2017 IEEE Intelligent Vehicles Symposium (IV)
June 11-14, 2017, Redondo Beach, CA, USA

V2I based Cooperation between Traffic Signal and Approaching Automated Vehicles*

Biao Xu, Xuegang (Jeff) Ban, Yougang Bian, Jianqiang Wang, and Keqiang Li

***Abstract*—Existing traffic signal optimization and vehicle speed optimization at signalized intersections cannot work together for the lack of proper cooperation methods. We propose the V2I (vehicle to infrastructure) based cooperation between traffic signal and approaching vehicles which optimizes the traffic signal and vehicles' speed trajectories simultaneously. The cooperation consists of roadside traffic signal optimization and onboard speed control, of which the former calculates the optimal traffic signal timing and vehicles' arriving time to minimize trip time and the latter optimizes the vehicle engine power and brake force to minimize the fuel consumption in the whole trip. A simulation study is conducted to compare the proposed cooperation method and the actuated signal control method. The simulation results show significant improvement of transportation efficiency and vehicle fuel economy by using the cooperation method.**

***Keywords*—Signalized Intersection, Traffic Signal Optimization, Vehicle Speed Control, V2I Cooperation, Intelligent Transportation Systems**

I. INTRODUCTION

There had been over 1.2 billion vehicles in the world until 2014[1] and the private car ownership is predicted to reach 14.7 billion in 2030[2]. A large number of vehicles have increased the vehicle fuel consumption and damaged the transportation efficiency in urban areas. In fact, vehicle fuel economy and transportation efficiency are affected by lots of factors such as road capacity and infrastructure design. Among these factors, signalized intersections in urban areas play a critical role. When vehicles are approaching a signalized intersection, they may stop at a red light, keep idling, and wait for the green light. During the idling time, vehicles cannot move, but consume fuel and discharge greenhouse gasses. According to a report from Texas Transportation Institute, fuel consumption wasted during vehicle idling exceeded 2.8 billion gallons in 2011[3].

To improve transportation efficiency, numerous researchers have proposed effective traffic signal optimization methods. In 1968, Robertson proposed the TRANSYT model to optimize the signal offsets in the signal network[4]. Since then, the SCOOT[5] and the SCATS[6] had been introduced which are widely applied in current traffic signal control. Since the 1990s, along with the development of intelligence algorithm, some methods such as reinforcement learning[7], fuzzy logic[8], and genetic algorithm[9] have been applied in traffic signal control, which showed reasonable performance.

In recent years, the development of V2I (vehicle to infrastructure) and V2V (vehicle to vehicle) communication technologies provides new opportunities to further improve transportation efficiency. Lee et al. took advantage of connected vehicles to get the vehicles' states and estimate the travel time which was used for the real-time intersection control[10]. Priemer and Friedrich designed a decentralized adaptive traffic signal control which estimated the queue length and traffic flow using the V2I communication data[11]. Cai et al. constructed a state-space using the vehicle speed and position acquired via V2I communication, predicted the travel time using the proposed traffic model, and optimized the traffic signal using dynamic programming methods[12]. Goodall used simulation methods to predict the queue length and delay after obtaining vehicle position and speed via V2I communication, which was then used to optimize traffic signal timing[13]. Zhao et al. developed a V2I-based signal timing optimization method by considering individual vehicles' fuel consumption characteristics[14].

Additionally, other researchers focused on vehicle speed optimization at signalized intersections. Asadi and Vahidi proposed a predictive cruise control method in signalized intersections which aimed to make vehicles timely arrival at the green light with the minimal use of braking, maintain a safe distance between vehicles, and cruise at or near the pre-set speed[15]. He et al.[16] and Wu et al.[17] made effort to optimize the eco-speed for the ICE (Internal combustion engine) vehicles and electric vehicles approaching the signalized intersections, respectively.

Besides, Levin et al.[18] and Dresner and Stone[19] proposed the reservation based intersection control which managed the autonomous vehicles at unsignalized intersections. Zohdy et al. used the cooperative adaptive cruise control to organize the vehicles' motion at intersections[20].

The aforementioned traffic signal optimization methods and the vehicle control methods can improve transportation efficiency and vehicle fuel economy, respectively. However, it is difficult to combine traffic signal control and vehicle control at signalized intersections since the vehicle control requires fixed signal timing while the adaptive signal adjusts the timing according to the real-time traffic flow, although the combination of the two has great potential to improve

*Research supported by National Natural Science foundation of China (NO.51475254 and NO.51625503) and National Science and Technology Major Project (No. 2016ZX03002019). (corresponding author: Keqiang Li).

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both transportation efficiency and vehicle fuel economy. In this paper, we propose a V2I based cooperation method between traffic signal and approaching vehicles which can simultaneously optimize traffic signal timing and vehicle speed trajectories, aiming to improve the transportation efficiency and decrease the vehicle fuel consumption. The cooperation method consists of traffic optimization and vehicle optimal control. The traffic optimization will calculate the optimal traffic signal timing and vehicles' arrival time at the end of the traffic signal cycle according to the vehicles' initial speed and position, and the vehicle optimal control is applied on each vehicle and plans the optimal trajectory based on the optimal arrival time calculated in the traffic optimization.

This paper is structured as follows. In Section II, the studied scenario is described. Section III presents the methodology of traffic signal and approaching vehicles cooperation. The simulation and results are presented in Section IV. Section V gives some concluding remarks.

II. Problem Statement

We consider a 4-legged and 3-lane intersection (see Fig. 1). The three lanes in each entrance of the intersection are a left-turning lane, a through lane, and a right-turning lane respectively. Here, we suppose that vehicles with different destinations are already on the corresponding lanes so we do not need to consider the lane changing. In other words, vehicle lane changing has been done before they enter the study area (when they approach the intersection) or after they leave the study area.

It is assumed that the right-turn vehicles, the through vehicles and the left-turn vehicles run into the nearside lanes, the middle lanes, and the inside lanes of each intersection exit, respectively. Therefore, the right-turning traffic flow will not conflict with the others, so that we do not consider it and the right-turning signal will keep always green. The traffic flow from other eight movements, i.e., northbound left (NBL), northbound though (NBT), westbound left (WBL), westbound through (WBT), southbound left (SBL), southbound through (SBT), eastbound left (EBL) and eastbound through (EBT) is organized by a traffic signal. Here, we use a dual-ring phase control[21] with predetermined fixed cycle C in the traffic signal (see Fig. 2). The phase sequence of Ring 1 is NBL – SBT – WBL – EBT and the phase sequence of Ring 2 is SBL – NBT – EBL – WBT. Each phase can be divided into effective green interval and clearance time. Clearance time is also predetermined and fixed. It is supposed that vehicles can pass the stop lines during the effective green intervals of the traffic signal. The vehicles passing the stop line at the end of the effective green time can be cleared during the clearance time.

For a vehicle, the movement it belongs to is denoted as L when $L \in \mathrm{F} = \{$NBL, NBT, WBL, WBT, SBL, SBT, EBL, EBT$\}$. We number the vehicles in L with $1 \sim N_L$ according to the vehicles' distance to the stop line where N_L represents the total vehicle number of movement L. As a result, a vehicle can be represented as the pair (L, i) where i is the serial number of the vehicle and $i \le N_L$.

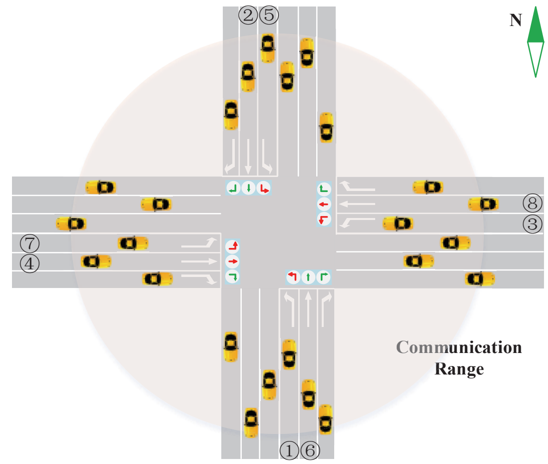

Figure 1 Studied scenario

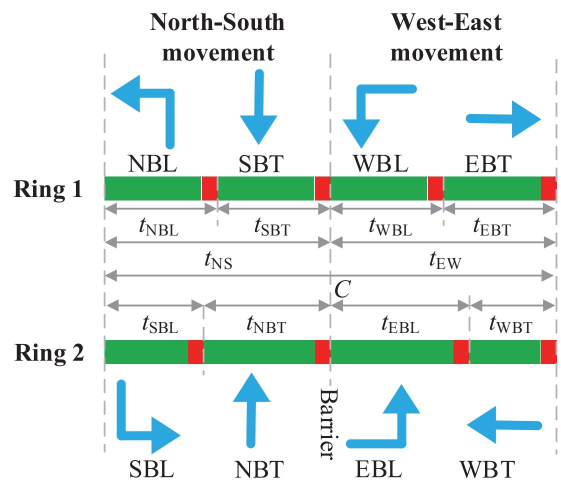

Figure 2 Signal phase sequence

In Fig.2, the green lines mean the effective green intervals of the traffic signal phases and the red lines means the clearance time. t_{NBL}, t_{SBT}, t_{WBL}, t_{EBT}, t_{SBL}, t_{NBT}, t_{EBL} and t_{WBT} denote the phase time of NBL, SBT, WBL, EBT, SBL, NBT, EBL, and WBT. t_{NS} and t_{EW} are the phase time of the northbound/southbound and eastbound/westbound movement, respectively. C is the traffic signal cycle length.

In this research, it is assumed that every vehicle owns positioning device and wireless communication device so that the vehicles can send their location and movement information to the roadside device when they are approaching the intersection and runs into the communication range of the intersection. Actually, the GNSS (global navigation satellite system) device and wireless communication technologies make it possible to share the location and movement information between vehicles and roadside device. Additionally, all approaching vehicles are assumed to be automated vehicles so that vehicles can control their speed, strictly follow the optimized speed trajectory, and pass the intersection automatically.

When vehicles enter the communication range of the roadside device, they will send their location and movement information to the roadside device. Then the roadside device will take the initial speed and location of these vehicles as inputs to optimize the phase time and the arriving time of the vehicles within the communication range at the end of the traffic signal cycle. Next, the roadside device will send the arriving time information to vehicles via wireless communication. Finally, vehicles optimize the speed profiles in the receding horizon and pass through the intersection automatically.

III. METHODOLOGY

A. Overview of Cooperation

The proposed cooperation between traffic signal and approaching vehicles simultaneously optimizes traffic signal timing and vehicle speeds, which consists of traffic optimization and vehicle control.

As shown in Fig. 3, the traffic optimization locates at the roadside, acquires the speed and position information from approaching vehicles, calculates the optimal signal timing, and plans the vehicles' arriving time with the aim of transportation efficiency. Then, the optimized vehicle's arriving time is sent to the corresponding vehicle. The onboard vehicle control designs the speed trajectory and optimizes the engine power and the brake force considering the constraint of the arriving time to minimize the fuel consumption in the whole trip.

It is worth noting that the roadside traffic optimization is implemented at the end of the traffic signal cycle, while the onboard vehicle control is conducted with the rolling horizon procedure.

B. Traffic Optimization

1) Traffic model

As all vehicles are assumed to be autonomous vehicles, we use some basic rules to build the traffic model in this paper. Specifically, when vehicles are approaching the intersection, they must:

- arrive at the stop line at the green interval of the corresponding phase;
- keep a safe time headway to avoid collisions.

Mathematically, if the vehicle (L, i) meets the first necessary condition above,

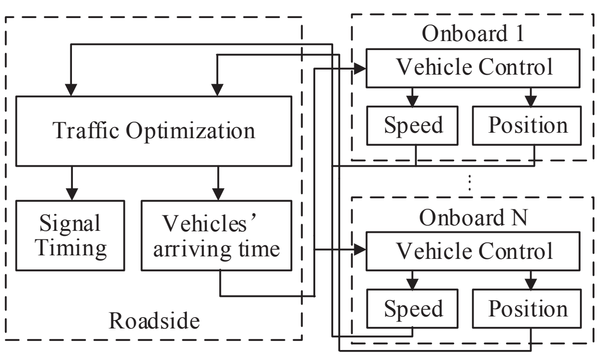

Figure 3 Overview of the cooperation of traffic signal and vehicles

$$t_L^{(i)} \in g_L, \forall i \le N_L, L \in \mathrm{F}, \tag{1}$$

where $t_L^{(i)}$ is the arriving time of the vehicle (L, i) which means the vehicle running time from the initial position to the stop line, and g_L is the green interval of the traffic signal for the traffic flow L.

Given the phase time of NBL, SBT, WBL, EBT, SBL, NBT, EBL and WBT as t_{NBL}, t_{SBT}, t_{WBL}, t_{EBT}, t_{SBL}, t_{NBT}, t_{EBL} and t_{WBT}, the effective green interval at the begin of the cycle can be written as

$$g_{\mathrm{NBL}} = \bigcup_{k=0}^{K} [kC,\ kC + t_{\mathrm{NBL}} - R], \tag{2}$$

$$g_{\mathrm{SBT}} = \bigcup_{k=0}^{K} [kC + t_{\mathrm{NBL}},\ kC + t_{\mathrm{SBT}} + t_{\mathrm{NBL}} - R], \tag{3}$$

$$g_{\mathrm{WBL}} = \bigcup_{k=0}^{K} [kC + t_{\mathrm{SBT}} + t_{\mathrm{NBL}},\ kC + t_{\mathrm{WBL}} + t_{\mathrm{SBT}} + t_{\mathrm{NBL}} - R], \tag{4}$$

$$g_{\mathrm{EBT}} = \bigcup_{k=0}^{K} [kC + t_{\mathrm{WBL}} + t_{\mathrm{SBT}} + t_{\mathrm{NBL}},\ kC + t_{\mathrm{EBT}} + t_{\mathrm{WBL}} + t_{\mathrm{SBT}} + t_{\mathrm{NBL}} - R], \tag{5}$$

$$g_{\mathrm{SBL}} = \bigcup_{k=0}^{K} [kC,\ kC + t_{\mathrm{SBL}} - R], \tag{6}$$

$$g_{\mathrm{NBT}} = \bigcup_{k=0}^{K} [kC + t_{\mathrm{SBL}},\ kC + t_{\mathrm{NBT}} + t_{\mathrm{SBL}} - R], \tag{7}$$

$$g_{\mathrm{EBL}} = \bigcup_{k=0}^{K} [kC + t_{\mathrm{NBT}} + t_{\mathrm{SBL}},\ kC + t_{\mathrm{EBL}} + t_{\mathrm{NBT}} + t_{\mathrm{SBL}} - R], \tag{8}$$

$$g_{\mathrm{WBT}} = \bigcup_{k=0}^{K} [kC + t_{\mathrm{EBL}} + t_{\mathrm{NBT}} + t_{\mathrm{SBL}},\ kC + t_{\mathrm{WBT}} + t_{\mathrm{EBL}} + t_{\mathrm{NBT}} + t_{\mathrm{SBL}} - R], \tag{9}$$

where R refers to the clearance time, k means the cycle number, and K denotes the considering cycle length that is pre-set.

Besides, the phase time of different traffic flow must meet the requirement of the dual-ring constraints:

$$t_{\mathrm{SBT}} + t_{\mathrm{NBL}} = t_{\mathrm{NBT}} + t_{\mathrm{SBL}} = t_{\mathrm{NS}}, \tag{10}$$

$$t_{\mathrm{EBT}} + t_{\mathrm{WBL}} = t_{\mathrm{WBT}} + t_{\mathrm{EBL}} = t_{\mathrm{EW}}, \tag{11}$$

$$t_{\mathrm{NS}} + t_{\mathrm{EW}} = C, \tag{12}$$

$$g_{\max} \ge t_{\mathrm{SBT}}, t_{\mathrm{NBL}}, t_{\mathrm{NBT}}, t_{\mathrm{SBL}}, t_{\mathrm{EBT}}, t_{\mathrm{WBL}}, t_{\mathrm{WBT}}, t_{\mathrm{EBL}} \ge g_{\min}. \tag{13}$$

In (13), $g_{\min}$ means the minimum phase time, and $g_{\max}$ means the maximum phase time.

Additionally, to ensure safety, vehicle (L, i) must keep a safe time headway to the vehicle (L, i-1):

$$t_L^{(i)} - t_L^{(i-1)} \ge \mathrm{THW}_{\min}, \forall 2 \le i \le N_L, i \in N^+, L \in \mathrm{F}, \tag{14}$$

where $\mathrm{THW}_{\min}$ represents the minimum safe time headway.

Remark: Since the signal timing is modeled via the dual diagram in Figure 2, the constraints (1) – (14) ensure that movement conflicts will not occur while compatible movements may occur concurrently if needed. We only focus on the arriving time of adjacent vehicles in the traffic optimization. Actually, the collision avoidance before arriving will be considered in *Vehicle Optimal Control*.

2) Vehicle kinematic model

The vehicle is a complex nonlinear dynamic system with numerous nonlinear components such as engine and transmission. In this paper, we build a simple vehicle kinematic model to describe the kinematics of the vehicle in the traffic optimization. It is assumed that the vehicle tends to accelerate to a target speed and keep uniform motion when running through the intersection. Based on the assumption, the vehicle model can be written as:

$$\dot{d} = -v\,,$$

$$\dot{v} = a\,,$$

$$a = \begin{cases} a(t) \text{ ,if } v \neq v_{\mathrm{t}} \\ 0 \text{ ,if } v = v_{\mathrm{t}} \end{cases},$$

where d, v, and a is the distance to the intersection, velocity, and acceleration respectively, and v_{t} is the target speed.

When given the speed limit $v_{\max}$ and the maximum comfortable acceleration $a_{\max}$, we can calculate the minimum arriving time $t_{L,\min}^{(i)}$ of the vehicle (L, i) with distance $d_L^{(i)}$ and velocity $v_L^{(i)}$. When a vehicle's distance is far enough so that the vehicle can speed up to the speed limit before arriving at the intersection (see Fig 3(a)), the minimum arriving time is

$$t_{L,\min}^{(i)} = \frac{2a_{\max} d_L^{(i)} + \left(v_{\max} - v_L^{(i)}\right)^2}{2a_{\max} v_{\max}} \text{,if } d_L^{(i)} \geq \frac{{v_{\max}}^2 - {v_L^{(i)}}^2}{2a_{\max}} \tag{15}$$

.

On the other hand, when the distance is not far enough (see Fig 3(b)), the minimum arriving time is

$$t_{L,\min}^{(i)} = \frac{-v_L^{(i)} + \sqrt{{v_L^{(i)}}^2 + a_{\max} d_L^{(i)}}}{2a_{\max}} \text{,if } d_L^{(i)} < \frac{{v_{\max}}^2 - {v_L^{(i)}}^2}{2a_{\max}}\,. \tag{16}$$

It is obvious that the vehicle's arriving time cannot be greater than its minimum arriving time:

$$t_L^{(i)} \geq t_{L,\min}^{(i)}, \forall i \leq N_L, L \in \mathrm{F}\,. \tag{17}$$

3) Cost function

In traffic signal control, the delay is usually used as the performance. Here, we use the total trip time (from the initial position to the stop line) of the approaching vehicles as the cost function:

$$f\left(t_L^{(i)}\right) = \sum_{L\in \mathrm{F}} \sum_{i=1}^{N_L} t_L^{(i)}\,.$$

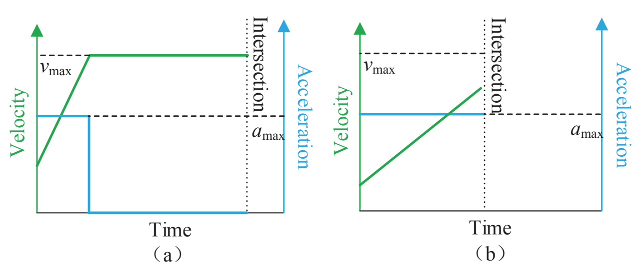

Figure 4 two cases for vehicle arriving at minimum time

4) Optimization model

The traffic optimization is aiming to optimize the phase time of the traffic signal and the arriving time of approaching vehicles which are regarded as control variables. Based on the traffic model, the vehicle model, and the cost function, we can build the optimization model:

$$\begin{aligned} &\left\{t_{\mathrm{SBT}}{}^*, t_{\mathrm{NBL}}{}^*, t_{\mathrm{NBT}}{}^*, t_{\mathrm{SBL}}{}^*, t_{\mathrm{EBT}}{}^*, t_{\mathrm{WBL}}{}^*, t_{\mathrm{WBT}}{}^*, t_{\mathrm{EBL}}{}^*, t_L^{(i)*}\right\} \\ &= \arg\min \sum_{L\in \mathrm{F}} \sum_{i=1}^{N_L} t_L^{(i)} \end{aligned}, \tag{18}$$

subject to:

Constraints: (1)~(17),

where $t_{\mathrm{SBT}}{}^*$, $t_{\mathrm{NBL}}{}^*$, $t_{\mathrm{NBT}}{}^*$, $t_{\mathrm{SBL}}{}^*$, $t_{\mathrm{EBT}}{}^*$, $t_{\mathrm{WBL}}{}^*$, $t_{\mathrm{WBT}}{}^*$, $t_{\mathrm{EBL}}{}^*$, and $t_L^{(i)*}$ are the optimal signal timing and the optimal vehicles' arriving time.

Remark: The traffic optimization is conducted at the every end of the traffic signal cycle, and the vehicle speed and position when optimizing are regarded as the input of the optimization model. Additionally, in the optimization, we consider multiple cycles, and the optimized signal timing is selected as the traffic signal timing in next cycle.

C. Vehicle Optimal Control

1) Vehicle model

In vehicle control, we use a longitudinal dynamic model as the vehicle model[15],

$$\dot{s} = -v\,, \tag{19}$$

$$\dot{v} = \frac{1}{m}\left(\frac{P}{v} - F_{\mathrm{b}} - \frac{1}{2} C_{\mathrm{D}} A \rho_{\mathrm{a}} v^2 - mgf\cos\alpha - mg\sin\alpha\right), \tag{20}$$

where P is the engine power, F_{b} means braking force, m is the vehicle's mass, C_{D} is the drag coefficient, A is the vehicle frontal area, ρ_{a} is the air density, f is the rolling resistance coefficient of the tires, g is the gravitational acceleration, α is the road slope, v is the vehicle speed, and s is the vehicle displacement.

We can adjust the vehicle speed trajectory by controlling the engine power P and the braking force F_{b}.

We then select the Virginia Tech Comprehensive Power-Based Fuel Consumption Model (VT-CPFM) [22] as the vehicle fuel model, which is a power-based model to calculate the fuel consumption, and is defined as follows:

$$F_{\mathrm{C}} = \begin{cases} \alpha_0 + \alpha_1 P + \alpha_2 P^2 \text{,if } P > 0 \\ \alpha_0 \text{ ,if } P \leq 0 \end{cases}, \tag{21}$$

where F_{c} is the fuel consumption rate, and α_0, α_1, and α_2 are the coefficients of the fuel consumption model.

2) Safety constraint

When the vehicle is approaching the intersection, it must keep a safe distance to the front vehicle to avoid collision:

$$s(t) - s_{\mathrm{p}}(t) \geq d_0\,, \tag{22}$$

where s_{p} is the displacement of the preceding vehicle and d_0 is the safe following distance.

3) Terminal constraints

Some terminal constraints should be met. Firstly, the initial state is determinate:

$$s(0)=0, \tag{23}$$

$$v(0)=v_0, \tag{24}$$

where v_0 is the initial velocity of the vehicle.

It is obvious that the terminal time which refers to the time to arrive the intersection is optimized in *Traffic Optimization*. Therefore,

$$s(t_f)=d, \tag{25}$$

where t_f is the fixed terminal time which is optimized in *Traffic Optimization* as $t_L^{(i)}$, i.e. $t_f = t_L^{(i)}$, and d is the initial distance to the stop line.

4) Cost function

Primarily, the fuel consumption of the whole trip is considered in the cost function. Besides, the terminal velocity of the vehicle which reflects the vehicle kinetic energy at the terminal time has great influence on the fuel consumption after the vehicle goes through the intersection. Consequently, the terminal velocity is also adopted in the cost function. Hence, the cost function is:

$$k_1\int_0^{t_f} F_C(t)\,dt - k_2 v(t_f)^2, \tag{26}$$

where k_1 and k_2 are the weight coefficients of the fuel consumption and vehicle kinetic energy.

5) Optimization model

An optimal control is built to optimize the vehicle engine power P and the brake force F_b. Combining the vehicle dynamics, the safety constraint, the terminal constraints and the cost function, we construct the vehicle optimal control model as:

$$\{P^*, F_b^*\} = \arg\min k_1\int_0^{t_f} F_C(t)\,dt - k_2 v(t_f)^2,$$

subject to:

vehicle dynamics: (19) and (20),
fuel consumption model: (21),
safety constraint: (22),
terminal constraints: (23), (24), and (25). (27)

IV. Simulation and Results

A. Simulation Setup

We conduct the simulation test based on the scenario of Figure 1 with the MATLAB and VISSIM. The traffic streams are generated at the entrances of the intersection of which the northbound/southbound flow is 300 vehicle/(hour · lane) and the eastbound/westbound flow is 400 vehicle/(hour · lane). The communication range is 1200m. Additionally, the parameters of vehicles are shown in TABLE I. .

To verify the performance of the proposed cooperation between traffic signal and vehicles (CTV), the actuated signal control[23] (ASC) is also simulated in the VISSIM as the comparing algorithm. In the ASC, the detectors are set at the upstream position of 20m away from the stop lines, the minimum and maximum green time are set as 7s and 50s respectively, the unit extension time is 3s, and the all-red time is 2s. In the ASC, the VISSIM is used to simulate the vehicles and the traffic signal, and the simulation data in VISSIM is transmitted to the Matlab and recorded. It is worth noting that the vehicles' motion with ASC is controlled by the driver model in VISSIM. Then the same scenario is built in Matlab for CTV simulation. In the CTV, g_{min} is 7s, g_{max} is 50s, and C is 80s.

TABLE I. VEHICLE PARAMETERS

Mass	**Drag Coefficient**	**Vehicle Frontal Area**
1500kg	0.4	1.5m^2
Air Density	**Rolling Resistance Coefficient**	**Maximum Power**
1.2kg/m^3	0.015	110kw
Fuel consumption model		
α_1	α_2	α_3
0.59	0.057	0.00014

B. Simulation Results

We select one of the vehicles from the NBL traffic flow and draw its position trajectories, speed profiles, engine power curves, and brake force curves of the CTV and ASC (Fig. 5). The colored wide lines in Fig. 5 (a) mean the effective green intervals of corresponding traffic flow that the vehicles belong to. It can be known from Fig. 5 (a) that the effective green interval of CTV is earlier than that of ASC. Fig. 5 (b) shows the velocity of the vehicle. The vehicle speed with ASC is fluctuant because of the driver model used in VISSIM. Additionally, the vehicle with ASC runs with higher speed during 150s ~ 220s, and brakes down and keeps idling after 220s. The vehicle speed fluctuation causes the engine power fluctuation of ASC in Fig. 5 (c), but the average engine power of ASC during 150s ~ 220s (about 4.5kW) is more than that of CTV (about 1.5kW), which means higher fuel consumption for the vehicle of ASC. From Fig. 5 (d), we can see that the vehicle of ASC brakes at about 230s, while the vehicle of CTV passes the intersection without any braking.

It is obvious that the CTV makes the vehicle slow down to avoid braking and idling at the intersection, and makes the green interval earlier, which results in less fuel consumption and trip time. Actually, the vehicle fuel consumption and the trip time of CTV and ASC in the whole trip are 92g, 109g, 133s, and 145s respectively, and the CTV algorithm saves the fuel by 15.6% and improves the trip efficiency by 8.3%. Actually, part of the increase of fuel consumption for ASC is caused by the speed fluctuation, but this part accounts for 2.6% (about 2.8g) according to our computation, which means that the CTV method improves the fuel economy by about 13% for the selected vehicle.

Fig. 6 and Fig. 7 show the trajectories of all vehicles with CTV and ASC. The thin lines in the figure mean the trajectories of vehicles, the red wide lines are the red interval of the traffic signal to clear the intersection, and the wide line with other colors represent the effective green interval of the corresponding traffic flow. The figures show that the vehicles from different movements pass the intersection during the green intervals. Additionally, there are more stops, longer queue length, and further idling time with ASC than with CTV, which means CTV leads to more efficient traffic and better fuel economy than ASC.

Specifically, as shown in TABLE II. , there are 406 vehicles and 361 vehicles passing the intersection within 600s with CTV and ASC respectively. For these vehicles, the average trip time with CTV and ASC is 94s and 117s, and the average fuel consumption in the whole trip with CTV and ASC is 74g and 97g. Additionally, the vehicles with the CVT method almost avoid idling and stop, which causes less fuel consumption than with the ASC method. In conclusion, the CTV improves the transportation efficiency and fuel economy by 19.7% (11.1% when considering the number of passing vehicles) and 23.7% respectively compared with ASC in the studied scenario.

V. Conclusion and Discussion

This paper proposes a V2I based cooperation between traffic signal and approaching automated vehicles which optimizes traffic signal and vehicles' trajectories concurrently. The suggested method includes traffic optimization in the roadside and vehicle optimal control onboard. The traffic optimization calculates the optimal signal timing and vehicles' arriving time according to the current vehicle state at the end time of each signal cycle, and then the optimized vehicles' arriving time is sent to the corresponding vehicle. In the vehicle optimal control, the engine power profile and the brake force are optimized with the constraints of vehicle dynamics, safe headway, and arriving time. The simulation is conducted using VISSIM and MATLAB with the baseline algorithm of ASC. The simulation results show that the proposed algorithm can improve transportation efficiency and fuel economy by 19.7% and 23.7% respectively in the case study.

In the future research, the influence of the communication range and the traffic signal cycle on the cooperation algorithm should be studied further. Besides, research on the performance in oversaturation cases is also needed. Additionally, the cooperation method needs to be extended for multiple intersections or traffic corridors cases. The geometry of the intersections (such as shared through and right-turn lanes), and pedestrians can be also considered in the cooperation method.

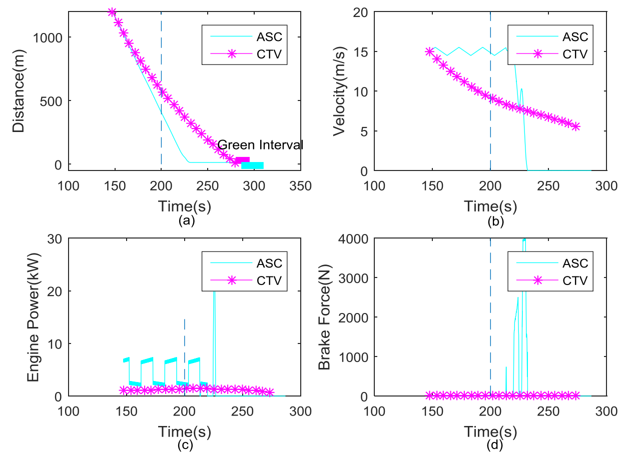

Figure 5 Vehicle State and Control Variables of ASC and CTV

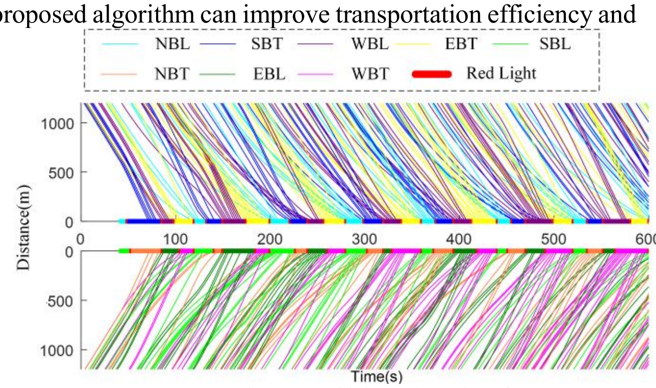

Figure 6 Vehicle Trajectories of CTV

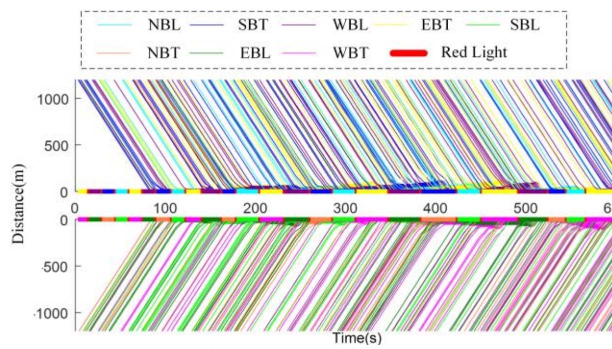

Figure 7 Vehicle Trajectories of ASC

TABLE II. Performance Comparison between ASC and CTV

Algorithm	Number of Passing Vehicles	Average Fuel consumption (g)	Average Trip Time (s)	Average Idling Time (s)	Total Number of Stop
ASC	361	97	117	33.8	307
CTV	406	74	94	0.92	12
Improvement (%)	11.1	23.7	19.7	97.3	96.1

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