Physica A 505 (2018) 136–143

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Impacts of carpooling on trip costs under car-following model

Hui Ou [a], Tie-Qiao Tang [b,*]

[a] Key Laboratory of High Performance Computing and Stochastic Information Processing (HPCSIP) (Ministry of Education of China), College of Mathematics and Computer Science, Hunan Normal University, Changsha, Hunan 410081, China
[b] School of Transportation Science and Engineering, Beijing Key Laboratory for Cooperative Vehicle Infrastructure Systems and Safety Control, Beihang University, Beijing 100191, China

HIGHLIGHTS

- Carpooling is incorporated into the commuting system.
- The influences of carpooling on the commuting problem without late arrival are studied.
- The influences of carpooling on the commuting problem allowing late arrival are studied.

ARTICLE INFO

Article history:
Received 4 December 2017
Received in revised form 12 February 2018
Available online 29 March 2018

Keywords:
Carpooling
Car-following model
Early arrival
Late arrival
Trip cost

ABSTRACT

Carpooling can relieve the traffic congestion, so it has been enforced in many countries. However, little effort has been made to study the impacts of carpooling on the commuting problem from the car-following model. In this paper, we apply a generalized car-following model to study each commuter's trip cost and the corresponding total cost in a traffic corridor when carpooling is allowed. The numerical result show that carpooling has some prominent positive influences on the commuting problem (i.e., each commuter's trip cost is reduced) and that the influences are directly dependent on the size of carpooling and each commuter's time headway at the origin. The results indicate that carpooling can be used to relieve the traffic congestion.

1. Introduction

Since Vickrey [1] proposed the first bottleneck model in 1969, many extended bottleneck models were developed to study the commuter's trip cost of the morning commuting problem [2–8]. However, the models [1–8] cannot reproduce 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 this shortcoming, Tang et al. [9–16] used a car-following model to explore each commuter's trip costs and found that the trip costs are dependent on each commuter's time headway at the origin; Leng et al. [17,18] studied the commuter's tip cost when the traffic tool is electric vehicle. However, the authors in Refs. [9–18] assumed that carpooling is not allowed, so the studies cannot reproduce the effects of carpooling on the commuter's trip cost. In fact, carpooling is encouraged to relieve the traffic congestion in many countries (e.g., Singapore). If carpooling can widely be accepted by each commuter, the traffic situation will become better (especially during the morning/evening rush hour) since the number of commuting vehicles drops. At this time, carpooling may influence each commuter's departure time and trip cost, which

* Corresponding author.
E-mail address: tieqiaotang@buaa.edu.cn (T.-Q. Tang).

https://doi.org/10.1016/j.physa.2018.03.042
0378-4371/

requires us to study the impacts of carpooling on each commuter's departure time and trip cost. In this paper, a generalized car-following model is used to explore the impacts of carpooling on each commuter's trip costs when his/her departure time is beforehand defined, where the first trip cost is the one without late arrival and the second trip cost is the one allowing late arrival. In comparison with the studies [9–18], this article has the two contributions: (1) carpooling is introduced into the commuting problem and (2) the effects of carpooling on each commuter's typical two trip costs under the car-following model are studied. The rest of this paper is organized as follows: the related car-following models and each commuter's two trip costs are in detail introduced in Section 2, some numerical tests are carried out to study the impacts of carpooling on each commuter's trip costs in Section 3, and some conclusions are summarized in Section 4.

2. Model

In this section, we focus on introducing the car-following model and defining the commuter's trip cost without late arrival and the commuter's trip cost allowing late arrival. Before introducing the models and defining the two trip costs, we should here give the following basic assumptions:

(1) The commuting system has N homogeneous commuters, i.e., the parameters related to each commuter can be defined as constant and each commuter has the same driving behavior under the same conditions.

(2) Each commuter has the same origin and destination.

(3) Each commuter's departure time interval is a fixed constant, 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 and n is larger than 1. For simplicity, we in this paper define $t_{1,0}$ as 0.

(4) The road is a single-lane system whose length is L. This shows that a car-following model can be used to depict each commuter's motion on the road.

(5) The carpooling size is k_0 (k_0 is a constant). This indicates that each vehicle accommodates k_0 commuters. Note: if k_0 equals to 1, the carpooling policy does not occur. Each vehicle can at most accommodate 5 persons, so we assume that k_0 is not larger than 6 in this paper.

In addition, we should further make the following assumptions:

(a) $\frac{N}{k_0}$ is an integer. i.e.,

$$\frac{N}{k_0} = M, \tag{1}$$

where M is an integer. Eq. (1) indicates that N is divided by M, where the number of commuters in each group is k_0.

(b) As for $n \in ((i-1)\cdot k_0, i\cdot k_0](i = 1, 2, \ldots, M)$, the k_0 commuters select the k_0th vehicle and enter the road at time $t_{i\cdot k_0,0}$, which shows that, as for $n \in ((i-1)\cdot k_0, i\cdot k_0)$, the nth commuter should stop at the origin after he/she reaches the destination.

(c) When a vehicle gets to the destination, it will automatically leave the destination and its following vehicle becomes the leading one.

Based on the fifth assumption, the above commuting problem can be simplified as a traffic corridor with M vehicles, where the time headway at the origin is $k_0 \cdot \Delta t_0$. To further simplify the above commuting problem, we here define the following two notations:

$\widetilde{t}_{i,0}$ ($i = 1, 2, \ldots, M$) is the ith vehicle's departure time at the origin;

$\widetilde{t}_i$ ($i = 1, 2, \ldots, M$) is the ith vehicle's arrival time at the destination;

where $\widetilde{t}_{i,0}$ can be calculated based on the following equation:

$$\widetilde{t}_{i,0} = t_{1,0} + i\cdot(k_0-1)\,\Delta t_0 = i\cdot(k_0-1)\,\Delta t_0. \tag{2}$$

Thus, the above commuting problem can be formulated as follows:

(a) The ith vehicle does not reach the road when $t < \widetilde{t}_{i,0}$ ($i = 1, 2, \ldots, M$), so the control equation can be formulated as follows:

$$x_i(t) = 0,\ v_i(t) = 0,\ \frac{\mathrm{d}v_i(t)}{\mathrm{d}t} = 0, \tag{3a}$$

where x_i, v_i are respectively the nth commuter's position and speed.

(b) When $\widetilde{t}_{i,0} \le t \le \widetilde{t}_i$: the ith vehicle's motion can be described by the following car-following model:

$$\begin{cases} \dfrac{\mathrm{d}v_i(t)}{\mathrm{d}t} = \begin{cases} f\left(v_i, \Delta x_i', \Delta v_i'\right), & \text{if } i = 1 \\ f\left(v_i, \Delta x_i, \Delta v_i, \ldots\right), & \text{otherwise} \end{cases} \\ v_i(t+\Delta t) = v_i(t) + \dfrac{\mathrm{d}v_i(t)}{\mathrm{d}t}\cdot\Delta t \\ x_i(t+\Delta t) = x_i(t) + v_i(t)\cdot\Delta t + \dfrac{1}{2}\cdot\dfrac{\mathrm{d}v_i(t)}{\mathrm{d}t}\cdot(\Delta t)^2, \end{cases} \tag{3b}$$

where f is the ith vehicle's acceleration determined by its current traffic state; $\Delta x_1' = L - x_1$ is the spatial distance between the first vehicle and the destination; $\Delta v_1' = -v_1$ is the speed difference between the first vehicle and the destination;