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An electric vehicle driving behavior model in the traffic system with a wireless charging lane

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HIGHLIGHTS

- A car-following model for EV is proposed.
- A rule is designed to study EV's lane-changing behavior.
- Each EV's driving behaviors in a two-lane system with a WCL are studied.

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ABSTRACT

In this paper, a car-following model is proposed to study each EV's (electric vehicle) motion behavior near the WCL (wireless charging lane) and a lane-changing rule is designed to describe the EV's lane-changing behavior. Then, the car-following model and lane-changing rule are used to explore each EV's micro driving behavior in a two-lane system with a WCL. Finally, the impacts of the WCL on each EV's motion behavior are investigated. The numerical results show that each EV should run slowly on the WCL if it needs charge of electricity, that the EV's lane-changing behavior has great effects on the whole system, that the delay time caused by the WCL turns more prominent when the traffic turns heavy, and that lane-changing frequently occurs near the WCL (especially at the downstream of the WCL).

1. Introduction

Electric vehicles (EV) are rapidly introduced worldwide as an environmentally friendly traffic tool (e.g., China) [1,2]. Correspondingly, some models are proposed to examine the complex traffic phenomena taking into account some special characteristics of EVs (e.g., the limited driving range) [3–6]. Clearly, popularization of EV depends heavily on the availability of convenient charging stations such as those at some public places (e.g., residential quarter) [7–12]. To circumvent the above problem, some innovative alternative charging methods are being developed and tested such as wireless charging lane (WCL). For example, the WCL deployed in the network was tested in South Korea [13], which shows that CWD (charging-while-driving) will soon come true in reality. Each vehicle on a road with WCL utilizes the WCL to charge if its remaining electricity is not enough [13–15]. If a vehicle needs charge of electricity on the WCL, the driver may run in advance on the

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lane with WCL (or change to the lane from the other lane) and thus move slowly in order that the battery has sufficient charging time to charge enough for reaching his destination. If the WCL is set in a single-lane road, the vehicle which does not need charge of electricity will be delayed even if only one vehicle requires charging, so it is desirable to deploy WCL in a multi-lane road where lane-changing is allowed. The vehicles' driving behaviors on the multi-lane road with WCL can be formulated as follows:

(1) For a non-charging vehicle delayed on the lane with WCL by its preceding charging vehicle, it changes to its adjacent lane; otherwise, it still runs on its current lane.
(2) For a vehicle in need of charging, it runs slowly after entering the WCL (changing in advance to the lane if it is not on the lane); but once the charging is over, it might change to its adjacent lane since its speed on other lane may be higher than the one on the lane with WCL.

Therefore, lane-changing and WCL should explicitly be considered in the multi-lane system with WCL. Each vehicle's driving behaviors are determined by its current speed, headway, relative speed and other related factors, a few car-following models were developed to study the driving behaviors [16–36]. In addition, some macro models [37,38] were proposed to explore the complex traffic phenomena. However, the models [16–38] cannot be used to explore the driving behaviors in the multi-lane system with WCL since they do not consider lane-changing. To describe lane-changing, Zheng [39] introduced some lane-changing models; Li et al. [40] proposed a method that combines the hidden Markov model with the Bayesian filtering method to recognize the lane-changing intention. In addition, lane-changing can be divided into discretionary and mandatory ones, where the discretionary lane-changing is to gain a speed advantage or better driving situation, and the mandatory lane-changing is to bypass one obstacle/merge. When a driver considers lane-changing, he may care the incentive and safety criterions, where the discretionary lane-changing only satisfies the safety criterion while the mandatory one instantaneously satisfies the two criterions [39–49].

However, the models [16–49] cannot describe the traffic phenomena caused by EV since they are developed for traditional vehicles and the EV's limited driving range is not considered. To study the EV's traffic flow, Tang et al. [4] proposed a car-following model to study the impacts of SOC (state-of-charge) on the EV's driving behavior. However, the models [1–49] did not consider the effects of WCL on the EV's driving behavior, so they cannot be used to study the EV's driving behavior in a multi-lane system with WCL. In this paper, we propose a driving behavior model to study the EV's driving behavior in a multi-lane system with WCL. In comparison with the previous driving behavior models [15–49], our work has three new contributions. Firstly, The EV's motion behavior in the WCL is explicitly revealed. Secondly, the lane-changing behavior is taken into consideration in the driving behavior model, and a new rule is proposed to model the EV's lane-changing behavior. Thirdly, each EV's trajectory, velocity and travel time are established in the two lane traffic system with WCL.

2. Model formulation

The car-following model on a single-lane road can be formulated as follows:

$$\frac{\mathrm{d}v_{\mathrm{n}}(t)}{\mathrm{d}t} = f\left(v_{\mathrm{n}}(t), \Delta x_{\mathrm{n}}(t), \Delta v_{\mathrm{n}}(t), \ldots\right), \tag{1}$$

where $v_{\mathrm{n}}, \Delta x_{\mathrm{n}}, \Delta v_{\mathrm{n}}$ are the nth vehicle's speed, headway and relative speed, respectively; f is the stimulus function determined by the nth vehicle's speed, headway, relative speed and other related factors. If f is defined as different equations, we can obtain different car-following models. For example, the full velocity difference (FVD) model [18] can be formulated as follows:

$$\frac{\mathrm{d}v_{\mathrm{n}}(t)}{\mathrm{d}t} = \kappa\left(V\left(\Delta x_{\mathrm{n}}\right) - v_{\mathrm{n}}\right) + \lambda_1 \Delta v_{\mathrm{n}}, \tag{2}$$

where κ, λ_1 are two reaction coefficients and V is the nth vehicle's optimal speed that are defined as follows [18]:

$$V\left(\Delta x_{\mathrm{n}}\right) = \mathrm{V}_1 + \mathrm{V}_2 \tanh\left(\mathrm{C}_1\left(\Delta x_{\mathrm{n}} - l_c\right) - \mathrm{C}_2\right), \tag{3}$$

where l_c is the vehicle's average length; $\mathrm{V}_1, \mathrm{V}_2, \mathrm{C}_1, \mathrm{C}_2$ are four constants.

Eqs. (1) and (2) are proposed to study the traditional vehicle's driving behavior, so they cannot be used to explore the EV's driving behavior. To overcome this limitation, Tang et al. [5] developed a car-following model accounting for SOC (state-of-charge), i.e.,

$$\begin{aligned}\frac{\mathrm{d}v_{\mathrm{n}}}{\mathrm{d}t} &= \frac{\varepsilon_{\mathrm{SOC}}}{\varepsilon_0}\left(\kappa\left(\left(1 + \varepsilon_{\mathrm{r}}\left(\mathrm{R}\left(x_{\mathrm{n}} + \Delta, t\right) - \mathrm{R}\left(x_{\mathrm{n}}, t\right)\right)\right)\left(V\left(\Delta x_{\mathrm{n}}\right) - v_{\mathrm{n}}\right)\right)\right)\\ &\quad + \frac{\varepsilon_{\mathrm{SOC}}}{\varepsilon_0}\left(\lambda \Delta_{\mathrm{n}} + \mu_{\mathrm{r}}\left(\left(\mathrm{R}\left(x_{\mathrm{n}} + \Delta, t\right) - \mathrm{R}\left(x_{\mathrm{n}}, t\right)\right)\right) a_{\mathrm{r}}\right),\end{aligned} \tag{4}$$

where $\varepsilon_{\mathrm{SOC}}$ is the SOC value of the nth EV; ε_0 is the critical value that the SOC affects the driving behavior; $\mathrm{R}(x, t)$ denotes the road condition at (x, t); a_{r} is the adjustment term of the road condition; $\varepsilon_{\mathrm{r}}, \mu_{\mathrm{r}}$ are two parameters related to the road condition.