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Analysis of electric vehicle's trip cost without late arrival

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HIGHLIGHTS

- Electric vehicle's trip cost and the system's total cost without 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 corresponding total trip cost without late arrival. The numerical result show that the electricity cost has significant effects on each electric vehicle's trip cost and the corresponding total trip costs and that the effects are dependent on its time headway at the origin, but the electricity cost has no prominent effects on the minimum value of the system's total trip cost.

1. Introduction

In 1969, Vickrey proposed the first bottleneck model [1], which was later extended to study the commuter's trip cost during the morning rush hour from different perspectives [2–8]. However, the models [1–8] cannot be used to explore the quantitative relationship between each commuter's trip costs (especially including the energy cost and the tolls of emissions) and his departure time because his instantaneous speed, acceleration and position, and travel time are not calculated from the models. To overcome the limitation, Tang et al. [9–16] used a car-following model to study each commuter's several trip costs and found that the trip costs are dependent to each commuter's time headway at the origin, but they assumed that the energy cost is the fuel cost, and that the emission cost is the total tolls of CO, HC and NO_X. Therefore, the studies [9–16] cannot be used to explore each electric vehicle's trip cost.

With the rapid development of the electric vehicle's technology, the electric vehicle is used in many countries (e.g., China), which just shows that the electric vehicle will be a potential traffic tool and that researchers should explore each electric vehicle's trip cost. As for the electric vehicle, Tang et al. used a car-following model to explore its motion behavior [17], and proposed a car-following model with the electric vehicle's SOC (state of charge) [18] to study each electric vehicle's running cost [19], but they considered neither the electricity cost nor the delay cost, so these studies cannot be used to study each electric vehicle's trip cost (that considers the electricity cost).

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In this paper, we explore each electric vehicle's trip cost without late arrival, where the trip cost includes the travel time cost, early arrival cost and electricity cost. This paper is organized as follows: the related models and the related costs are introduced in Section 2, some numerical tests are conducted in Section 3, and some conclusions are summarized in Section 4.

2. Model

In this section, we should introduce some related models (including the car-following models and electricity consumption models) and define each electric vehicle's trip cost. Here, we should 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., $\Delta t_{n,0} = t_{n,0} - t_{n-1,0} = \Delta t_0 =$ 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 when n is greater 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.,

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

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

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

where T_n^{I}, T_n^{II}, T_n^{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; Γ_{CO}, Γ_{HC}, Γ_{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 explore each electric vehicle's trip cost without late arrival. 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] and the second trip cost can 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.