected vehicles outside the communication range, the SPaT information can be obtained by V2V communication. The position and velocity of the connected vehicles, as well as the position of the two intersections can be acquired by global positioning system (GPS) device. The dynamic optimization algorithm loaded on the on-board computer can show the optimal speed trajectory to drivers. The complete layout of communication is shown in Figure 1.

The following assumptions are made:

- (1) The traffic signals in this study follow the fixed timing.
- (2) The connected vehicles can obtain the SPaT information, position and velocity information accurately.
- (3) The connected vehicles can follow the speed advisory provided by the optimization model strictly.
- (4) The gradient of road at any time is specified as zero.

2.2. Scene Analysis. As shown in Figure 2 (dotted lines show the trajectories without speed adjustment, solid lines show the trajectories with speed adjustment), when the test vehicles are arriving at signalized arterial corridor with two successive intersections and the current phase is green, there are four different scenes and are described as follows:

Scene 1. The time to red of the first intersection and signal timing of the second intersection are sufficient for the vehicles

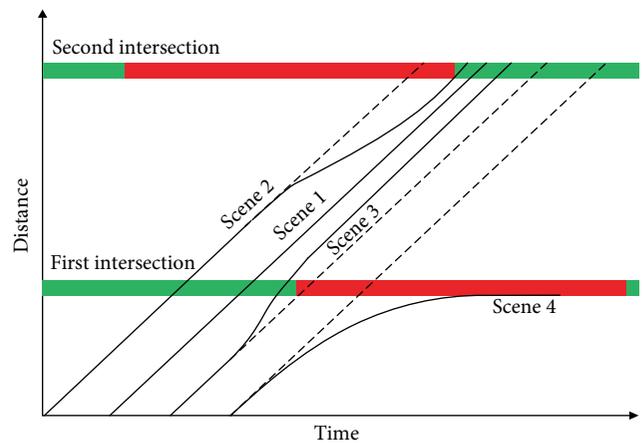


FIGURE 2: Possible trajectories when arriving at the intersections.

to go through the intersections without changing their speed. The optimal action is cruising to pass the intersections.

Scene 2. If the vehicles can pass the first intersection but can not pass the second one, without V2X communications, the vehicles would keep current speed and stop at the second stop line until the green light comes again. However, if the vehicles can receive accurate information, decelerating to pass the intersections can yield fuel saving due to the reduction of long idling time and unnecessary start-up loss time.

Scene 3. If the time to red of the first intersection is not sufficient for the vehicles to pass the first intersection without speed adjustment, the vehicles need accelerate to pass it under safety and then adjust to a feasible velocity to travel through the second intersection. At least one complete stop could be prevented in this scene. The fuel consumption resulting from idling and accelerating from zero to initial speed could be avoided.

Scene 4. If there is no possibility to pass the first intersection even if the vehicles accelerate to the maximum speed under safety, they have to stop and wait for the next green light.

Scenes 2 and 3 required a simulation/optimization algorithm and provide most flexibility as far as fuel savings are

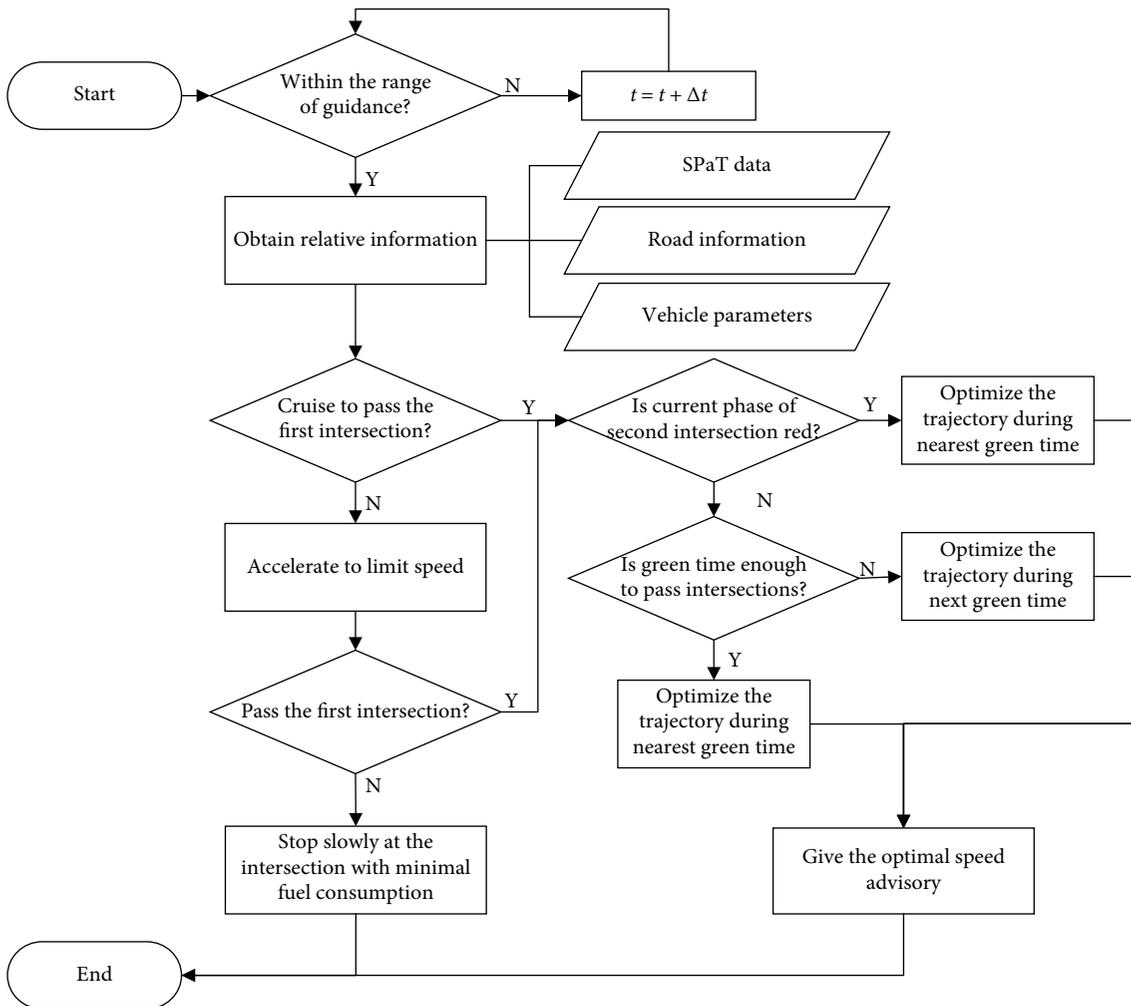


FIGURE 3: Optimization logic of the algorithm.

concerned. And the trajectories of the test vehicles are subject to some factors: (1) Road speed limit (Speed at any time must not exceed the maximum allowable speed). (2) Temporal constraints (vehicles must pass the intersections during the green phase). (3) Spatial constraints (vehicles must travel fixed distance from the time when they receive the SPaT and distance information to the time when they pass the two intersections). (4) Manoeuvres to change speed should be as gentle as possible. In addition, the acceleration and deceleration should satisfy vehicle dynamics.

2.3. Optimization Process. When the test vehicle travels into the communication range, SPaT data, road information and vehicle parameters would be acquired to calculate the optimal speed trajectory. The algorithm calculates the fuel-optimum speed profile and provides speed advisory. Optimization is updated every Δt to produce optimal speed trajectory and realize dynamic adjustment. The optimization logic of the algorithm (as shown in Figure 3) is described as follows:

Step 1. Collect SPaT data, road information and vehicle parameters, including traffic signals status, current speed and distance to the intersections.

Step 2. Calculate the time that the vehicle cruises to the first intersection according to the distance to the first intersection and current speed. If the vehicle can not pass the first intersection with current speed, turn to Step 3. Otherwise, turn to Step 4.

Step 3. Judge whether the test vehicle could pass the first intersection with the maximum allowed speed. If not, the vehicle must stop at the stop line. Otherwise, turn to Step 4.

Step 4. If the traffic signal of the second intersection is red, the optimization algorithm would optimize the trajectory to let vehicles go through the second intersection during the forthcoming green light with the consideration of global fuel consumption. Otherwise, turn to Step 5.

Step 5. If the traffic light of the second intersection is green and the remaining green time is enough to cross, provide optimal speed advisory for the vehicle to pass the intersection. Otherwise, turn to Step 6.

Step 6. If the remaining green time is not sufficient to cross the intersection, optimize the speed trajectory to let the vehicles pass the second intersection during the green time of next signal cycle.

In addition, too low speed is not acceptable as a result of out of drivers' expectations for efficiency and comfort whilst too high speed at the intersection is not available because of the safety and complexity near intersection.

3. Eco-Driving Optimization Model

The eco-driving optimization model is used to compute the fuel-optimum speed profile for the test vehicle when it traverses two successive signalized intersections. The dynamic speed advisory can be shown to drivers in real time. This model employs the virginia tech comprehensive power-based fuel consumption (VT-CPFM) model, which is proposed in [43, 44] to estimate fuel consumption for various alternative speed profiles. The VT-CPFM model is formulated as follows:

$$F(t) = \begin{cases} \alpha_0 + \alpha_1 P(t) + \alpha_2 P^2(t) & \forall P(t) \geq 0, \\ \alpha_0 & \forall P(t) < 0 \end{cases}, \quad (1)$$

where, $F(t)$ is the fuel consumption rate (L/s); $\alpha_0, \alpha_1, \alpha_2$ are the model constants, which are calibrated with different types of vehicles, corresponding values are 4.89E-04, 4.29E-05, 1.00E-06 (the values of the parameters are taken from the literature [45], hereafter); $P(t)$ is the instantaneous power at time t , which is formulated in Equation (2).

$$P(t) = \frac{R(t) + 1.04ma(t)}{3600\eta_d} v(t), \quad (2)$$

where, m is the mass of the vehicle (kg); $a(t)$ is the acceleration at time t (m/s^2); η_d is the driveline efficiency, $\eta_d = 0.75$; $v(t)$ is the speed at time t (m/s); $R(t)$ is the total resistance force at time t (N), which is formulated as Equation (3).

$$R(t) = \frac{\rho}{25.92} C_d C_h A_f v^2(t) + mg \frac{C_r}{1000} (c_1 v(t) + c_2) + mgG(t), \quad (3)$$

where, ρ is the air density at sea level, $\rho = 1.2256 \text{ kg/m}^3$; C_d is the drag coefficient of the vehicle, $C_d = 0.3$; C_h is the altitude correction factor, $C_h = 0.95$. A_f is the frontal area of the vehicle (m^2); g is the gravitational acceleration $g = 9.8067 \text{ m/s}^2$; C_r and c_2 is the rolling resistance parameter, $C_r = 1.25$ and $c_2 = 6.10$; c_1 is the rolling resistance constant, $c_1 = 0.0438 \text{ h/km}$; $G(t)$ is the gradient of road at time t .

The mathematical formulation for the optimal problem consists of two stages: (i) first stage: the fuel consumption before the first intersection, (ii) second stage: the fuel consumption after the first intersection. Figure 4 depicts the two stages of the optimization problem. The subscripts f and s represent the first intersection and second intersection, respectively. The definitions of parameters marked in Figure 4 are shown in Table 1.

The fuel consumption rate at time t can be calculated according to VT-CPFM model, which is closely relative to speed and acceleration. To obtain the accumulated fuel consumption of the whole process, an integration of fuel consumption rate is constructed from the time that the vehicle arrives at the communication range to the time that the vehicle passes the second intersection. Therefore, the

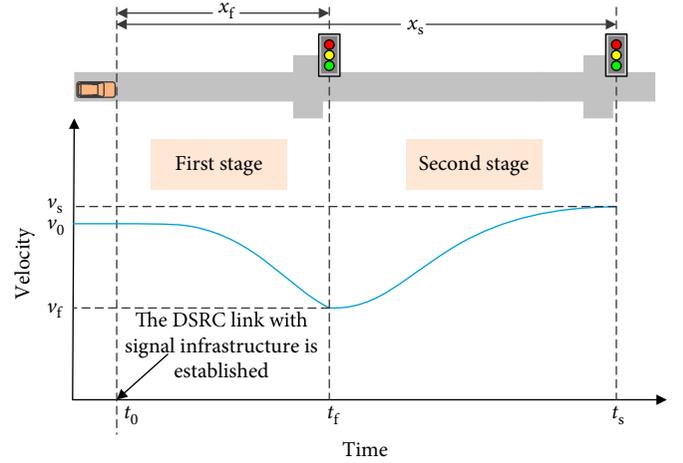


FIGURE 4: Two stages of speed optimization problem.

TABLE 1: Parameters/variables and corresponding definitions.

Parameters	Corresponding definitions	Unit
T_R	Red time of the signal cycle	s
T_G	Green time of the signal cycle	s
t_{rf}	Time to red of the first intersection	s
t_{gs}	Time to green of the second intersection	s
t_{rs}	Time to red of the second intersection	s
t_0	Initial time	s
x_f	Distance to the first intersection	m
x_s	Distance to the second intersection	m
v_0	Initial velocity	m/s
v_{lim}	Speed limit	m/s
Variables	Corresponding definitions	Unit
t_f	Time to the first intersection	s
t_s	Time to the second intersection	s
v_f	Velocity at the first intersection	m/s
v_s	Velocity at the second intersection	m/s

objective function of the optimization problem is shown in Equation (4).

$$F_{acc} = \min \int_{t_0}^{t_s} F(t) dt = \min \left(\int_{t_0}^{t_f} f(v(t)) dt + \int_{t_f}^{t_s} f(v(t)) dt \right), \quad (4)$$

where, F_{acc} is the accumulated fuel consumption (L), $v(t)$ is the control variable, $f(v(t))$ is a function over $v(t)$ derived from the Equations (1)–(3).

Subject to:

$$\int_{t_0}^{t_f} v(t) dt = x_f, \quad (5)$$

$$\int_{t_f}^{t_s} v(t) dt = x_s - x_f,$$

$$a_{min} \leq a(t) \leq a_{max}, \quad (6)$$

$$0 \leq v(t) \leq v_{lim},$$

$$\begin{aligned}
t_f &\in [0, t_{rf}] \\
t_s &\in \begin{cases} [\max(t_f, t_{gs}), t_{gs} + T_G] \cup [t_{gs} + kT, t_{gs} + kT + T_G], & \text{current signal} = \text{red} \\ [t_f, t_{rs}] \cup [t_{rs} + T_R + (k-1)T, t_{rs} + kT], & \text{current signal} = \text{green} \end{cases} \quad k \in \{1, 2, \dots, N\}.
\end{aligned} \quad (7)$$

Constraint 5 ensures that the distance of first stage from t_0 to t_f should be x_f and the distance of the second stage from t_f to t_s should be the distance between the two intersections, i.e. $x_s - x_f$. Constraint 6 specifies the lower and upper bound of acceleration and velocity due to the demand for vehicle dynamic, traffic efficiency and drivers' comfort.

The constraint 7 ensures that the time to pass the first intersection should be in the range of zero to the time to red of the first intersection. Time to the second intersection t_s depends on the traffic light of the second intersection. Whether the traffic light is red or green, the algorithm need judge if the vehicle can pass the intersections during nearest green time in compliance with all constraints. Otherwise, the constraint on t_s is extended to the next green indication range.

4. Speed Profile Optimization Algorithm

This paper proposes a dynamic optimization algorithm to obtain the optimal speed profile based on proposed eco-driving optimization model last section. Based on the fuel consumption model, instantaneous acceleration and velocity are pre-requisite to estimate the fuel consumption. As mentioned in Section 3, we formulated the speed profile optimization model for the two stages. The initial and final velocities of each stage are easy to be identified. Accounting for the relationship between velocity, acceleration and distance, we transform the dynamic optimization problem into an approximate solution of the linearization with six decision variables including $[s_1, s_2, v_f, v_s, t_f, t_s]$. The velocity function over time is formulated as Equation (8).

$$v(t) = \begin{cases} v_f - (v_f - v_0) \times e^{-s_1 t} & t \leq t_f, \\ v_s + (v_f - v_s) \times e^{-s_2 (t-t_f)} & t < t_f, \end{cases} \quad (8)$$

where, the variables s_1 and s_2 are coefficients of the linearization solution. Proceeding from the kinematics equations, the acceleration is derived from the differential of velocity as shown in Equation (9).

$$a(t) = \begin{cases} (v_f - v_0) \times s_1 \times e^{-s_1 t} & t \leq t_f, \\ (v_f - v_s) \times (-s_2) \times e^{-s_2 (t-t_f)} & t < t_f, \end{cases} \quad (9)$$

Due to the continuous nonlinear model, this dynamic optimization problem is identified as nonconvex [29]. This constrained optimization problem is solved by the 'fmincon' solver in the MATLAB optimization toolbox. Optimal velocity trajectory is obtained through multiple iterations. The process costs about 0.89 s on average to give a profile when other unrelated application is all closed using a desktop computer (Lenovo TianYi 510 Pro with Intel (R) Core (TM) i5-7400 3.00 GHz CPU and 8.0 GB memory), which could be applied to provide real-time speed advisory.

5. Simulations and Field Experiments

Numerous simulations and experiments are utilized to demonstrate the significance of the proposed eco-driving optimization model and dynamic speed profile algorithm. We first conducted simulations and field experiments to illustrate the effect of the connected vehicle compared with the uninformed vehicle. Then, three signalized intersections are extended to apply the rolling optimization to test the advantages of the proposed model under multiple intersections. 2011 Honda Accord is specified as the test vehicle in these simulations based on the study [45], whose mass is 1487 kg and the frontal area is 2.12 m².

5.1. Verification of Effectiveness. In order to test the effectiveness of the algorithm between the connected vehicle and the uninformed vehicle, some simulations were conducted to emulate the connected vehicle and lots of field experiments were carried out to simulate the uninformed vehicle. To make the experiment performance more realistic, a driver who holds more than 6-year driving license and more than 5000 kilometres driving experience on average every year, was employed to perform the experiments to obtain the trajectory of the uninformed vehicle.

Connected and Automated Vehicle (CAV) Test Field of Chang'an University was selected to conduct the field experiments. Positioning accuracy of GNSS/INS integration system (OXTS RT2000) is up to decimetre and rate is 10 Hz. It is mounted on the test vehicle to obtain the data including time, velocity, position and latitude and longitude, which is presented at our previous work [46]. Hence, to enhance the comparability, the reference time interval in the simulations is set to 0.1 s.

Two signalized intersections in the northwest (point F shown in Figure 5) and southwest (point S shown in Figure 5) are applied to simulate the situations, where the driver could not get the accurate signal status. The simulation parameters are list in Table 2. The phase difference between the adjacent intersections is 25 s.

As indicated by the curves in Figure 6(a), the uninformed vehicle could not keep smooth trajectory to pass intersections, which causes frequency and magnitude of velocity fluctuations and generates extra fuel consumption. The uninformed vehicle stops at the second intersection to wait for the next green time, which consumed excessive fuel as a result of the idling and acceleration from zero to desired speed. The instantaneous fuel consumption curve has similar trends with the acceleration curve. Total fuel consumption of the connected vehicle is significantly less than that of the uninformed vehicle (shown in Figure 6(c)), which benefits 37.07% as listed in Table 3. It is worth noting that travel time of the connected vehicle is 43.62% lower than that of the uninformed vehicle. If the drivers on the connected vehicle could follow the speed advisory strictly, the results of this algorithm would be reliable and a great of benefits in fuel would be gained. Further experiments for model validation would be carried out after building a

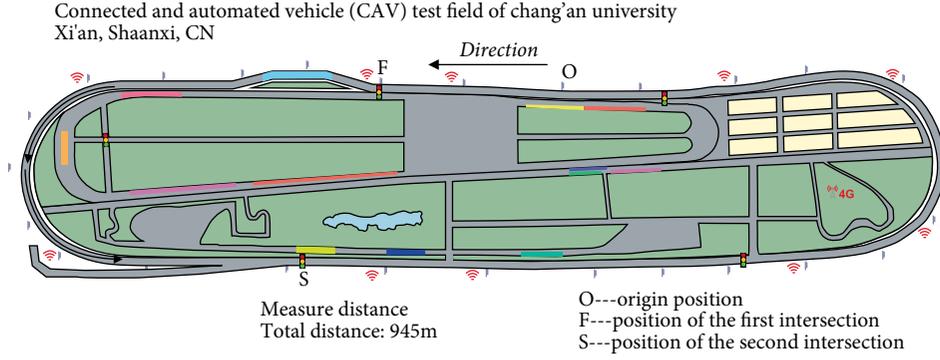


FIGURE 5: Experiment and simulation environment.

TABLE 2: Simulation parameters during once optimization.

Parameter	Value
t_0	0 s
v_0	13.89 m/s
v_{lim}	19.44 m/s
a_{max}	3 m/s ²
a_{min}	-5 m/s ²
T_G	30 s
T_R	30 s
x_f	200 m
x_s	945 m
t_{rf}	27 s

TABLE 3: Fuel consumption and travel time of the connected vehicle and the uninformed vehicle.

	Uninformed vehicle	Connected vehicle
Travel time (s)	94	53 (-43.62%)
Fuel consumption (L)	0.0723	0.0455 (-37.07%)
Fuel economy (L/100 km)	7.65	4.81 (+37.07%)

well-developed reliable communication circumstance and speed advisory system.

5.2. A Small Case of Multiple Intersections. Considering the cooperative optimization of two intersections, when the vehicles pass the current intersection according to the optimized trajectory, the subsequent two intersections can be regarded as another optimization issue to generate a rolling optimization problem among number of traffic signals on the arterial corridors.

Some simulations are conducted to test if the fuel consumption would be declined when the dynamic optimization algorithm works iteratively. We extend to three intersections to make rolling optimization for twice and then conduct a comparison analysis between the rolling optimization and the one-by-one optimization. The simulation parameters are listed in Table 4 and x_t represents the distance from origin to the third intersection.

TABLE 4: Simulation parameters in rolling optimization.

Parameter	Value
t_0	0 s
v_0	12.5 m/s
v_{lim}	19.44 m/s
a_{max}	3 m/s ²
a_{min}	-5 m/s ²
t_{rf}	15 s
T_G	30 s
T_R	30 s
x_f	200 m
x_s	615 m
x_t	1040 m

TABLE 5: Fuel consumption and travel time of the rolling optimization and the one-by-one optimization.

	One-by-one optimization	Rolling optimization
Travel time (s)	71	66 (-9.09%)
Fuel consumption (L)	0.06	0.0555 (-8.11%)
Fuel economy (L/100 km)	5.769	5.336 (+8.11%)

Figure 7 depicts the trajectories and fuel consumption of the test vehicle in the rolling optimization and the one-by-one optimization. As shown in Figure 7(a), the vehicle in the one-by-one optimization passes the third intersection just 1-2 s before it turns red, which is regarded as a danger behavior. There are two sharp accelerations and a slight deceleration in the rolling optimization while three sharp acceleration and a slight deceleration occur in the one-by-one optimization. The fluctuations of instantaneous fuel consumption in the one-by-one optimization is more intense than that in the rolling optimization. Total fuel consumption in the one-by-one optimization is higher than that in the rolling optimization as shown in Figure 7(c).

The comparison of the vehicle performance is listed in Table 5. In terms of travel time, the rolling optimization takes 66 s to pass three intersections, which saves 9.09% than that

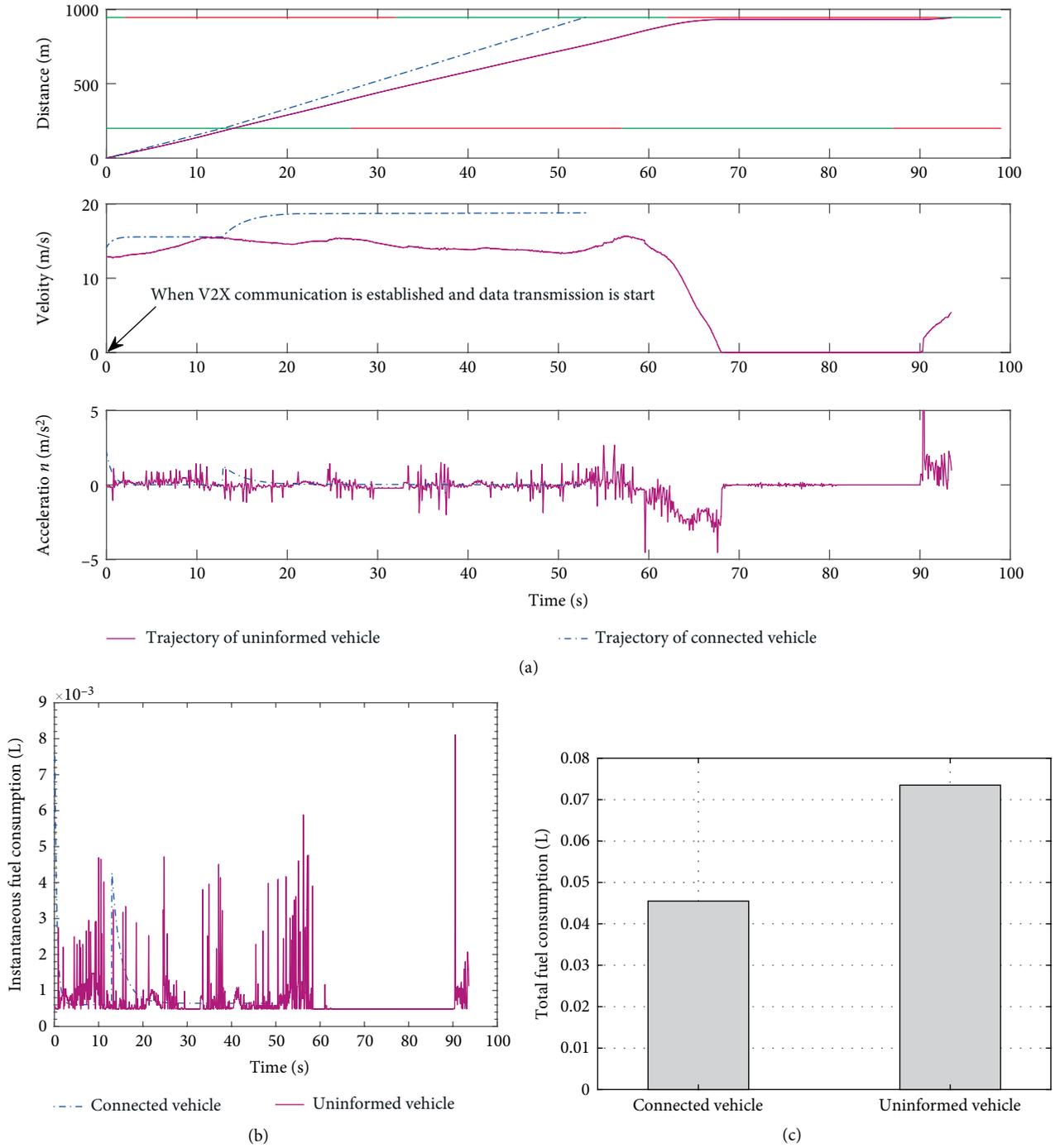


FIGURE 6: Comparisons between the connected vehicle and the uninformed vehicle. (a) Vehicle trajectories; (b) instantaneous fuel consumption; (c) total fuel consumption.

in the one-by-one optimization. Total fuel consumption in the rolling optimization saves 8.11% from 0.06 to 0.0555-L, which makes a significant improvement.

6. Conclusion

This study proposes a dynamic eco-driving optimization model, which can be applied to the scenario that the test

vehicles pass two successive intersections on signalized arterial corridors during the green phase. The dynamic optimization algorithm is adopted to optimize the trajectories via evaluating the fuel consumption upon the trip. Numerous simulations for the connected vehicle and field experiments for the uninformed vehicle are respectively carried out to test that the proposed dynamic optimization algorithm can provide an effective solution to the issue. As the results demonstrated, the fuel saving has a significant improvement using the proposed dynamic

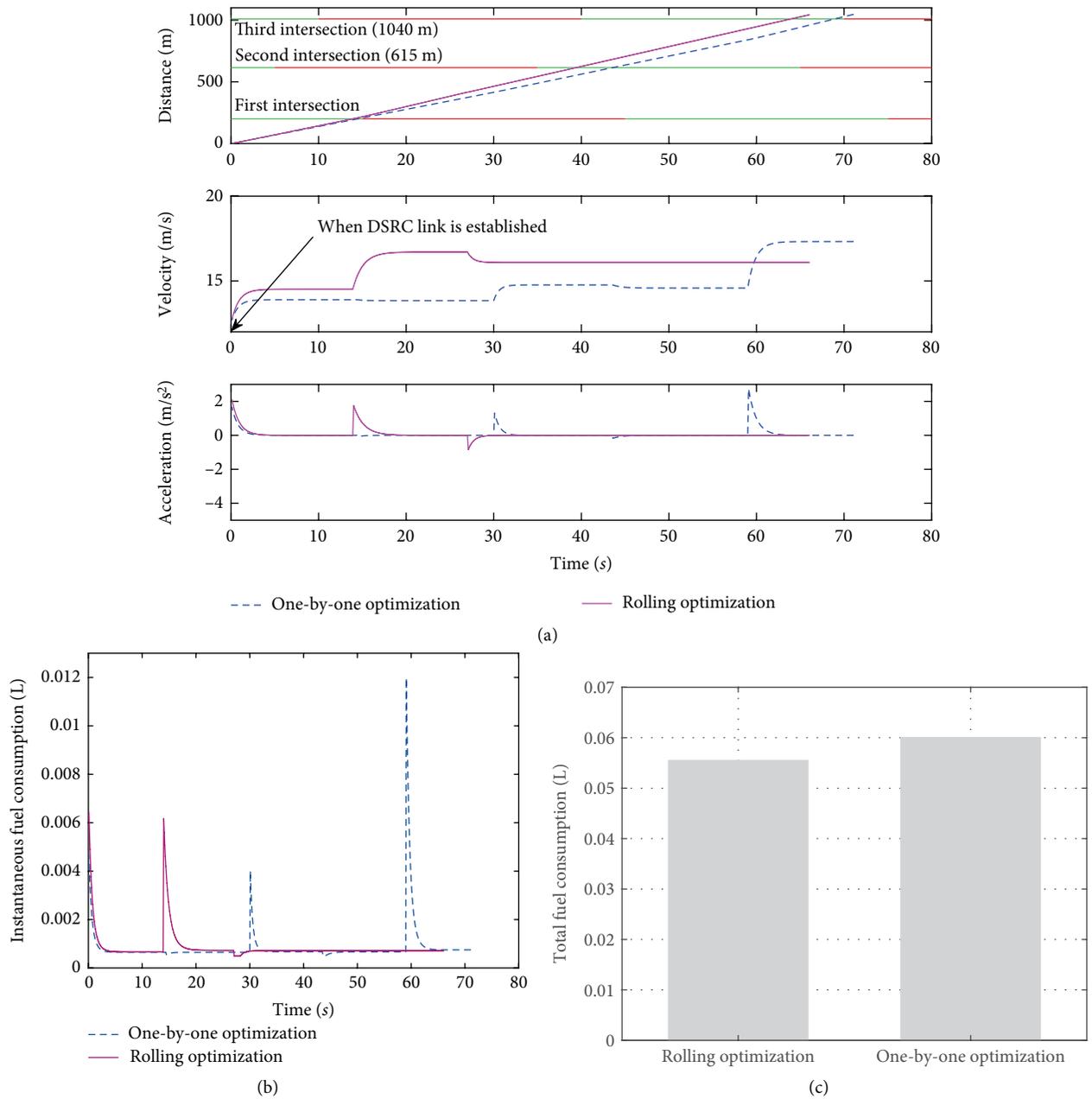


FIGURE 7: Comparisons between the rolling optimization and the one-by-one optimization. (a) Vehicle trajectories; (b) instantaneous fuel consumption; (c) total fuel consumption.

optimization algorithm. More importantly, a considerable fuel benefits have been gained in the rolling optimization compared with the one-by-one optimization when the algorithm is applied to three continuous signalized intersections.

Nevertheless, moving queues and platoon dissipation before the test vehicles, cut-in vehicles from other lanes and relevant effects are ignored in this study. Moreover, the dynamic eco-driving optimization model is put forward based on the connected vehicles that have a good capacity of V2X communication. Due to the incomplete communication circumstance and the unaccomplished on-board system establishment, the speed advisory algorithm hasn't been embedded into the in-vehicle computer. Once the speed advisory system and communication environment are well developed, the field experiments that drivers follow

the speed advisory strictly would be carried out. On the other hand, considering the impacts of the signals on the traffic flow, coordinated signal control can also be integrated with speed advisory, which can cooperatively improve the traffic throughput both from the extent of roadside end and in-vehicle end. Moreover, the cooperative optimization of both signal control and speed advisory can not only applies to the signalized arterial corridors but also the road network.

Data Availability

The original codes of the numerical tests used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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References

- [1] L. Zhang, Z. Song, X. Tang, and D. Wang, “Signal coordination models for long arterials and grid networks,” *Transportation Research Part C Emerging Technologies*, vol. 71, pp. 215–230, 2016.
- [2] W. Ma, L. Zou, K. An, N. Gartner, and H. M. Wang, “A partition-enabled multi-mode band approach to arterial traffic signal optimization,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 1, pp. 313–322, 2018.
- [3] J. T. Morgan and J. D. C. Little, “Synchronizing traffic signals for maximal bandwidth,” *Operations Research*, vol. 12, no. 6, pp. 896–912, 1964.
- [4] N. H. Gartner, S. F. Assman, F. Lasaga, and D. L. Hou, “A multi-band approach to arterial traffic signal optimization,” *Transportation Research Part B Methodological*, vol. 25, no. 1, pp. 55–74, 1991.
- [5] R. E. Allsop, “Some possibilities for using traffic control to influence trip distribution and route choice,” in *Proceedings of the Transportation and Traffic Theory 6*, pp. 345–373, Elsevier, New York, NY, USA, 1974.
- [6] N. Gartner, “Area traffic control and network equilibrium,” *Traffic Equilibrium Methods*, M. A. Florian, Ed., pp. 274–297, Springer, Berlin, Heidelberg, 1976.
- [7] B. Alonso, Á. Ibeas, G. Musolino, C. Rindone, and A. Vitetta, “Effects of traffic control regulation on network macroscopic fundamental diagram: a statistical analysis of real data,” *Transportation Research Part A: Policy and Practice*, vol. 126, pp. 136–151, 2019.
- [8] H. Yan, F. He, X. Lin, J. Yu, M. Li, and Y. Wang, “Network-level multiband signal coordination scheme based on vehicle trajectory data,” *Transportation Research Part C: Emerging Technologies*, vol. 107, pp. 266–286, 2019.
- [9] J. De Dios Ortuzar and L. G. Willumsen, *Modelling transport*, John Wiley & Sons, Hoboken, NJ, USA, 2011.
- [10] E. Cascetta, A. Papola, V. Marzano, F. Simonelli, and I. Vitiello, “Quasi-dynamic estimation of o-d flows from traffic counts: formulation, statistical validation and performance analysis on real data,” *Transportation Research Part B: Methodological*, vol. 55, pp. 171–187, 2013.
- [11] M. Luisa De Maio and A. Vitetta, “Route choice on road transport system: a fuzzy approach,” *Journal of Intelligent & Fuzzy Systems*, vol. 28, no. 5, pp. 2015–2027, 2015.
- [12] A. Vitetta, “A quantum utility model for route choice in transport systems,” *Travel Behaviour and Society*, vol. 3, pp. 29–37, 2016.
- [13] C. Wu, G. Zhao, and B. Ou, “A fuel economy optimization system with applications in vehicles with human drivers and autonomous vehicles,” *Transportation Research Part D Transport & Environment*, vol. 16, no. 7, pp. 515–524, 2011.
- [14] Y. Zhang, J. Lv, and W. Wang, “Evaluation of vehicle acceleration models for emission estimation at an intersection,” *Transportation Research Part D Transport & Environment*, vol. 18, no. 1, pp. 46–50, 2013.
- [15] S. Pandian, S. Gokhale, and A. K. Ghoshal, “Evaluating effects of traffic and vehicle characteristics on vehicular emissions near traffic intersections,” *Transportation Research Part D Transport & Environment*, vol. 14, no. 3, pp. 180–196, 2009.
- [16] K. S. Nwizege, M. Bottero, S. Mmeah, and E. D. Nwiwure, “Vehicles-to-Infrastructure Communication Safety Messaging in DSRC,” *Procedia Computer Science*, vol. 34, pp. 559–564, 2014.
- [17] K. C. Dey, A. Rayamajhi, M. Chowdhury, P. Bhavsar, and J. Martin, “Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication in a heterogeneous wireless network-performance evaluation,” *Transportation Research Part C: Emerging Technologies*, vol. 68, pp. 168–184, 2016.
- [18] X. Yang, K. Huang, W. Hao, and Y. Lu, “Development of two-stage-based eco-driving system for connected automated vehicles,” in *Transportation Research Board 97th Annual Meeting*, The National Academies of Sciences, Engineering, and Medicine Washington, DC, USA, 2018.
- [19] T. Q. Tang, Z. Y. Yi, J. Zhang, and N. Zheng, “Modeling the driving behaviour at a signalised intersection with the information of remaining green time,” *IET Intelligent Transport Systems*, vol. 11, no. 9, pp. 596–603, 2017.
- [20] M. Sanchez, J. C. Cano, and D. Kim, “Predicting traffic lights to improve urban traffic fuel consumption,” in *International Conference on ITS Telecommunications Proceedings*, pp. 331–336, IEEE, St. Petersburg, 2007.
- [21] A. Stevanovic, J. Stevanovic, K. Zhang, and S. Batterman, “Optimizing traffic control to reduce fuel consumption and vehicular emissions: integrated approach with VISSIM, CMEM, and VISGAOST,” *Transportation Research Record Journal of the Transportation Research Board*, vol. 2128, no. 1, pp. 105–113, 2009.
- [22] G. Wu, K. Boriboonsomsin, W. B. Zhang, M. Li, and M. Barth, “Energy and emission benefit comparison of stationary and in-vehicle advanced driving alert systems,” *Transportation Research Record Journal of the Transportation Research Board*, vol. 2189, no. 1, pp. 98–106, 2010.
- [23] G. Mahler and A. Vahidi, “Reducing idling at red lights based on probabilistic prediction of traffic signal timings,” in *American Control Conference*, pp. 6557–6562, IEEE, Canada, 2012.
- [24] S. Suzuki and N. Horiuchi, “A study of the signal control for the minimization of CO₂ emission,” *World Congress on Intelligent Transport Systems*, vol. 12, pp. 41–44, 2005.

- [25] S. Chen, J. Sun, and J. Yao, "Development and simulation application of a dynamic speed dynamic signal strategy for arterial traffic management," in *14th International IEEE Conference on Intelligent Transportation Systems*, pp. 1349–1354, IEEE, Washington, DC, USA, 2011.
- [26] R. S. Trayford, B. W. Doughty, and J. W. V. D. Touw, "Fuel economy investigation of dynamic advisory speeds from an experiment in arterial traffic," *Transportation Research Part A General*, vol. 18, no. 5–6, pp. 415–419, 1984.
- [27] R. S. Trayford, B. W. Doughty, and M. J. Wooldridge, "Fuel saving and other benefits of dynamic advisory speeds on a multi-lane arterial road," *Transportation Research Part A General*, vol. 18, no. 5–6, pp. 421–429, 1984.
- [28] K. J. Malakorn and B. Park, "Assessment of mobility, energy, and environment impacts of IntelliDrive-based cooperative adaptive cruise control and intelligent traffic signal control," in *IEEE International Symposium on Sustainable Systems and Technology*, pp. 1–6, IEEE, Arlington, VA, USA, 2010.
- [29] B. Asadi and A. Vahidi, "Predictive cruise control: utilizing upcoming traffic signal information for improving fuel economy and reducing trip time," *IEEE Transactions on Control Systems Technology*, vol. 19, no. 3, pp. 707–714, 2011.
- [30] H. Rakha and R. K. Kamalanathsharma, "Eco-driving at signalized intersections using V2I communication," in *International IEEE Conference on Intelligent Transportation Systems*, pp. 341–346, IEEE, Washington, DC, USA, 2011.
- [31] F. Mensing, E. Bideaux, R. Trigui, and H. Tattegrain, "Trajectory optimization for eco-driving taking into account traffic constraints," *Transportation Research Part D Transport & Environment*, vol. 18, no. 1, pp. 55–61, 2013.
- [32] R. K. Kamalanathsharma and H. A. Rakha, "Multi-stage dynamic programming algorithm for eco-speed control at traffic signalized intersections," in *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, pp. 2094–2099, IEEE, The Hague, The Netherlands, 2013.
- [33] R. K. Kamalanathsharma and H. A. Rakha, "Leveraging connected vehicle technology and telematics to enhance vehicle fuel efficiency in the vicinity of signalized intersections," *Journal of Intelligent Transportation Systems*, vol. 20, no. 1, pp. 33–44, 2014.
- [34] G. Abu-Lebdeh and H. Chen, "Development of a framework for an integrated dynamic signal-dynamic speed traffic management algorithm for signalized networks," in *Proceedings of the 85th Annual Meeting of the Transportation Research Board*, The National Academies of Sciences, Engineering, and Medicine, Washington, DC, USA, 2006.
- [35] G. Abu-Lebdeh, "Integrated adaptive-signal dynamic- speed control of signalized arterials," *Journal of Transportation Engineering*, vol. 128, no. 5, pp. 447–451, 2002.
- [36] G. Abu-Lebdeh and H. Chen, "Exploring the potential benefits of intellidrive-enabled dynamic speed control in signalized networks," in *Proceedings of the 89th Annual Meeting of the Transportation Research Board*, The National Academies of Sciences, Engineering, and Medicine, Washington, DC, USA, 2010.
- [37] C. Sun, J. Guanetti, F. Borrelli, and S. Moura, "Robust eco-driving control of autonomous vehicles connected to traffic lights," 2018, <https://arxiv.org/abs/1802.05815>.
- [38] T. Q. Tang, Z. Y. Yi, J. Zhang, T. Wang, and J. Q. Leng, "A speed guidance strategy for multiple signalized intersections based on car-following model," *Physica A: Statistical Mechanics and its Applications*, vol. 496, pp. 399–409, 2018.
- [39] G. De Nunzio, C. De Wit, C. Moulin, and P. D. Di Domenico, "Eco driving in urban traffic networks using traffic signals information," *International Journal of Robust and Nonlinear Control*, vol. 26, no. 6, pp. 1307–1324, 2016.
- [40] S. Mandava, K. Boriboonsomsin, and M. Barth, "Arterial velocity planning based on traffic signal information under light traffic conditions," in *12th International IEEE Conference on Intelligent Transportation Systems*, pp. 1–6, IEEE, St. Louis, MO, USA, 2009.
- [41] X. Haitao, B. Kanok, and B. Matthew, "Dynamic eco-driving for signalized arterial corridors and its indirect network-wide energy/emissions benefits," *Journal of Intelligent Transportation Systems*, vol. 17, no. 1, pp. 31–41, 2013.
- [42] X. Wu, X. Zhao, Q. Xin, Q. Yang, S. Yu, and E. Sun, "Dynamic cooperative speed optimization at signalized arterials with various platoons," *Transportation Research Part D: Transport and Environment*, vol. 2673, no. 5, pp. 528–537, 2019.
- [43] H. A. Rakha, K. Ahn, K. Moran, B. Saerens, and E. Van den Bulck, "Virginia tech comprehensive power-based fuel consumption model: model development and testing," *Transportation Research Record Journal of the Transportation Research Board*, vol. 16, no. 7, pp. 492–503, 2011.
- [44] S. Park, H. Rakha, K. Ahn, and K. Moran, "Virginia tech comprehensive power-based fuel consumption model (VT-CPFM): model validation and calibration considerations," *International Journal of Transportation Science & Technology*, vol. 2, no. 4, pp. 317–336, 2013.
- [45] H. Rakha, I. Lucic, S. H. Demarchi, J. R. Setti, and M. V. Aerde, "Vehicle dynamics model for predicting maximum truck acceleration levels," *Journal of Transportation Engineering*, vol. 127, no. 5, pp. 418–425, 2001.
- [46] X. Zhao, H. Min, Z. Xu, X. Wu, X. Li, and P. Sun, "Image antiblurring and statistic filter of feature space displacement: application to visual odometry for outdoor ground vehicle," *Journal of Sensors*, vol. 2018, Article ID 2987819, 14 pages, 2018.