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A route-based traffic flow model accounting for interruption factors

Tie-Qiao Tang [a,*], Wei-Fang Shi [a], Hai-Jun Huang [b], Wen-Xiang Wu [c], Ziqi Song [d]

[a] School of Transportation Science and Engineering, Beihang University, Beijing 100191, China
[b] School of Economics and Management, Beihang University, Beijing 100191, China
[c] Beijing Key Lab of Urban Intelligent Traffic Control Technology, North China University of Technology, Beijing 100041, China
[d] Department of Civil and Environmental Engineering, Utah State University, Logan, UT 84322, United States

HIGHLIGHTS

- A route-based network traffic flow model is proposed.
- The impacts of three bus stations on each link's traffic flow are studied in a simple network.
- The impacts of an accident on each link's traffic flow are studied under two situations.

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ABSTRACT

In this paper, we utilize route flow to propose a network traffic flow model with consideration of interruption factors. The proposed model is then used to study the effects of two typical interruption factors (e.g., bus station and accident) and the divergence effect at the shared node on each link's traffic flow. The model is conducted under the stochastic route choice behavior in a network with an origin–destination (OD) pair and two routes, where the numerical results indicate that the proposed model can qualitatively describe some complex physical phenomena (e.g., shock, rarefaction wave, stop-and-go, jam and route divergence). The above phenomena are related to each route's initial density, where the formation and propagation speed are affected by network structure and route choice behavior.

1. Introduction

Since the 1950s, many traffic flow models have been proposed to study various complex traffic phenomena (e.g., stop-and-go, phase transition, etc.) from different perspectives [1,2]. The existing models can roughly be sorted into micro model [3–29] and macro model [30–62], where the micro models primarily study micro traffic phenomena caused by driving behavior, and the macro models focus on exploring the macro traffic phenomena (e.g., the relationships among density, speed and flow).

However, the models [3–62] cannot be used to explore the complex traffic behaviors (e.g., route choice behavior) and the corresponding traffic phenomena in a network since they were proposed to study the traffic phenomena on a road. Certainly, many network flow models (e.g., the traffic assignment model) have been developed to explore route choice, but the traditional traffic assignment models cannot describe the dynamic features of density, speed and flow on each link [63].

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

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As for network traffic flow, an important research topic is to construct models that have the advantages of road traffic flow models and network traffic flow models. For this purpose, researchers proposed many network traffic flow models to study network traffic flow, where the models mainly include the kinematics models [64–71], the dynamic models [72–74], the ordinary differential equation models [75], and the simulation models [76–84].

However, the models [63–71] cannot exactly describe the micro driving behaviors in the urban traffic network. For example, the impacts of some interruption factors (e.g., bus station) should be embodied in the network traffic flow models since these factors widely exist in the urban traffic system; the interactions among different routes that share the same nodes should be explicitly considered. In this paper, we propose a route-based flow model with interruption factors to explore traffic behaviors associated with bus station, accident and route divergence in a one-to-one fixed demand network from the numerical perspective.

2. The model

The first macro traffic flow model, called the Lighthill–Whitham–Richard (LWR) model, can be written as follows [30,31]:

$$\frac{\partial \rho}{\partial t}+\frac{\partial\left(\rho v_{\mathrm{e}}\right)}{\partial x}=0, \tag{1}$$

where ρ, v_{e} are the density and equilibrium speed, respectively, and x, t are space and time, respectively. Although Eq. (1) can depict the formation and propagation of shock, it cannot be used to explore non-equilibrium traffic flow since the speed is determined by v_e. To conquer this limitation, researchers used an acceleration equation to substitute v_e and proposed some high-order models, which can be classified into DG (density-gradient) models [33–36] and SG (speed-gradient) models [38–41]. The first DG model can be formulated as follows [33]:

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}=\frac{v_{\mathrm{e}}-v}{\tau}-\frac{c^2(\rho)}{\rho}\frac{\partial \rho}{\partial x}, \tag{2}$$

where v is the speed, τ is the reaction time, and $c(\rho) > 0$ is the sonic speed. The simple SG model can be formulated as follows [39]:

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}=\frac{v_{\mathrm{e}}-v}{\tau}+c_0\frac{\partial v}{\partial x}, \tag{3}$$

where $c_0 > 0$ is the propagating speed of small perturbation.

However, the above models cannot be used to study the effects of the interruption factor on various complex traffic phenomena because they did not consider this factor. In fact, many interruption factors (e.g., bus station) widely exist in a traffic system. In order to explore these effects, Tang et al. [85] proposed an SG model with interruption probability, where the control equation can be formulated as follows:

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}=\frac{v_{\mathrm{e}}\left(\rho\right)-v}{\tau}-\frac{1}{\tau_1}pv+c_0\left(1-p\right)\frac{\partial v}{\partial x}, \tag{4}$$

where p is the interruption probability, and τ_1 is the reaction time.

As for network traffic flow, researchers extended Eq. (1) to explore some complex traffic phenomena in a network and developed some extended LWR models [64–66], i.e.,

$$\frac{\partial \bar{\rho}_{\mathrm{n}}}{\partial t}+\frac{\partial\left(\bar{\rho}_{\mathrm{n}}\bar{v}_{\mathrm{ne}}\right)}{\partial \bar{x}_{\mathrm{n}}}=\bar{s}_{\mathrm{n}}\left(\bar{x}_{\mathrm{n}},t\right),\ \mathrm{n}=1,2,\ldots,\mathrm{N} \tag{5}$$

where $\bar{\rho}_{\mathrm{n}}$, $\bar{v}_{\mathrm{ne}}$ are respectively the density and equilibrium speed of link n, N is the number of links, $\bar{s}_{\mathrm{n}}\left(\bar{x}_{\mathrm{n}},t\right)$ is the net inflow/outflow of link n, and $\bar{x}_{\mathrm{n}}$ is the ordinate of link n. Based on the properties of the net inflow/outflow of each link in a network, we can define $\bar{s}_{\mathrm{n}}\left(\bar{x}_{\mathrm{n}},t\right)$ as follows:

$$\bar{s}_{\mathrm{n}}\left(\bar{x}_{\mathrm{n}},t\right)=\begin{cases}\text{the net inflow of link } n, & \text{if } \bar{x}_{\mathrm{n}}=0,\\ 0, & \text{if } 0<\bar{x}_{\mathrm{n}}<\bar{\mathrm{L}}_{\mathrm{n}},\\ \text{the net outflow of link } n, & \text{if } \bar{x}_{\mathrm{n}}=\bar{\mathrm{L}}_{\mathrm{n}},\end{cases} \tag{6}$$

where $\bar{\mathrm{L}}_{\mathrm{n}}$ is the length of link n.

However, Eq. (5) cannot describe the non-equilibrium traffic flow in a network since the speed of each link is determined by its equilibrium speed. To study the non-equilibrium traffic flow in a network, Tang et al. [74] introduced the acceleration equation of each link into Eq. (5) and proposed a high-order model for network traffic flow, i.e.,

$$\frac{\partial \bar{v}_{\mathrm{n}}}{\partial t}+\bar{v}_{\mathrm{n}}\frac{\partial \bar{v}_{\mathrm{n}}}{\partial x_{\mathrm{n}}}=\frac{\bar{v}_{\mathrm{ne}}-\bar{v}_{\mathrm{n}}}{\bar{\tau}_{\mathrm{n}}}+\bar{c}_{\mathrm{n}0}\frac{\partial \bar{v}_{\mathrm{n}}}{\partial \bar{x}_{\mathrm{n}}}, \tag{7}$$

where $\bar{v}_{\mathrm{n}}$, $\bar{\tau}_{\mathrm{n}}$, $\bar{c}_{\mathrm{n}0}$ are the speed, reaction time, and propagation speed of small perturbation on link n, respectively.

However, Eq. (4) cannot be used to explore network traffic flow since it does not consider any factors related to a network. Eqs. (5) and (6) cannot be used to study the impacts of some interruption factors on the complex traffic phenomena occurring