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Impacts of SOC on car-following behavior and travel time in the heterogeneous traffic system

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HIGHLIGHTS

- A car-following model for electric vehicle is proposed.
- The effects of battery swap on each vehicle's driving behavior are studied.
- The effects of battery swap on each vehicle's travel time are studied.

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ABSTRACT

Since the SOC (state of charge) of the battery of each electric vehicle directly determines whether the battery should be charged/swapped, the SOC may affect the electric vehicle's driving behavior. In this paper, we introduce the SOC of battery into the electric vehicle's driving behavior model and propose a car-following model for electric vehicles, and then use the proposed model to study the effects of the SOC of battery and battery swap on each vehicle's driving behavior in the heterogeneous traffic system consisting of traditional vehicles and electric vehicles. The numerical results show that the proposed model can reproduce some complex traffic phenomena resulted by the SOC of battery and battery swap and that the influences on each vehicle's driving behavior are directly related to the initial traffic state, the electric vehicle's proportion, and the SOC of battery.

1. Introduction

With the rapid increasing of the number of vehicles, traffic problems (e.g., congestion, safety, energy consumption, air pollution) have become serious and attracted researchers to propose models to study the complex traffic phenomena, and then develop control methods or new technologies to relieve/solve the traffic problems. For example, researchers developed many traffic flow models to explore the complex traffic phenomena (e.g., congestion) [1–45], but the models cannot be used to study the traffic fuel consumption and emissions because they do not consider the two factors. The studies [46,39,47,48] show that the traffic fuel consumption has become an important part of petroleum consumption and its emissions have turned a major source of air pollution, thus researchers developed many models to study the fuel consumption and emissions [49–56], but the models cannot completely eliminate the emissions. Thus, the electric vehicle has been a new traffic tool because it does not have emissions, but the studies on the electric vehicle mainly focus on the vehicle's structure (e.g., electromotor) and the effects of the electric vehicle's property (e.g., the battery's driving range) on the electricity consumption and micro driving behavior [57–61]. The electric vehicle has a fatal limitation (i.e., the battery's

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short driving range), but there are three modes to solve the battery's short driving range, i.e., quick charge, slow charge and battery swap, where quick charge and slow charge cannot make the battery completely satisfy the driving range in short period while battery swap can let the driver exchange the battery in short period, which just indicates that battery swap can only satisfy the driver's requirement in short period. Therefore, we in this paper propose a car-following model for electric vehicle based on the influences of battery swap on each vehicle's driving behavior, and then study the effects of the SOC of the electric vehicle's battery on each vehicle's driving behavior in the heterogeneous traffic system consisting of the traditional vehicles and electric vehicles.

2. Model

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

$$\frac{\mathrm{d}v_n}{\mathrm{d}t} = f\left(v_n, \Delta x_n, \Delta v_n, \ldots\right), \tag{1}$$

where v_n, Δx_n, and Δv_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. However, Eq. (1) and its some extensions cannot be used to explore the effects of real-time road condition on the car-following behavior, so Tang et al. [45] proposed a car-following model accounting for real-time road condition, i.e.,

$$\begin{aligned}\frac{\mathrm{d}v_n(t)}{\mathrm{d}t} &= \kappa\left(\left(1+\varepsilon_{\mathrm{r}}\left(R\left(x_n+\varDelta, t\right)-R\left(x_n, t\right)\right)\right)V\left(\Delta x_n(t)\right)-v_n(t)\right)\\ &\quad +\lambda\Delta v_n(t)+\mu_{\mathrm{r}}\left(R\left(x_n+\varDelta, t\right)-R\left(x_n, t\right)\right)\cdot a_{\mathrm{r}},\end{aligned} \tag{2}$$

where R is a real-time variable reflecting real-time road condition[1]; V is the optimal speed; a_{r} is an adjustment term resulted by real-time road condition; κ, ε_{r}, λ, μ_{r} are four parameters. Based on the empirical data of Beitaipingzhuang Segment of the Third Ring Road in Beijing, Tang et al. [45] defined $V\left(\Delta x_n\right)$, ε_{r}, μ_{r}, a_{r} as follows:

$$V\left(\Delta \bar{x}\right) = 19.037\mathrm{e}^{-18.94\frac{1}{\Delta\bar{x}+l}}, \tag{3}$$

$$\varepsilon_{\mathrm{r}} = \mu_{\mathrm{r}} = \begin{cases}0, & \text{if } \Delta x_n < 25.25 \text{ or } \Delta x_n > 100\\ 0.2, & \text{otherwise,}\end{cases} \tag{4}$$

$$a_{\mathrm{r}} = \begin{cases}0, & \text{if } \Delta x_n < 25.25 \text{ or } \Delta x_n > 100\\ 0.2, & \text{otherwise}\end{cases} \tag{5}$$

where $l = 5$ m is the vehicle's average length. As for the parameters κ, λ, we here define them as follows [16]:

$$\kappa = 0.41, \qquad \lambda = \begin{cases}0.5, & \text{if } \Delta x_n \le 100\\ 0, & \text{otherwise.}\end{cases} \tag{6}$$

Eq. (2) cannot be used to study the electric vehicle's driving behavior due to its own properties, so we should propose a car-following model for electric vehicle. Before proposing the model, we should first analyze the influences of the SOC of battery on the electric vehicle's driving behavior. Qualitatively, the effects can be defined as follows:

(i) When the value of SOC is relatively high, the SOC of battery has little effect on the electric vehicle's driving behavior, i.e., we assume that the electric vehicle's driving behavior is the same as that of the traditional vehicle;
(ii) When the value of SOC is relatively low, the SOC of battery will reduce the performance of the electric vehicle's acceleration but has little effect on the performance of deceleration.

Based on the above discussions, we can propose a new car-following model accounting for the SOC of battery, where the control equation can be divided into two separate parts, i.e.,

(i) when the value of SOC is relatively low (i.e., SOC $< \varepsilon_0$) and when the nth electric vehicle's acceleration is positive, the nth electric vehicle's acceleration can be formulated as follows:

$$\begin{aligned}\frac{\mathrm{d}v_n(t)}{\mathrm{d}t} &= \frac{\mathrm{SOC}}{\varepsilon_0}\left(\kappa\left(\left(1+\varepsilon_{\mathrm{r}}\left(R\left(x_n+\varDelta, t\right)-R\left(x_n, t\right)\right)\right)V\left(\Delta x_n(t)\right)-v_n(t)\right)\right)\\ &\quad +\frac{\mathrm{SOC}}{\varepsilon_0}\left(\lambda\Delta v_n(t)+\mu_{\mathrm{r}}\left(R\left(x_n+\varDelta, t\right)-R\left(x_n, t\right)\right)\cdot a_{\mathrm{r}}\right),\end{aligned} \tag{7}$$

[1] Note: R is a random digit in the interval $[-1, 1]$ [45], where $R < 0$ means bad road, $R = 0$ means neutral road, $R > 0$ means good road, $R = -1$ means the worst road and $R = 1$ means the best road.