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Analysis of electric vehicle's trip cost allowing late arrival

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HIGHLIGHTS

- Electric vehicle's trip cost and the system's total cost allowing late arrival are defined.
- The effects of the electricity cost on each electric cost trip cost are studied.
- The influences of the electricity cost on the system's total cost are studied.

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ABSTRACT

In this paper, we use a car-following model to study each electric vehicle's trip cost and the total trip cost allowing late arrival. The numerical result show that the electricity cost has great effects on each commuter's trip cost and the total trip costs and that these effects are dependent on each commuter's time headway at the origin, but the electricity cost has no prominent impacts on the minimum value of total trip cost under each commuter's different time headway at the origin.

1. Introduction

Since Vickrey proposed the first bottleneck model [1], many models have been proposed to study the commuter's trip cost during the morning rush hour [2–8], but the models cannot explicitly describe the quantitative relationship between each commuter's trip cost (especially including the energy cost and the toll of emissions) and his departure time because his instantaneous speed, acceleration and position, and travel time cannot be calculated. In order to conquer this limitation, Tang et al. [9–16] utilized a generalized car-following model to study each commuter's trip cost under different trip costs and found that each commuter's trip costs are directly dependent on his time headway at the origin and the definition of trip cost, but they assumed that the traffic tools are the traditional vehicles, i.e., the traffic cost is that of the fuel consumed by each commuter's vehicle, and the tolls of emissions is the tolls of CO, HC and NO_X discharged by each commuter's vehicle. Therefore, the studies [9–16] cannot be used to study each commuter's trip cost when the traffic tool is electric vehicle.

Electric vehicle will become a potential traffic tool since it is used in many countries (e.g., China). Therefore, researchers should explore each commuter's trip cost under electric vehicle. To study this topic, Tang et al. used a car-following model to explore the electric vehicle's running cost [17], proposed a car-following model with SOC (state of charge) [18] and further explored each electric vehicle's running cost [19], but they did not consider the electricity cost or the early (arrival) late cost in each electric vehicle's running cost, so the studies [17–19] cannot be used to study each commuter's trip cost (especially

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considering the electricity cost) when the traffic tool is electric vehicle. To overcome this limitation, Leng and Zhao [20] extended the work [13] to explore each commuter's trip cost without late arrival under electric vehicle, but they did not study the influences of arrival late on each commuter's trip cost.

In this paper, we extend the work [20] to explore the impacts of late arrival on each commuter's trip cost under electric vehicle. This paper is organized as follows: the related models and costs are in detail introduced in Section 2, some numerical tests are carried out in Section 3, and some conclusions are summarized in Section 4.

2. Model

In this section, we should introduce the related car-following models, the electricity consumption models and each commuter's trip cost. Before introducing the models and cost, we should here give the following basic assumptions:

(1) The N commuters and electric vehicles are both homogeneous, i.e., each commuter's parameters are the same and each electric vehicle's parameters are the same; each commuter's No. and the No. of his electric vehicle are the same.
(2) Each commuter's origin and destination are both the same.
(3) Each commuter cannot lately arrive at the destination.
(4) Each commuter leaves the origin with a fixed time headway, i.e., $\Delta t_{n,0} = t_{n,0} - t_{n-1,0} = \Delta t_0 = \text{constant}$, where $t_{n,0}$ is the nth commuter's departure time at the origin. For simplicity, we in this paper define $t_{1,0}$ as 0.
(5) When each commuter will automatically leave the road when he reaches the destination, i.e., his following vehicle will become the leading vehicle.
(6) The road is a single-lane system whose length is L.

Based on the above assumptions, we can divide the nth commuter's motion behavior into the following three stages:

(a) The nth commuter does not enter the road when $t < t_{n,0}$, i.e.,

$$x_n(t) = 0, \qquad v_n(t) = 0, \qquad \frac{\mathrm{d}v_n(t)}{\mathrm{d}t} = 0, \tag{1a}$$

where x_n, v_n are respectively the nth commuter's position and speed.

(b) When $t_{n,0} \le t \le t_n$, the commuter runs on the road according to the following equation:

$$\begin{cases} \dfrac{\mathrm{d}v_n(t)}{\mathrm{d}t} = \begin{cases} f\left(v_n, \Delta x_n', \Delta v_n'\right), & \text{if } n = 1 \\ f\left(v_n, \Delta x_n, \Delta v_n, \ldots\right), & \text{otherwise} \end{cases} \\ v_n(t + \Delta t) = v_n(t) + \dfrac{\mathrm{d}v_n(t)}{\mathrm{d}t} \cdot \Delta t \\ x_n(t + \Delta t) = x_n(t) + v_n(t) \cdot \Delta t + \dfrac{1}{2} \cdot \dfrac{\mathrm{d}v_n(t)}{\mathrm{d}t} \cdot (\Delta t)^2, \end{cases} \tag{1b}$$

where t_n is the nth commuter's arrival time at the destination; f is the acceleration function which is determined by the nth commuter's current traffic state; Δt is the time-step length; Δx_n, Δv_n are respectively the nth commuter's headway and relative speed, where n is larger than 1; $\Delta x_1'$ is the distance between the first commuter and the destination; $\Delta v_1' = -v_1$ is the first commuter's relative speed between him and the destination. Note: Eq. (1b) cannot guarantee that the solution of $x_n(t) = L$ is $K\Delta t$ (K is a positive integer), i.e., the solution is in the interval $(K_1\Delta t, (K_1 + 1)\Delta t)$ (K_1 is a positive integer), so we should calculate the approximate solution of $x_n(t) = L$. For simplicity, we here define $t_n = (K_1 + 1)\Delta t$.

(c) The nth commuter will automatically leave the road when $t > t_n$.

As for the nth commuter's trip cost, Tang et al. [9–16] defined three trip costs, i.e.,

$$T_n^{\mathrm{I}} = \alpha\left(t_n - t_{n,0}\right) + \beta \cdot \max\{0, t_{N0} - t_n\} + \gamma \cdot \max\{0, t_n - t_{N0}\}, \tag{2a}$$ [1]

$$T_n^{\mathrm{II}} = T_n^{\mathrm{I}} + \Gamma_{\mathrm{Fuel}} \cdot (\mathrm{FC})_n, \tag{2b}$$

$$T_n^{\mathrm{III}} = T_n^{\mathrm{II}} + \Gamma_{\mathrm{CO}} \cdot (\mathrm{CO})_n + \Gamma_{\mathrm{HC}} \cdot (\mathrm{HC})_n + \Gamma_{\mathrm{NO}_X} \cdot (\mathrm{NO}_X)_n, \tag{2c}$$

where $T_n^{\mathrm{I}}, T_n^{\mathrm{II}}, T_n^{\mathrm{III}}$ are the nth commuter's first, second and third trip costs, respectively; α, β, γ are the coefficients of travel time, early arrival time and late arrival time, respectively; Γ_{Fuel} is the price of fuel; $(\mathrm{FC})_n$ is the nth commuter's total fuel consumption; $\Gamma_{\mathrm{CO}}, \Gamma_{\mathrm{HC}}, \Gamma_{\mathrm{NO}_X}$ are the tolls of CO, HC and NO_X, respectively; $(\mathrm{CO})_n$, $(\mathrm{HC})_n$, $(\mathrm{NO}_X)_n$ are the nth commuter's total CO, HC and NO_X, respectively.

In this paper, we study each commuter's trip cost without late arrival when the traffic tool is electric vehicle. Electric vehicle has no emissions, so each commuter only has the first and second trip costs, where the first trip cost is the same as the one defined in Refs. [9–16] while the second trip cost should be redefined as follows:

$$T_n^{\mathrm{II}} = T_n^{\mathrm{I}} + \Gamma_{\mathrm{Ele}} \cdot (\mathrm{EleC})_n, \tag{3}$$

[1] Note: $N0$ is the No. of the commuter who punctually reaches the destination, where $N0 = N$ in the traffic system without late arrival.