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An Eco-Driving Signal Control Model for Divisible Electric Platoons in Cooperative Vehicle-Infrastructure Systems

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ABSTRACT This paper proposed an eco-driving model for divisible electric platoons at a signalized intersection in the environment of cooperative vehicle-infrastructure systems (CVIS). Platoon releasing plan and signal control scheme are obtained through platoon splitting and speed guidance. One main contribution of the method is the proposal of a new multi-objective optimization model with the objective functions aiming at minimizing platoon passing time and energy consumption, as well as the optimal solution is obtained by Matlab programs. According to the optimal scheme, the platoons are split up, and speed guidance is conducted. Combining with the phase plan, the platoons are released at the signalized intersection. The simulation of the proposed eco-driving platoon control model (EPCM) and actuated platoon control model (APCM) are conducted with Matlab and Simulation of Urban Mobility (SUMO) invoked by Python. The simulation results show that the average waiting time of vehicles decreased by 8.97%, the maximum queuing time of vehicles in four directions decreased from 38.1% to 54.3%, respectively, and the total energy consumption decreased by 21.3%, which indicate that the EPCM can effectively reduce the energy consumption of electric platoons while through the intersection. The passing efficiency can be ensured, and the average waiting time at the stop line can be reduced in the meantime.

INDEX TERMS Cooperative vehicle-infrastructure systems (CVIS), divisible platoon, electric vehicle, eco-driving, speed guidance, signalized intersection.

I. INTRODUCTION

With the rapid development of the urban economy, the demand for vehicle travels has been increasing significantly. Vehicles are incredibly convenient for door-to-door trips. In addition, as one of the supporting pillar industries of the state, the automobile industry has a large influence on the development of the national economy and other industries. However, environmental pollution, energy consumption, traffic congestion, and traffic safety issues caused by traditional oil-fueled vehicles have brought about great negative effects.

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As an approach to relieve the problems above, battery electric vehicle (BEV) has become the current research hot spot. A BEV is driven completely through an electric motor with the high-efficiency battery as the energy source. BEV has the advantages of reducing air and noise pollution and can greatly alleviate the current situation of automobile exhaust pollution. In addition, the control of the pure electric vehicle is simpler than traditional vehicles, and the energy conversion efficiency of the motor drive system is higher, which has great advantages in energy conservation.

Therefore, the energy-saving driving strategy for pure electric vehicles has become the research focus of many scholars [1]–[4]. Based on the theoretical study on the energy conservation driving technology of electric vehicles, Koriyama, Yamamoto, et al. establish an optimized control model with Bellman dynamic planning method to obtain speed optimization scheme of electric vehicles with known starting and ending points, running time and route status [5]. Zheng et al. propose a predictive driving control strategy for pure electric vehicles. The optimal control theory and predictive traffic information, including vehicle speed limit and path length, are used to provide the best energy-saving driving path for pure electric vehicles [6]. On the basis of accurate modeling of longitudinal dynamics, motors, batteries and other parts of electric vehicles, a speed optimization profile is set up through dynamic programming and integrated into an energy-saving driving assistance system [7]. Apart from the researches on energy-saving driving control strategies for pure electric vehicles, the regenerative braking system is also an important character of pure electric vehicle in when considering Eco-driving methods. Based on the analysis of the proprieties and influences of motors and batteries, the ability of regenerative braking system under various combinations of vehicle speeds and desired accelerations are tested. The results indicate that the proper combination of vehicle motors and batteries should be considered in order to achieve the desired performance with various speeds [8]. (Analysis of influence factors of electric vehicle on the following characteristics)

Meanwhile, the technologies of Vehicle to Everything (V2X) communication that applied in intelligent transport systems provide more effective strategies for the control and management of vehicles on the road. In CVIS environment, connected vehicles can exchange information with the intersection control center, roadside facilities, and other vehicles for perception and judgment of surrounding traffic conditions, so as to optimize the vehicle control and effective management. Numerous scholars have made in-depth studies on vehicle release mode at the intersection through V2X technology [9]–[11]. Li et.al. propose a signal control method with a DP formulation and a combination of the end stage cost and a branch and bound algorithm to optimize the signal timing for a single intersection in the CV environment [12] Paruchuri et.al. make effort to optimize traffic signal control by utilizing vehicle arrival times [13]. A dynamic traffic light control system based on vehicle speed information from V2I is proposed to maximize intersection throughput to reduce congestion and pollution [14]. Goodall et al. put forward a signal optimization control method based on micro-prediction, and search for the optimal timing scheme through accurate prediction and evaluation of traffic conditions under different schemes [15]. Liu et al. combine the modeling skills of deep learning and the domain knowledge in transportation into a prediction of metro passenger flow.[16] Wang et al. proposed a model incorporating a diffusion approximation method to explore the correlation between failure rate and bus-stop operation.[17]

Integration of pure electric vehicle with CVIS technology is an effective way to improve traffic efficiency by utilizing a large amount of information in the traffic system while saving energy and protecting the environment. Ojeda, HAN et al. took connected automatic cars (CAV) as research objects, proposed a CAV control system considering safety and Eco-driving. Under the premise of avoiding collision with the front vehicle, the acceleration and deceleration of vehicles are optimized under the condition of speed constraint to achieve the minimum energy consumption and the operational effectiveness of the control system in a variety of different driving scenarios is evaluated [18]. Zhang et al. acquire the state of the vehicle and prejudge the motion state of vehicles with wireless communication between connected vehicles. Based on the relevant information, an EMPC control method is proposed to realize real-time control of pure electric vehicles by keeping a certain distance from the vehicle in front while minimizing energy consumption [19]. In [20], a hybrid model predictive control method is established by using road and traffic condition information obtained by V2X communication. On the premise of security assurances, energy saving optimization control is carried out for pure electric vehicles to extend their driving range. A real-time adaptive speed control method for a pure electric vehicle in a connected vehicle environment is proposed in [21]. The armature voltage of the motor is manipulated through fuzzy logic and PID controller to achieve better performance on acceleration and speed control.

Considering the operation characteristics of pure electric vehicles, the control strategy of signal intersection under CVIS environment can make use of the spatial and temporal resources at the intersection more effectively and reduce the consumption of energy. Taking into account of the spatial-temporal influence of vehicles queuing at intersections, Wu et al. propose a multistage optimization control model to reduce the energy consumption of electric vehicles at multiple signal intersections on urban arteries through velocity trajectory planning [22]. In view of the characteristic of electric vehicles, Zhang and Yao propose a microscopic energy consumption rate model for different operation modes based on the VT-micro model developed from conventional vehicle fuel consumption and emission. The influences of speed, acceleration and the duration of different states on energy consumption are studied and then signal control information obtained by TLVC technology is used to develop the energy-saving driving model, which optimizes the energy consumption of electric vehicles through the upstream and downstream of the intersection [23].

Compared with discrete vehicles, the platoon has smaller vehicle spacing, which can reduce energy consumption by decreasing air resistance and simplify vehicle control operations. It can also improve the efficiency of road space resource utilization and optimize signal control effect at the intersection. The technologies of CVIS provides great convenience for platoon formation and management. [24] searches for a speed optimization scheme to minimize average idling time and stop times at signalized intersection for platoons formed by autonomous vehicles. The speed of leading autonomous vehicle is optimized under different phase, and TTI circumstances and the platoon is considered to be split if necessary in order to decrease the delay and stop-and-go behaviors of all vehicles in the platoon. Yang et al. [25] proposed a signal control method for platoons at a single intersection under Intelligent Vehicle Infrastructure Cooperation Systems. In the model, a notion of dynamic formation of platoons is brought forward, which takes the real-time headway between two consecutive vehicles as the basis of platoon segmentation. The release time of platoon is computed according to the motion state of the last vehicle of the platoon and the total waiting time of unreleased platoons in other directions is taken as the criterion of phase switch. Jin et al. put forward a multi-agent intersection management system for platoons composed by vehicle agents through V2V communication [26]. Three main components of the system, leading vehicle agent, following vehicle agent and intersection management agent, integrate to realize platoon forming, passing platoon arrangement, and information exchange.

The results of existing researcher have shown that, with the development of technology, the performance of pure electric vehicles will be prior to traditional oil-fueled vehicles in environment protection, maintenance cost, and other aspects. Besides, the application of pure electric vehicles is able to alleviate the energy crisis caused by the consumption of non-renewable fossil energy, which would give electric vehicles the potential to take a bigger market share than traditional vehicles in the future [27]. At the same time, the development of an eco-driving system for electric vehicles is able to plan vehicle velocity trajectories under various scenarios to get energy and mobility benefits taking advantage of the signal control information via I2V communication [28]. Considering the advantages mentioned above and the mileage of electric vehicles at present can meet the demand of urban transport [29], the platoon formed by pure electric vehicles is chose as the object of the proposed eco-driving control model in this research.

This research contributes a traffic control model which considers operations of both the traffic signal and the platoons according to the schemes provided by a multi-objective optimization model aiming at improving the traffic condition and economizing energy consumption. The muti-objective optimization model is constructed combining speed guidance and platoon splitting to seek the optimal platoon releasing strategy considering the energy-saving efficiency and traffic efficiency at the intersection. Then, the traffic signal and the motivation of platoons are both adjusted following the relevant signal phase plans and platoon motion schemes given by the multi-objective optimization model.

This paper is structured as follows. In section 2, the studied scenario and assumptions are presented. Section 3 provides a methodology of the proposed Eco-driving platoon control model (EPCM) with phase planning, speed guidance, and platoon splitting. Then the EPCM model and an actuated signal control model for comparison are evaluated in SUMO, and the analysis results are presented in Section 4. Section 5 provides conclusions and future research directions.

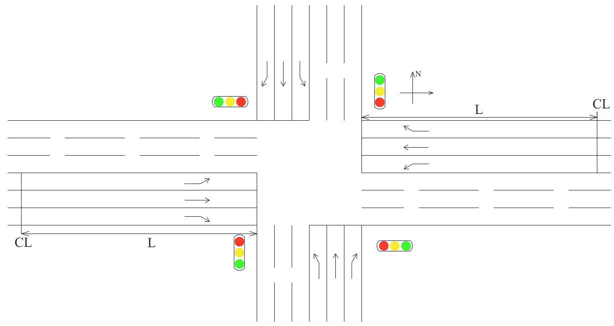

FIGURE 1. Studied scenario.

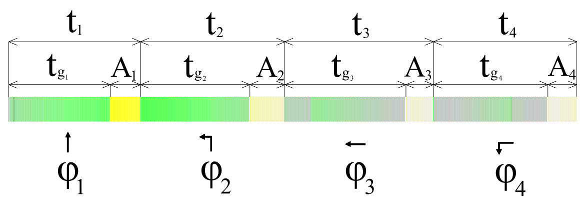

FIGURE 2. Simplified signal phase sequence.

II. PROBLEM STATEMENT AND ASSUMPTIONS

This paper considers a 4-legged signalized intersection (Figure 1). Each approach of the intersection has 3 lanes. The intersection is controlled by a 4-phase plan. For simplification, this paper assumes that the left-turn, through and right-turn traffic flows of northbound and westbound, i.e., NL, NT, NR, WL, WT, WR, are critical traffic flows and only considers these 8 movements in the model and the simplified signal phase sequence is applied (Figure 2). As for the right-turn traffic, they are released as soon as they arrive since they don't conflict with traffic flows from other approaches.

A control line (CL) is set L meters from the stop line in each approach of the intersection. The area between the control line and stop line is the control area (CA) in which the platoons adjust their driving status according to the scheme received from the control center. The platoons in the queue (F_q) and the platoons in motion ($F_1, F_2, \ldots, F_i$) are detected in this area.

The proposed method adopts the following assumptions: Vehicles on the road are pure electric passenger cars equipped with communication facilities, trucks, non-motor vehicle, and pedestrians are not in consider; a control center at the intersection fully manipulates the operation of platoons in the CA and inside the intersection while the platoons pass through the intersection; only consider the ideal circumstance without communication delay and packet loss; the roads under ideal conditions and all lanes are level ground.

III. METHODOLOGY

The following signal control-platoon splitting method is conducted firstly by judging whether the divisible platoons entering the control area could pass through the intersection under the constraints of phase time limitation, the average waiting time of platoons from other directions and safety constraints. For the platoon which can completely pass the intersection during the current releasing time, the multi-objective model aiming at traffic efficiency improvement and energy consumption reservation is established. Then the statement of the platoon is adjusted according to the target acceleration and velocity obtained from the model to pass through. As for the platoon that needs to be separated, the main control objective is that the total energy consumption of passing part and decelerating part of the original platoon is minimized while the passing vehicles could go through the intersection as soon as possible. The state judgment of unreleased platoons of other phases is carried out during the release of the target phase, and their control schemes are determined based on multiple constraints.

A. PHASE RELEASE TIME DETERMINATION

Taking the divisible electric platoons (DEP) released by phase m (m = 1, 2, 3, 4) to describe the control method of EPCM. The DEP in the release direction of phase m is denoted as F_{mi} (i = 0, 1, 2, 3, ...) when i = 0 the platoon refers to the queuing platoon. The first vehicle of F_{mi} arrives at the CL at $T_{mi,0}$, $T_{mi,arrive}$ is the time the first vehicle arrived at the stop line and at T_{mi} the whole platoon passes the stop line completely. The starting time of phase m is T_{ms}, the actual ending time is T_{me}, and the latest ending time is $T_{me,max}$. Phase m release time $t_{phase,m}$ determination method is described as follow:

First, set the maximum and minimum green time $g_{m,max}$ and $g_{m,\min}$. The minimum green light release time is the time taken by queuing platoon to complete passing through the stop line. The maximum green time is calculated based on the traffic volume in all directions at the intersection and $\mathrm{T_{me,max}} = \mathrm{T_{ms}} + \mathrm{g_{m,max}}$.

Then considering the current operation status of the platoon arriving at the CL (F_{mi}) and the platoon behind ($F_{m(i+1)}$). According to the average waiting delay $\bar{t}_{m,d}$ of platoons from other unreleased phases at the time $\mathrm{T_{mi,0}}$ and the time T_{mi} , $t_{phase,m}$ and $\mathrm{T_{me}}$ are determined.

The average delay time of queuing platoons from the unreleased direction:

$$\bar{t}_{d_{m,d}} = \sum_{k=1}^{4} \frac{\sum_{p=1}^{N_{kq}} t_{dkp}}{N_{kq}}, (k \neq m) \tag{1}$$

where t_{dkp} is the waiting time of the p th vehicle in the queue at the release direction of phase k, and $\mathrm{N_{kq}}$ is the number of vehicles in the queue at the release direction of phase k.

The upper limit of average waiting time is set as $\bar{t}_{dmax}$, and in case $T_{mi,0} < T_{me,max}$, the release time of phase m determined by the operation status of F_{mi} and $F_{m(i+1)}$ is:

$$t_{phase,m} = \begin{cases} T_{mi,0} - T_{ms}, & \bar{t}_{m,d} \geq \bar{t}_{d\,\max} \\ T_{mi} - T_{ms}, & \bar{t}_{m,d} < \bar{t}_{d\,\max} and T_{m(i+1),0} \geq T_{me,\max} \\ g_{m,\max}, & \bar{t}_{m,d} < \bar{t}_{d\,\max} and T_{m(i+1),0} < T_{me,\max} \end{cases} \tag{2}$$

At the time when F_{mi} reaches the CL (time point $\mathrm{T_{mi,0}}$), if the average waiting time of queuing platoons in the unreleased direction at this time has reached the upper limit, then the phase is switched and F_{mi} drive to the stop line in a way that minimizes energy consumption and waits for the next release.

If the average waiting time of $\mathrm{T_{mi,0}}$ does not reach the prescribed limit value, but the subsequent platoon $F_{m(i+1)}$ has exceeded the maximum release time of phase m when driving to the control line at the current speed, the release time of phase m will be cut off until F_{mi} passes the stop line completely.

If the current average waiting time still meets the requirements when F_{mi} arrives at CL, and $F_{m(i+1)}$ is still within the maximum release time of this phase when arriving at CL according to the current speed, the current phase will continue, and the release time is tentatively set as $g_{m,max}$. If in this phase $T_{mi,0} \geq T_{me,\max}$, F_{mi} will not be allowed to pass through. The end time of current phase m is determined by the operation status of the arrival platoon F_{mi} and subsequent platoon $F_{m(i+1)}$:

$$T_{me} = T_{ms} + t_{phase,m} \tag{3}$$

For each platoon arriving at the control line within the maximum release time, a determination of the actual release time of this phase is conducted until the time when the phase m is determined to be switched.

B. PLATOON TRANSIT CONTROL METHOD

The judgment condition that platoon F_{mi} can completely pass the intersection without splitting is that F_{mi} can reach the stop line at the original speed within the time period $\mathrm{T_{me,max}} - \mathrm{T_{mi,0}}$, otherwise it needs to split up or stop waiting, which is:

$$v_{mi0}(T_{me,\max} - T_{mi,0}) \geq L \tag{4}$$

For platoon F_{mi}, the arrival speed at CL is v_{mi0}, the target speed of the speed guidance is v_{mi1} and the acceleration of uniform variable motion is a_{mi}. The speed guidance is conducted one by one for the platoons completely passing the intersection. For F_{mi} , consider the constraints on the operation of the previously platoon $F_{m(i-1)}$ and other constraints in the environment. The muti-objective traffic optimization model of F_{mi} is constructed with the aim of the shortest transit time and the minimum energy consumption at the intersection:

a. Objective function

i). Minimization of platoon transiting time through the intersection

From the moment the platoon passes through the control line, the optimization scheme is calculated. To avoid complicated traffic situation at the intersection, the platoons should pass through the intersection at a constant speed after speed guidance:

$$J(v_{mi}, a_{mi})_1 = t_{mi} = \left|\frac{v_{mi0} - v_{mi1}}{a_{mi}}\right| + \frac{L + L_{mi} - \left|\frac{v_{mi0}^2 - v_{mi1}^2}{2a_{mi}}\right|}{v_{mi1}} \tag{5}$$

where L_{mi} is the length of roads occupied by F_{mi} , $L_{mi} = \sum_{1}^{N_{mi}} l_{mi,k} + (N_{mi} - 1)\Delta l$; $l_{mi,k}$ is the length of the k th vehicle in the platoon; N_{mi} is the number of vehicles in F_{mi} , and Δl is the distance between vehicles in the platoon.

ii). Minimization of energy consumption while through the intersection

In this study, the energy consumption model of pure electric vehicle in [11] is adopted to construct the energy-saving model. Assuming that the electric energy generated by an electric vehicle is equal to the electric energy required to generate traction, and the energy consumption of other parts within the vehicle is ignored, the total energy consumption E of a certain distance of travel can be obtained by the power integration against time:

$$J(v, a, t)_2 = \int_0^T P(t)dt \tag{6}$$

The instantaneous power of an electric vehicle can be estimated as:

$$P(v, a) = \frac{rR^2}{K^2}(ma + kv^2 + f_{rl}mg + mg\sin\theta)^2 + v(kv^2 + f_{rl}mg + mg\sin\theta) + mav \tag{7}$$

where F is traction force, m is vehicle mass, v is speed, a is acceleration, $k = (\rho/2)C_D A_f$, C_D is traction coefficient, A_f is the area of vehicle frontal area, f_{rl} is rolling resistance constant, g is gravity acceleration, and θ is road slope. I is the current and r is the resistance of the conductor in the motor. $K = K_a\Phi_d$, K_a is the armature constant, Φ_d is the magnetic flux; I is the current; R is the radius of the tire.

Since the platoon gets its adjusting message as soon as it arrives at the control line, the integral upper limit T in (6) contains the whole time span of the speed adjustment and passing through the intersection with the constant speed after speed guidance, which can be regarded as the approaching and departure stages of the target platoon. In this model, the length of CA, denoted as L, is set as 300 m so that the whole process of platoon approaching, speed guidance and departure could be considered.

The objective function is:

$$f_1 = \min(J(v, a)_1, J(v, a, t)_2) \tag{8}$$

b. Constraints

Velocity constraint:

$$v_{mi0}, v_{mi1} \in [v_{m,\min}, v_{m,\max}] \tag{9}$$

Acceleration constraint:

$$a_{mi} \in [a_{m,\min}, a_{m,\max}] \tag{10}$$

Safety constraint: the current platoon arrives at the stop line after the previous platoon has passed the stop line completely. In order to ensure traffic safety at the intersection, the speed change process is completed before reaching the stop line, and the platoon passes through the intersection at a constant speed. Thus, the time when the first vehicle of the platoon reaches the stop line is $T_{mi,arrive} = T_{mi,0} + t_{mi} - L_{mi}/vmi1$, and the constraint is denoted as:

$$T_{mi,arrive} \geq T_{m(i-1)} \tag{11}$$

Based on the above analysis, the control model of the undivided platoon in phase m is shown in (8) ~ (11).

C. ENERGY-CONSERVING PLATOON SPLITTING METHOD

For platoon F_{mk} , if it reaches the control line within the maximum release time, still meets the average waiting time constrain but cannot pass through the stop line completely at current speed in the remaining time, then it is considered to be separated. From the analysis above, the splitting condition is $v_{mk,0}(T_{me,\max} - T_{mk,0}) < L$. Speed guidance is conducted for both the passing part F_{mk1} and halting part F_{mk2} . The splitting scheme with the minimum total energy consumption is selected for platoon separation.

The speed and acceleration constraints are the same as for undivided platoon. Besides, F_{mk1} should reach the stop line after the passage of the former platoon and pass through the stop line before the end of release time, which is:

$$T_{mk1,arrive} \geq T_{m(k-1)} \tag{12}$$

$$T_{mk1} \leq T_{me} \tag{13}$$

F_{mk2} needs to complete the process of slowing down to 0 and stopping at the stop line in the control area. The speed should be adjusted from the moment F_{mk} reaches the control line. The energy consumption of F_{mk1} is E_1 , and for F_{mk2} is E_2 .

$$J(v, a, t)_3 = E_1 + E_2 \tag{14}$$

In addition, considering that F_{mk1} should pass through as soon as possible, the objective function is:

$$f_2 = \min(J(v_{mk1}, a_{mk1})_1, J(v, a, t)_3) \tag{15}$$

Based on the above analysis, the control model of the divided platoon in phase m is shown in (8) ~ (10), (12)~ (13), (15).

TABLE 1. Simulation parameters.

Parameter	Value	Parameter	Value
$m(kg)$	1266.0	$v_{max}(m/s)$	16.7
f_{rl}	0.006	$v_{min}(m/s)$	8.3
k	1.30	$a_{max}(m/s^2)$	4.8
$K(V\cdot s)$	10.08	$a_{min}(m/s^2)$	-3.4
$r(\Omega)$	0.11	$L(m)$	300
$R(ft)$	1.64	$g(m/s^2)$	9.8
$\eta(\%)$	95	GA Generations	500
$\theta(°)$	0	GA Population Size	50

D. STATUS JUDGMENT FOR PLATOONS IN THE NEXT PHASE

The time when platoon $F_{(m+1)j}$ released by phase $m+1$ reaches its corresponding control line is $T_{(m+1)j,0}$, and the time when the current speed reaches the stop line or the end of the queue with the current speed is $T_{(m+1)j,arrive}$.

If $T_{(m+1)j,\ arrive} \geq T_{me}$: there is no need to stop and queue, adjust the speed to pass through under the scheme acquired from EPCM.

If $T_{(m+1)j,\ arrive} < T_{me}$: Conduct speed guidance to join the queue in the way that minimizes energy consumption.

IV. RESULTS OF SIMULATION ANALYSIS

In this study, Python, Matlab and the urban traffic simulation platform SUMO, were combined for the joint simulation. The TraCI interface of SUMO was called by Python to realize the generation of divisible platoons, platoon splitting, speed guidance, and signal control at the intersection. The GA multi-objective function in Matlab was called to implement the genetic algorithm for vehicle transit time-energy consumption muti-objective optimization planning with 500 generations and population size 50. The gamultiobj function uses a variation of NSGA-II to find Pareto front and the Pareto optimal solutions of the multi-objective problem beginning with the initial generation population randomly produced by the algorithm. In this research, the number of Pareto optimal solutions depends on the situation of the target platoon and the parameter ParetoFraction set in Matlab. While establishing the multi-objective model with Matlab, the objective function for platoons passing through completely is set as (8) and for platoons need to be split, the objective function is (15). The constraints are set in accordance with the relevant parts in section III. The relevant information such as vehicle velocity, platoon length, the number of vehicles in the platoon and other parameters are received from the traffic control interface of SUMO. The speed, acceleration and related performance parameters of pure electric platoons are shown in Table 1, where the relevant performance parameters refer to the values adopted in (11). Besides, the parameter min-gap in SUMO was set as 1.5 m in the simulation as the safe distance in vehicle insertion and car follow the model to guarantee the driving safety.

An actuated platoon control model (APCM) was constructed through SUMO in order to conduct a comparative analysis with the proposed EPCM method. Four induction loops were set 500 m from the stop line on lanes of direction NL, NT, WL, WT to collect platoon arrival information. Then a gap-based actuated traffic control program was built by SUMO with the minimum duration 5 seconds and the maximum duration 45 seconds for each direction. When platoons reach the control line, they accept the actuated signal control at the intersection. The vehicles are detected by the pre-set detectors and the phase is prolonged or switched based on the time gap between the arriving platoons.

The EPCM method and actuated platoon control model are simulated for comparative analysis. In the same platoon generation environment, the two models were simulated with 3,800 steps in SUMO. The traffic demand for each direction of the single intersection were generated through different probability and the final traffic volumes for NL, NT, NR, WL, WT, WR were recorded as well as other simulation results (Table 2). The time-varying trend of average wait time, energy consumption and queue time for both models are shown below (Figure 3 – 5).

According to the simulation results (Table 2), compared with APCM in the same simulation time and traffic condition, the condition of traffic efficiency and energy consumption both improved under the control of EPCM. The average waiting time of vehicles decreased by 8.97%, the maximum queuing time of vehicles in four decreased from 38.1% to 54.3% respectively, and the total energy consumption decreased by 21.3%.

The total energy consumption per second in the simulation process is shown below (Figure 3). It can be seen from the figure that the energy consumption of EPCM is less than APCM in most cases, and the energy consumption of EPCM is relatively stable within a certain range, while the APCM has a large fluctuation. As the energy consumption of the pure electric vehicle is related to the speed and acceleration, this result indicates that the speed change of pure electric

TABLE 2. Simulation indicators.

	TRAFFIC VOLUME (veh/h)	
NL 189	NT 356	NR 182
WL 201	WT 322	WR 163
SIMULATION INDICATOR	EPCM	APCM
MEAN WAITING TIME(S)	3.45	3.79
	MAXIMUM QUEUING TIME(S)	
PHASE 1	32	70
PHASE 2	33	70
PHASE 3	39	63
PHASE 4	37	77
ENERGY CONSUMPTION(Wh)	196727	250032

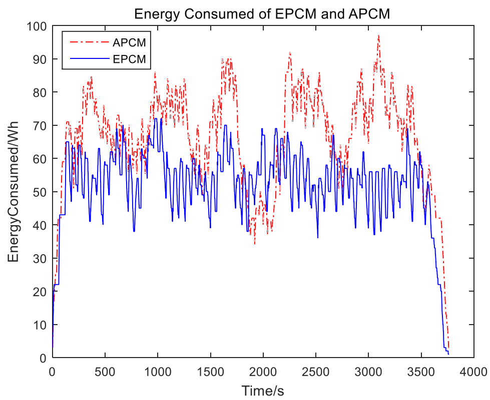

FIGURE 3. Energy consumption of EPCM and APCM.

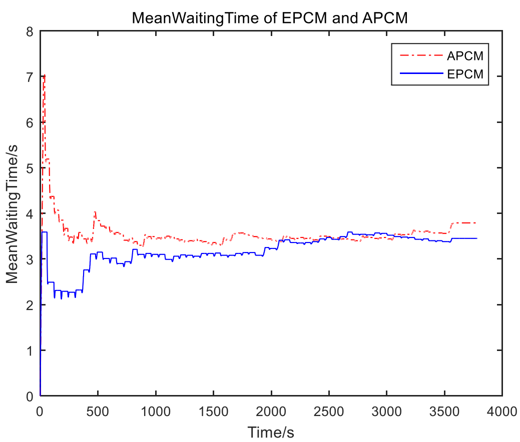

FIGURE 4. Mean waiting time of EPCM and APCM.

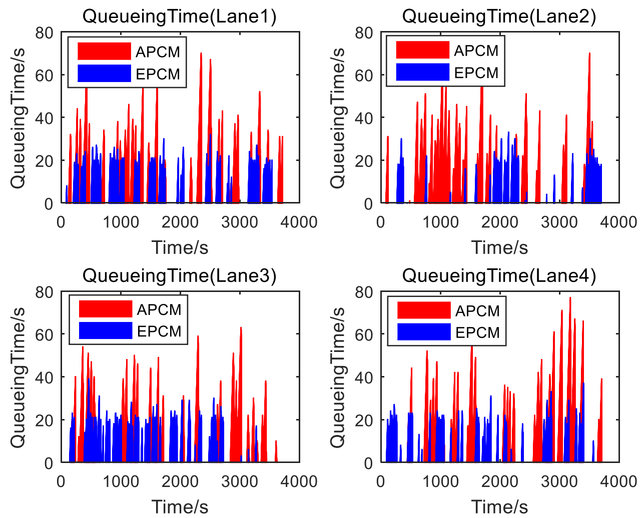

FIGURE 5. Queuing time of 4 phases.

platoons under EPCM control is relatively small and can be maintained within a certain range to ensure the stability and comfort of driving. The average waiting time curve of EPCM in the simulation process is mostly below or near the APCM curve (Figure 4), indicating that the platoons under the control of EPCM has a shorter waiting time at the stop line and can guarantee the traffic efficiency at the intersection.

The change of queue time of the lane corresponding to each phase (Figure 5) demonstrates that, through the analysis of queuing condition of the four release phases, the platoons under the EPCM control have less queuing time at the intersection. This is consistent with the changing trend of average waiting time, indicating that the EPCM control takes full account of the queues at the intersection and effectively reduces the queuing time when calculating the release strategy, which can keep the traffic condition at the intersection at a good level and avoid congestion.

There are several reasons the EPCM control method performs better than APCM. Firstly, EPCM is more flexible in phase switching and platoon releasing. The releasing time of each platoon and the end time point of the current phase is achievable through the computation so that the control center could end the current phase timely if the following platoon is known to stop at the intersection. However, as for APCM, the phase continues until the time gap is long enough for switching. During this time gap, no platoon arrives at the detectors and it is actually wasted while the vehicles from other directions are waiting to be released, which is the reason that APCM has longer waiting time and queuing time than EPCM. Secondly, EPCM not only considers the traffic efficiency and energy consumption for the released platoons but also develop control strategies for the ones that cannot pass through. As mentioned in section III, the energy consumption of the part of platoon that cannot pass through is considered in the multi-objective optimization model while APCM only conducts platoon releasement for the ones arriving at the detectors within the maximum release duration and simply cut off the current phase when the time limit is reached without adjusting the motivation of the platoons that need to stop.

In conclusion, compared with APCM, the EPCM control method proposed in this paper can reduce the energy consumption of pure electric platoons while ensuring traffic efficiency at the intersection. At the same time, the variation of speed and acceleration is smaller, manifesting that the sudden change of velocity rarely occurs, so as to ensure the stability and comfort of traveling.

V. CONCLUSION

This paper proposed a CVIS-based Eco-driving control model for divisible electric platoons which could improve traffic efficiency as well as reducing energy consumption at the signalized intersection. In this method, a multi-objective optimization model is established to obtain the release schemes which ensures the shortest transit time and the least energy consumption for electric platoons and the relevant signal phase plans. Then the platoon separation and speed guidance schemes calculated by EPCM are conducted to adjust the vehicle fleet and release the vehicle fleet at the intersection. The simulation of EPCM was implemented using Python, Matlab and SUMO, and compared with the actuated signal control method. The results indicated that under the control of EPCM, the average waiting time decreased by 8.97%, the maximum decline of maximum queuing time in different directions was 54.3% and the total energy consumption was saved by 21.3% compared to APCM. It is shown that the proposed EPCM method has a good energy-saving effect and less average waiting time, which proves that the passage efficiency can be guaranteed while receiving good energy saving effect.

At present, the mileage of pure electric vehicles is shorter than oil-fueled vehicles due to the influence of battery capacity limitation, however, the brake energy regeneration of electric vehicles makes it possible to utilize the limited power more efficiently thereby extending the mileage. In addition to energy conservation, the mileage extension of electric vehicles will also be taken into account while developing the platoon control strategy at signalized intersection in further study. On this basis, the proposed platoon control method is also considered to be improved and extended to arterial control in the future.

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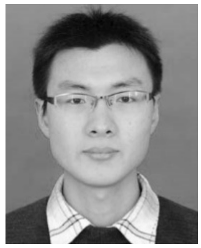

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