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ECO-DRIVING CONTROL FOR ELECTRIC VEHICLES AT INTERSECTIONS WITH WIRELESS CHARGING

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ABSTRACT

Electric vehicles (EVs) have been viewed by many as a method to reduce greenhouse emissions, operate mobility efficiently, and decrease energy consumption. The limited driving range is a huge challenge to promote the popularization of EVs. The wireless charging lane can charge EV when it travels, thus can decrease the driving range anxiety of the driver. In this paper, we propose a new wireless charging scheme which combines the signalized intersection and partial wireless charging lane. We develop an eco-driving control strategy for EVs at intersections with wireless charging. The numerical results show that the wireless charging scheme with the eco-driving control strategy can increase the driving range and decrease the travel cost.

Keywords: electric vehicles, eco-driving control, signalized intersections, wireless charging

NOMENCLATURE

Abbreviations	
EV	Electric vehicle
Symbols	
ECR	Electricity consumption rate (w)
v	Velocity (m/s)
a	Acceleration (m/s^2)
$\alpha_{i,j}$	The coefficient for *ECR* at speed power *i* and acceleration power *j* in accelerating state
$\beta_{i,j}$	The coefficient for *ECR* at speed power *i* and acceleration power *j* in decelerating state
γ_i	The coefficient for *ECR* at speed power *i* in cruising state
$\overline{ecr}$	Average electricity consumption rate for the idling mode (w)
$E_{discharge}$	Electricity discharging amount (J)
E_{charge}	Electricity charging amount (J)
p_{charge}	Charging power (w)
T_{charge}	Charging time (s)
$\mathbf{x}$	Status vector of an EV
s	Location (m)
$\mathbf{u}$	Control variable vector
L	Travel cost (RMB)
ω_1	Value of time (RMB/s)
ω_2	Electricity price (RMB/J)
t_0	The time when a vehicle enters the intersection (s)
t_f	The time when a vehicle leaves the intersection (s)
s_0	The start position of the road segment (m)
D	The end position of the road segment (m)
D_1	The start position of the wireless charging area (m)
D_2	The end position of the wireless charging area (m)
D_3	Stop line position (m)
t_r	End-of-red time (s)
t_g	End-of-green time (s)
$v_{\max}$	Maximal velocity (m/s)
$a_{\min}$	Maximal deceleration (m/s^2)
$a_{\max}$	Maximal acceleration (m/s^2)

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a_1	Acceleration in the first shift phase (m/s^2)
a_2	Acceleration in the second shift phase (m/s^2)
v_0	Initial speed (m/s)
v^*	Speed in the cruising state (m/s)
v_f	End speed (m/s)
t_1	The start time of the first shift phase (s)
t_2	The end time of the first shift phase (s)
t_3	The start time of the second shift phase (s)
t_4	The end time of the second shift phase (s)
$\tilde{T}$	The earliest time that vehicle could pass the intersection (s)

1. INTRODUCTION

Electrification of vehicles is the future of the transport sector to achieve energy conservation and sustainable development. The limited driving range is a critical factor that hinders the popularization of EVs. Wireless charging lane can recharge the electric vehicle when it is in motion, and some field experiments are carried out to test wireless charging lane in many countries [1-3]. It is shown that charging-while-driving can significantly reduce the driver's driving range anxiety and can promote the popularization of EVs.

As a bottleneck in the urban transport system, signalized intersection generates stopped or slow traffic in front of it. In the meantime, the stopped or low-speed EVs can charge much more electricity on the wireless charging lane than the high-speed vehicles. Therefore, it gives us a chance to combine the signalized intersection with wireless charging facilities to improve the driving range of EVs in the urban road system. Mohrehkesh and Nadeem [4] have proven the effectiveness of wireless charging at traffic intersections, but they only considered the stopped vehicles. However, many studies have shown that a proper speed control strategy can help cars go through the intersection without any stop and increase traffic efficiency significantly [5-7]. It comes to a trade-off between electricity charging amount and traffic efficiency.

In this paper, we first propose a new wireless charging scheme which combines the signalized intersection and partial wireless charging lane. Then, we develop an eco-driving control strategy for EVs at intersections with wireless charging. We further develop an approximation model to increase the computation efficiency. The remainder of this paper is organized as follows. Section 2 presents the methodology. We introduce electricity consumption and wireless charging models for EVs. Then, we develop the eco-driving control model and its simplified model. Next, we conduct numerical tests and discuss the simulation results in section 3. Finally, the concluding remarks are provided in section 4.

2. METHODOLOGY

2.1 Electricity consumption and wireless charging models for EVs

Several studies are carried out to study the EV's energy consumption [8-10]. Here, we use the statistical model proposed by Yao et al. [9] to calculate the electricity consumption rate for EV. The structure of this model is as follows.

$$ECR=\begin{cases}\sum_{i=0}^{3}\sum_{j=0}^{3}\left(\alpha_{i,j}\times v^i\times a^j\right) & a>0\\ \sum_{i=0}^{3}\sum_{j=0}^{3}\left(\beta_{i,j}\times v^i\times a^j\right) & a<0\\ \sum_{i=0}^{3}\left(\gamma_i\times v^i\right) & a=0, v\neq 0\\ \overline{ecr} & a=0, v=0\end{cases}. \quad (1)$$

Zhang and Yao [10] calibrated the parameters with real condition data collected on typical urban travel routes. See Table 1 for the values of the coefficients. Here we should note that the regenerative braking energy is included in the *ECR*.

Table 1 Values of coefficients

Coefficients	Values	Coefficients	Values
$\alpha_{0,0}$	871.011	$\beta_{1,1}$	1043.669
$\alpha_{1,0}$	567.202	$\beta_{3,1}$	1.008
$\alpha_{3,0}$	-0.420	$\beta_{3,3}$	-0.324
$\alpha_{1,1}$	1775.196	$\gamma_{0,0}$	1098.639
$\beta_{0,0}$	895.857	$\gamma_{1,0}$	501.635
$\beta_{1,0}$	378.482	$\gamma_{3,0}$	0.467
$\beta_{3,0}$	0.840	$\overline{ecr}$	3420.702
$\beta_{0,3}$	-713.417	-	-

The electricity consumption is calculated as

$$E_{discharge}=\int_{t_0}^{t_f} ECR\left(v(t),a(t)\right)dt. \quad (2)$$

The wireless charging power can be regarded as a constant so the electricity charging amount can be calculated as

$$E_{charge}=p_{charge}T_{charge}. \quad (3)$$

2.2 Eco-driving control model with wireless charging

This section presents the optimal speed control model with wireless charging. Denote $\mathbf{x}(t)$ as the state vector of an EV at time *t*

$$\mathbf{x}(t) \triangleq \left[s(t), v(t)\right]'. \tag{4}$$

The relationship between $s(t)$, $v(t)$ and $a(t)$ can be formulated as

$$s(t)' = v(t), \tag{5a}$$

$$v(t)' = a(t). \tag{5b}$$

Then, we put (5a) and (5b) into a vector form and get an ordinary differential equation system which defines vehicle longitudinal control problems as

$$\dot{\mathbf{x}}(t) \triangleq \left[v(t), a(t)\right]' = f\left(\mathbf{x}(t), \mathbf{u}(t)\right), \tag{6}$$

and the control variable $\mathbf{u}(t)$ in the above system is the acceleration rate at time *t*, i.e.,

$$\mathbf{u}(t) = \left[a(t)\right]. \tag{7}$$

In this study, we use travel cost which includes time cost and electricity cost as the objective function

$$\min_{a(t)} L = \omega_1\left(t_f - t_0\right) + \omega_2\left(E_{discharge} - E_{charge}\right). \tag{8}$$

The minimization problem (8) is subject to several sets of constraints

$$\dot{\mathbf{x}}(t) = f\left(\mathbf{x}(t), \mathbf{u}(t)\right), t_0 \le t \le t_f \tag{9}$$

$$\mathbf{x}(t_0) = \mathbf{x}_0, \tag{10}$$

$$t_r \le t_{d3} \le t_g, \tag{11}$$

$$s(t_{d1}) = D_1, \tag{12}$$

$$s(t_{d2}) = D_2, \tag{13}$$

$$s(t_{d3}) = D_3, \tag{14}$$

$$s(t_f) = D, \tag{15}$$

$$0 \le v(t) \le v_{\max}, \tag{16}$$

$$a_{\min} \le a(t) \le a_{\max}. \tag{17}$$

In the above model, (9) and (10) are state constraints; (11) is traffic state constraint which makes sure that vehicle can go through the intersection during the green time; (12) to (15) are distance constraints; and (16) and (17) are boundary constraints for the vehicle's speed and acceleration.

Since the above optimal speed control problem is time continuous, it can be solved by discretizing the temporal and spatial dimensions into a sequence of collocation points. However, it will induce a large number of decision variables and take substantial time to find a solution. Therefore, it is not suited for real-time control. To solve this issue, we propose an approximation model in this research. According to the previous studies [11,12], we divide the control problem into five phases: (i) cruising at the initial speed; (ii) accelerating or decelerating at a constant rate; (iii) cruising at a specific speed; (iv) again accelerating or decelerating at a constant rate and (v) cruising at the end speed.

The approximation model can be formulated as follows:

$$\min_{a_1, a_2, t_1, t_2, t_3, t_4, v^*, v_f} L = \omega_1\left(t_f - t_0\right) + \omega_2\left(E_{discharge} - E_{charge}\right) \tag{18}$$

$$\begin{aligned} E_{discharge} = {} & \int_{t_0}^{t_1} ECR\left(v_0, 0\right) dt + \int_{t_1}^{t_2} ECR\left(v(t), a_1\right) dt \\ & + \int_{t_2}^{t_3} ECR\left(v^*, 0\right) dt + \int_{t_3}^{t_4} ECR\left(v(t), a_2\right) dt \\ & + \int_{t_4}^{t_f} ECR\left(v_f, 0\right) dt \end{aligned} \tag{19}$$

$$E_{charge} = p_{charge}\left(t_{d2} - t_{d1}\right) \tag{20}$$

subject to:

$$\mathbf{x}(t_0) = \mathbf{x}_0 = \left[s_0, v_0\right]', \tag{21}$$

$$v_0 + a_1\left(t_2 - t_1\right) = v^*, \tag{22}$$

$$v^* + a_2\left(t_4 - t_3\right) = v_f, \tag{23}$$

$$s(t_{d1}) = s_0 + \int_{t_0}^{t_{d1}} v(t) dt = D_1, \tag{24}$$

$$s(t_{d2}) = s_0 + \int_{t_0}^{t_{d2}} v(t) dt = D_2, \tag{25}$$

$$s(t_{d3}) = s_0 + \int_{t_0}^{t_{d3}} v(t) dt = D_3, \tag{26}$$

$$\begin{aligned} s(t_f) & = s_0 + \int_{t_0}^{t_f} v(t) dt \\ & = s_0 + \left[v_0\left(t_2 - t_0\right) + \frac{1}{2} a_1 \left(t_2 - t_1\right)^2\right] \\ & \quad + \left[v^*\left(t_f - t_2\right) + \frac{1}{2} a_2 \left(t_4 - t_3\right)^2\right] = D \end{aligned}, \tag{27}$$

$$t_{d3} = \tilde{T}, \tag{28}$$

$$t_0 \le t_1 \le t_2 \le t_3 \le t_4 \le t_f, \tag{29}$$

$$t_0 < t_{d1} < t_{d2} < t_{d3} < t_f, \tag{30}$$

$$0 \le v^* \le v_{\max}, \tag{31}$$

$$0 \le v_f \le v_{\max}, \tag{32}$$

$$a_{\min} \le a_1 \le a_{\max}, \tag{33}$$

$$a_{\min} \le a_2 \le a_{\max}. \tag{34}$$

In the approximation model, (19) and (20) are equations to calculate electricity consumption and charging amount; (20) is the initial state constraint; (22) and (23) ensure that the cruising speed v^* and v_f can be reached at t_2 and t_4, respectively; (24) to (27) are distance constraints; (28) ensures that the vehicle can pass the intersection as soon as possible determined by signal status; (29) and (30) are time constraints; and (31) to (34) are boundary constraints for the vehicle's speed and acceleration. Here we should note that we substitute constraint (11) for (28) to increase the traffic efficiency further.

3. NUMERICAL TESTS

In this section, the proposed eco-driving control is evaluated for a specific intersection configuration, as illustrated in Fig 1. The control segment includes the upstream and downstream of the intersection. The parameters in the numerical tests are shown in Table 2.

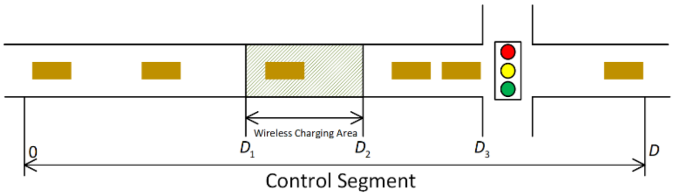

Fig 1 Intersection configuration

Table 2 Parameters in the simulation

Parameters	Values
Vehicle Initial Speed (m/s)	22.2
Max Speed (m/s)	22.2
Max Acceleration (m/s^2)	4.88
Min Acceleration (m/s^2)	-3.41
D_1 (m)	300
D_2 (m)	400
D_3 (m)	500
D (m)	600
Signal Cycle (s)	80
Green Split	0.5
Wireless Charging Power (kW)	20
Value of Time (RMB/s)	0.01
Electricity Price (RMB/kWh)	0.8

To evaluate the performance of the eco-driving control model with wireless charging, we conduct three simulations which are no control, control without considering wireless charging, and control with considering wireless charging. Note we remove E_{charge} in (18) to achieve control without considering wireless charging. We use the approximation model to search for the optimal speed profile for the last two simulations.

Fig 2 presents the trajectories of EV under different scenarios. As shown in Fig 2, both eco-driving control with and without considering wireless charging indicate that the EV travels the intersection without any stops. The eco-driving control strategies also increase traffic efficiency compared with no control condition. Due to the above points, these two eco-driving control both lead to a more than 20% total cost saving, as shown in Table 3. However, we can find that the trajectory with considering wireless charging is significantly different from that without considering wireless charging. The reason is that the EV will travel as much as possible in the wireless charging area for a longer period to increase the amount of charge. We further present the speed profiles of EV in different simulations in Fig 3. The different speed patterns also suggest that the EV will adopt different acceleration/deceleration strategy to achieve a lower total cost. From Table 3, one can find that the travel times of two eco-driving scenarios are identical, and the electricity consumptions are nearly the same. The main difference between these two eco-driving control results is the electricity charging amount. Eco-driving control considering wireless charging can reduce the travel cost by nearly 4%.

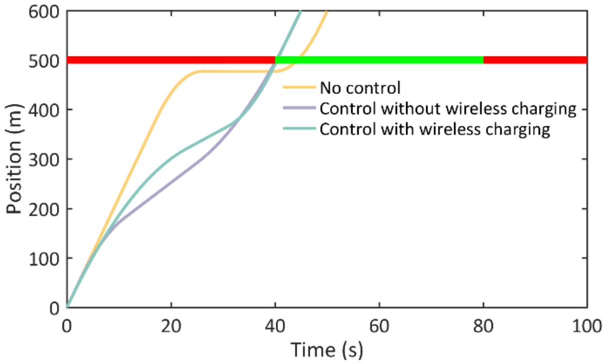

Fig 2 EV trajectories in different simulations

Table 3 EV performance comparisons

Performance Measurements	No Control	Control without Wireless Charging	Control with Wireless Charging
Total Travel Time (s)	51	46	46
Electricity Consumption (kWh)	0.2487	0.1522	0.1519
Electricity Charging (kWh)	0.0278	0.0500	0.0833
Total Travel Cost (RMB)	0.6868	0.5417	0.5148
Travel Cost Saving (%)	-	21.12%	25.04%

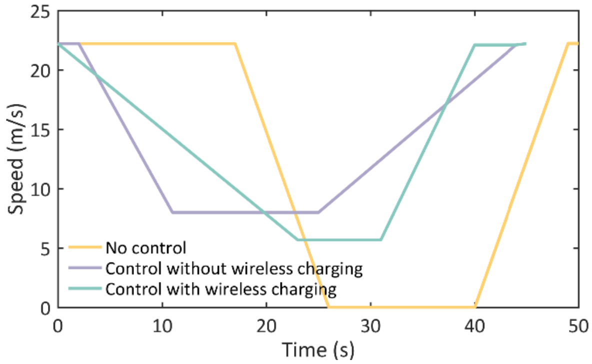

Fig 3 EV speed profiles in different simulations

4. *CONCLUSIONS*

EVs are getting more and more attention from the market and the government because of their energy saving and emission reduction. However, the limited driving range is still hindering the large-scale promotion of EVs. In this paper, we propose a wireless charging scheme for EVs at signalized intersections to increase the driving range of EVs while traveling through the intersection. An eco-driving control method is developed under the proposed wireless charging scenario. To solve the control problem more efficient, we propose an approximation model with five driving phases. Numerical tests under a specific signalized intersection are conducted to evaluate the effectiveness of the proposed control strategy. Simulation results show that eco-driving control can significantly reduce total travel cost. Comparison between the results of with and without considering wireless charging indicates that the speed profile will be substantially different to achieve more power charging. And the travel cost can be further reduced by considering wireless charging when implementing eco-driving control.

However, we only evaluate the proposed control strategy in a specific scenario. Furthermore, we only optimize the EV's speed profile without optimization of the position of the wireless charging area. In further research, we will test our control method in other situations and propose a joint optimization method to optimize both EV's driving behavior and the position of the wireless charging area.

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