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Influences of battery exchange on the vehicle's driving behavior and running time under car-following model

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ABSTRACT

In this paper, we use car-following model to study the effects of battery exchange at the on-line charging station on the vehicle's driving behavior and running time. The numerical results illustrate that battery exchange will produce one prominent starting process at the upstream of the charging station and one prominent braking process at the downstream of the charging station and enhance each vehicle's running time and the system's total running time and that the influences of battery exchange on each vehicle's driving behavior (including the starting and braking processes, the personal running time and the system's total running time) are directly related to each vehicle's arrival rate at the origin, the electric vehicle's proportion and each electric vehicle's series number in the vehicle fleet. The results can help traffic engineer to reasonably design the on-line charging station and optimize each vehicle's arrival rate at the origin.

1. Introduction

With the rapid increasing of the number of the vehicles, energy and environment sustainability have been a major social concern, which have attracted researchers to propose many models to explore the vehicle's fuel consumption and exhaust emissions [1–9]. The existing studies show that the vehicle's fuel consumption has become an important source of energy consumption and that the vehicle's exhaust emissions have been a major source of air pollution [10–12].

The above studies can reproduce the mechanism of the vehicle's fuel consumption and exhaust emissions and some researchers have proposed some new strategies to reduce the vehicle's fuel consumption and exhaust emissions, but these models, methods and strategies cannot eliminate the air pollution produced by the traditional vehicles. To eliminate or reduce the air pollution resulted by the traditional vehicles, engineers developed the electric vehicle that has no exhaust emissions [13–17] and researchers proposed many models to study the effects of the electric vehicle's related factors (e.g., charging station and its distribution) on traffic flow [18–22], and the vehicle's electricity consumption under some typical traffic states [23–25]. However, the models [18–25] do not study the impacts of battery exchange on each vehicle's driving behavior. In order to study the electric vehicle's driving behavior, Yang et al. [26] proposed a new car-following model to explore the effects of charging station on each vehicle's driving behavior, but they do not explore the effects of battery exchange on each vehicle's running time. Besides the above models, researchers developed other traffic flow models [27–38], but the models do not study the effects of battery exchange on each vehicle driving behavior or running time. In this paper, we use the car-following model [38] to explore the impacts of battery exchange on each vehicle's driving behavior, running time

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and the system's total running time since the car-following model has considered real-time road conditions.

2. Model formulation

In this section, we use car-following model to study the influences of battery exchange on each vehicle's driving behavior. Before studying the influences, we should give the following assumptions:

(1) The road is a single-lane system with open boundary, its length is L and there is an on-line charging station at the midpoint.
(2) All the N drivers are homogeneous.
(3) There are the traditional vehicles and electric vehicles, where the electric vehicles' proportion is p; the electric vehicle's driving behavior is the same as that of the traditional vehicle.
(4) Each electric vehicle should exchange its battery when it reaches the charging station; the time of battery exchange is a random digit in the interval $[t_{min}, t_{max}]$, where t_{min}, t_{max} are the minimum and maximum values of battery exchange, respectively.
(5) The time gap between any two adjacent vehicles at the origin is a constant. Here, we set the vehicle's time headway at the origin as γ.
(6) Each vehicle will automatically leave the road, i.e., its following vehicle will automatically be the leading vehicle when the vehicle arrives at the destination.

There exist many traffic flow models [27–38], but we here apply the car-following model [38] to study the effects of battery exchange on each vehicle's motion behavior because the model has considered the real-time road conditions, where the control equation can be written as follows:

$$\begin{aligned}\frac{dv_n(t)}{dt} = \kappa((1+\varepsilon_r(R(x_n+\Delta,t)-R(x_n,t)))V(\Delta x_n(t)) - v_n(t)) \\ +\lambda\Delta v_n(t) + \mu_r(R(x_n+\Delta,t)-R(x_n,t))\cdot a_r\end{aligned}, \quad (1)$$

where $v_n, \Delta x_n, \Delta v_n$ are the nth vehicle's speed, headway and relative speed, respectively; $R(x, t)$ is a real-time variable that can reflect the real-time road conditions at (x, t); a_r is the adjustment term which is resulted by $R(x, t)$, $\kappa, \varepsilon_r, \lambda, \mu_r$ are four reaction coefficients. In this paper, we assume that R is a random digit in the interval $[-1, 1]$, where $R < 0$ shows that the road condition is bad, $R = 0$ shows that the road condition is neutral, $R > 0$ shows that the road condition is good, $R = -1$ shows that the road condition is the worst and $R = 1$ show that the road condition is the best.

Before defining the optimal velocity and other parameters of Eq. (1), we here use the empirical data of Fig. 1 to the speed-density function [38], i.e.,

$$V(\rho) = 19.037e^{-18.94\rho}, \quad (2)$$

where $R^2 = 0.9553$. Using the relationships between headway and density, the optimal speed of Eq. (2) can be defined as follows:

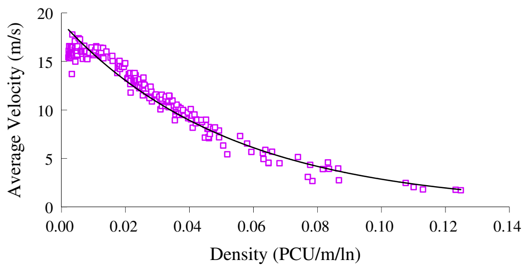

Fig. 1. The speed empirical data on the Beitaipingzhuang segment of the third ring road in Beijing [27].

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

where $l = 5$ m is the vehicle's length. Based on the empirical data in Fig. 1, Tang qualitatively defined $\varepsilon_r, \mu_r, a_r$ as follows [38]:

$$\varepsilon_r = \mu_r = \begin{cases} 0, & \text{if } \Delta x_n < 25.25 \text{ or } \Delta x_n > 100 \\ 0.2, & \text{otherwise} \end{cases}, \quad (4)$$

$$a_r = \begin{cases} 0, & \text{if } \Delta x_n < 25.25 \text{ or } \Delta x_n > 100 \\ 0.2, & \text{otherwise} \end{cases}. \quad (5)$$

As for Eqs. (4) and (5), we should here give the following notes: the three parameters are very complex but have no qualitative impacts on the numerical results, so we define them from the qualitative perspective; as for the exact definitions, we should use empirical data to calibrate them in the future. As for the parameters κ, λ, we define them as follows [27]:

$$\kappa = 0.41, \lambda = \begin{cases} 0.5, & \text{if } \Delta x_n \leqslant 100 \\ 0, & \text{otherwise} \end{cases}. \quad (6)$$

Other parameters are as follows:

$$N = 100,\ L = 10\ \text{km},\ t_{min} = 120\ \text{s},\ t_{max} = 300\ \text{s}. \quad (7)$$

Because Eq. (1)consists of N non-autonomous ordinary differential equations, it is difficult to obtain the analytical solution. Thus, we should use numerical scheme to discretize Eq. (1). Eq. (1)has different numerical schemes, but the numerical schemes have little qualitative impacts on the numerical results, so we here use the Euler forward difference, i.e.,

$$\begin{aligned} v_n(t+\Delta t) &= v_n(t) + \frac{dv_n(t)}{dt}\cdot\Delta t \\ x_n(t+\Delta t) &= x_n(t) + v_n(t)\cdot\Delta t + \frac{1}{2}\frac{dv_n(t)}{dt}\cdot(\Delta t)^2 \end{aligned}, \quad (8)$$

where $\Delta t = 0.5$ s is the time-step length.

3. Numerical tests

In this section, we use two situations to study the impacts of battery exchange on each vehicle's driving behavior and running time, where the two cases are defined as follows:

Case I: The electric vehicles are randomly distributed in the vehicle fleet.