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Impacts of energy consumption and emissions on the trip cost without late arrival at the equilibrium state

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HIGHLIGHTS

- The traditional vehicle's trip costs without late arrival are defined.
- The electric vehicle's trip costs without late arrival are defined.
- The effects of the energy consumption and emissions on each commuter's trip cost without late arrival at the equilibrium state are studied.

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ABSTRACT

In this paper, we apply a car-following model, fuel consumption model, emission model and electricity consumption model to explore the influences of energy consumption and emissions on each commuter's trip costs without late arrival at the equilibrium state. The numerical results show that the energy consumption and emissions have significant impacts on each commuter's trip cost without late arrival at the equilibrium state. The fuel cost and emission cost prominently enhance each commuter's trip cost and the trip cost increases with the number of vehicles, which shows that considering the fuel cost and emission cost in the trip cost will destroy the equilibrium state. However, the electricity cost slightly enhances each commuter's trip cost, but the trip cost is still approximately a constant, which indicates that considering the electricity cost in the trip cost does not destroy the equilibrium state.

1. Introduction

To date, many theoretical models have been proposed to explore traffic dynamics during rush hours [1–13], but most are the extensions of the basic bottleneck model [1]. However, the basic bottleneck model [1] made a basic assumption that a vertical queue representing congestion will occur when the commuters' arrival rate is larger than the bottleneck capacity. Therefore, the theoretical models [1–13] cannot be used to study the dynamics of rush-hour congestion produced the queue at the bottleneck upstream. To overcome this limitation, Newell [14] used the LWR (Lighthill–Whitham–Richards) model [15,16] to explore the morning commute problem where a fixed number of identical commuters travel on a road of constant width. Later, DePalma and Arnott [17] explored a special case of the work [14], obtained a closed-form solution of the SO (system optimal) problem and a quasi-analytical solution of the UE (user equilibrium) problem, and discussed the

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economic properties of the two solutions. The methods [14,17] can reproduce some quantitative relationships among each commuter's trip cost without late arrival, departure time, and the cumulative flow at the origin and destination under the SO and UE principles, but each commuter's instantaneous speed, acceleration, travel time and an explicit relationship between each commuter's trip cost and his departure time cannot be obtained, so the methods [14,17] cannot accurately calculate each commuter's trip cost, energy consumption or emissions from a microscopic perspective.

To calculate each vehicle's instantaneous acceleration and speed, some car-following models [18–22] were proposed to explore the driving behavior. Due to the above the merit, Tang et al. [23] used the car-following model to explore each commuter's trip cost without late arrival, but they assumed that each commuter's departure time is pre-determined, so the method [23] is not realistic in modeling the morning commute problem, i.e., the pre-determined departure pattern cannot be used to explore each commuter's trip cost at the equilibrium state because it does not guide each commuter to reduce his trip cost by adjusting his departure time. To overcome this limitation, Tang et al. [24] used a car-following model to study each commuter's trip cost without late arrival at the equilibrium state, but they did not consider the energy cost or the emission cost in each commuter's trip cost, so the method [24] cannot be used to directly study the impacts of the energy cost and the emission cost on each commuter's trip cost at the equilibrium state.

In this paper, we utilize a car-following model to explore the impacts of the energy cost and emission cost on each commuter's trip cost without late arrival at the equilibrium state defined in Ref. [24]. This paper is organized as follows: each commuter's three trip costs without late arrival are defined in Section 2; some numerical tests are carried out to study the three trip costs at the equilibrium state [24] in Section 3; some conclusions are summarized in Section 4.

2. Model formulation

In this paper, we should give the following assumptions and notations:

(a) The road is a single-lane system and its length is L.

(b) There are N homogeneous commuters; their origin and destination are respectively the road's entry and exit; each commuter is assumed to drive alone, so the commuter's No. and vehicle's No. can be used interchangeably; each commuter cannot lately arrive at the destination and has the same work start time (i.e., the last commuter's arrival time); $t_{n,\mathrm{d}}$, $t_{n,\mathrm{a}}$ are respectively the nth commuter's departure time and arrival time, where $t_{1,\mathrm{d}}$ is here set as 0.

(c) The minimum time headway at the origin is long enough, i.e., there is no waiting time for each commuter to enter the road at the origin.[1]

(d) When each commuter reaches the destination, he will automatically leave the road and his following vehicle becomes the leading one.

Based on the above assumptions, we can formulate the nth commuter's motion behaviors as follows:

(1) The nth commuter does not enter the road when $t < t_{n,\mathrm{d}}$ and has left the road when $t > t_{n,\mathrm{a}}$, so we do not have to explore his movement during the two periods.

(2) When $t_{n,\mathrm{d}} \le t \le t_{n,\mathrm{a}}$, the nth vehicle operates on the road based on the following model:

$$\begin{cases} a_n(t) = \begin{cases} f\left(v_n(t), \Delta x_n(t)\right), & \text{if } n = 1 \\ f\left(v_n(t), \Delta x_n(t), \Delta v_n(t), \ldots\right), & \text{if } n > 1 \end{cases} \\ v_n(t+\Delta t) = v_n(t) + a_n(t)\,\Delta t \\ x_n(t+\Delta t) = x_n(t) + v_n(t)\,\Delta t + 0.5 a_n(t)\,(\Delta t)^2, \end{cases} \tag{1}$$

where a_n, v_n, Δx_n, Δv_n, x_n are the nth commuter's acceleration, speed, headway, relatively speed and position, respectively; f is the stimulus function; and Δt is the time-step length in the numerical tests. Note: $t_{n,\mathrm{a}}$ calculated from Eq. (1) is not $K\Delta t$ but in $(K\Delta t, (K+1)\,\Delta t)$ (K is a non-negative integer). At this time, we should approximately define $t_{n,\mathrm{a}}$ as $(K+1)\,\Delta t$.

Based on the aforementioned discussions, the nth commuter's first trip cost without late arrival can be defined as follows:

$$T_n^{\mathrm{I}} = \alpha\left(t_{n,\mathrm{a}} - t_{n,\mathrm{d}}\right) + \beta\left(t_{N,\mathrm{a}} - t_{n,\mathrm{a}}\right) \quad (\alpha \text{ is larger than } \beta), \tag{2}$$

where T_n^{I} is the nth commuter's first trip cost without late arrival; α, β are the per unit costs of travel time and early arrival time, respectively.

Since we study the effects of the energy cost and emission cost on each commuter's trip cost without late arrival at the equilibrium, we should define the energy cost and emission cost, where the energy cost can be divided into the fuel cost of traditional vehicle and the electricity cost of electric vehicle, and the emission cost includes the costs of the traditional vehicle's CO, HC, and NO_X. As for traditional vehicle, the nth commuter will care the fuel cost and emission cost and has second and third trip costs, where his second trip cost without late arrival as follows:

$$T_{n,t}^{\mathrm{II}} = T_n^{\mathrm{I}} + \tau_n^{\mathrm{f}}, \tag{3}$$

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[1] Note: If the time headway is less than a certain threshold, the arrival rate at the origin will exceed the road's capacity and commuters will experience queuing at the origin.