Transportation Research Part C 32 (2013) 89–102

Contents lists available at SciVerse ScienceDirect

Transportation Research Part C

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

A traffic-condition-based route guidance strategy for a single destination road network

Zhengbing He [a], Wei Guan [a,*], Shoufeng Ma [b]

[a] MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University, China
[b] Institute of Systems Engineering, Tianjin University, China

ARTICLE INFO

Article history:
Received 16 May 2012
Received in revised form 7 April 2013
Accepted 7 April 2013

Keywords:
Route guidance
Traffic conditions
User optimal equilibrium
Road network
Simulation model

ABSTRACT

Most of existing route guidance strategies achieves user optimal equilibrium by comparing travel time. Measuring travel time, however, might be uneasy on an urban road network. To contend with the issue, the paper mainly considers easily obtained inflow and outflow of a link and road capacity as input, and proposes a route guidance strategy for a single destination road network based on the determination of free-flow or congested conditions on alternative routes. An extended strategy for a complex network and a feedback approximation for avoiding forecast are further explored. Weaknesses of the strategy are also explicitly analyzed. To test the strategy, simulation investigations are conducted on two networks with multiple parallel routes. The results indicate that the strategy is able to provide stable splitting rates and to approximate user optimal equilibrium in different conditions, in particular when traffic demand is high. This strategy has potential to be applied in an urban road network due to its simplicity and easily obtained input data. The strategy is also applicable for single destination if some alternatives and similar routes are available.

1. Introduction

Congestion is one of the most prevalent transportation problems in urban areas. To alleviate congestion, variable message signs (VMS) aiming at providing a variety of traffic information are being deployed in urban areas not only in freeway networks. Route guidance strategies for freeway networks have been widely investigated in the last two decades. However, proper strategies applicable for VMS located in urban areas are still urgently needed, since characteristics of urban road networks are quite different from those of freeway networks.

Existing route guidance strategies are usually divided into two classes: (1) iterative strategies, which consider various influences in traffic flow models in a future time horizon and optimize routing strategies by iteratively comparing optimization results (see e.g. Jifeng Wu, 1999; Kotsialos and Papageorgiou, 2002; Liu and Chang, 2011). The strategies involve various disturbances, however, the practical effects still highly rely on the models and the computational effort is usually high. (2) Feedback strategies, which divert incoming flow based on the traffic conditions in the past. Classic feedback controllers in the automatic control theory are usually adopted, such as a PI controller and a state-feedback controller. The strategies are easier to be implemented and have higher efficiency despite lower stability and accuracy sometimes. We mainly review the feedback strategies in the following part due to the scope of the paper.

Papageorgiou (1990) developed a macroscopic modeling framework for different kinds of road networks, and first introduced an optimal control approach and a feedback concept into the dynamic traffic assignment. Messmer et al. (1998) attempted to put the road network control problem in the format of a traditional automatic control problem, and to solve

* Corresponding author.
E-mail address: weig@bjtu.edu.cn (W. Guan).

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http://dx.doi.org/10.1016/j.trc.2013.04.005

it by using the automatic control theory. A number of control strategies, such as a bang-bang controller, a P controller, and a state-feedback controller, were employed to regulate splitting rates for route guidance. The proposed models and strategies were then tested and validated in a simulation scenario. Pavlis and Papageorgiou (1999) proposed a feedback route guidance strategy in order to achieve user optimal equilibrium in travel time on alternative routes. A series of simulation scenarios demonstrated effectiveness of the strategy in equalizing the travel time as well as comparing different influences of details of the strategy. Those literature lay the foundation of travel-time-based feedback route guidance strategies.

Messmer et al. (1998) presented a number of practical issues in deploying a VMS guidance system. An interurban highway network of Scotland in reality was considered and the potential improvements were further demonstrated in a simulation model. Wang and Papageorgiou (2000) validated the effectiveness of bang-bang, P, PI and LQI controllers, and compared the influences of various factors in a simple freeway network model developed using a freeway simulation software, METANET (Messner, 1990). Wang et al. (2001) compared the feedback and iterative guidance strategies in a simulation model of a complex freeway network, and verified the effectiveness of the feedback strategies. Sawaya and Doan (2000), Wang et al. (2002a,b) considered predictive travel time instead of reactive travel time in feedback strategies. The results showed improvement of the change in equalizing travel time on alternative routes. To overcome the impact of model-mismatch such as drivers' unknown compliance rates, Wang et al. (2002b) involved an additional controller into the feedback loop. Wang and Papageorgiou (2006) further presented that the feedback route guidance strategy could assist in alleviating heavy non-recurrent traffic congestion occurring in a large-scale express ring-road. In addition, average travel time on a hyperpath was introduced in the feedback framework in Deflorio (2000, 2003), in which equalizing travel time on all hyperpathes was taken as the objective of the feedback strategy.

Most of these strategies were proposed for freeway networks by directly comparing travel time. Estimating travel time, however, is more difficult on an urban network than that on a freeway network due to the complexity of drivers' behavior, network topology and dynamic OD matrices (Daganzo, 1996, 1998, 2007). In addition, applying the automatic controllers might also encounter various practical problems, such as tuning parameters for P or PI controllers. To avoid the difficulties, the paper proposes a route guidance strategy that generates splitting rates based on free-flow and congested conditions instead of travel time, as they are easier to be estimated in a complex network. This strategy has potential to be applied in a complex road network of a metropolitan area due to its simplicity and easily obtained input data. The strategy is also useful to direct high traffic flow to a meeting point for a big event. In such situations, avoiding the propagation of saturation phenomena along the network is usually more important than equalizing travel time on alternative routes.

We keep taking user optimality as the objective, because system optimality would sacrifice benefits of some drivers; it is incompatible with drivers' own decision criteria and may lead to large scale rejection of route guidance in the long practical run (Chiu and Huynh, 2007; Papageorgiou et al., 2007). We also assume that drivers completely follow recommendations of route guidance information. The remainder of the paper is organized as follows: Section 2 first introduces an analytical solution for the user optimal equilibrium problem addressed in Laval (2009); based on the solution we propose a traffic-condition-based route guidance strategy in Section 3, including a basic strategy, an extended strategy and a feedback approximation; weaknesses of the strategy are explicitly analyzed in Section 4; two simulation scenarios are employed to test the effectiveness of the strategy in Section 5; conclusions are made at last.

2. Background: an analytical solution for the single destination dynamic user equilibrium problem

This section briefly presents a sequential solution of the dynamic user optimal problem (we call an analytical solution for short) addressed in Laval (2009), and a route guidance strategy based on it will be proposed and compared in the next section.

Denote by $r \in R = \{1, 2, \ldots, N\}$ an alternative route, and let the index increase with free-flow travel time on the routes. We simply call a route with shorter or longer free-flow travel time a shorter or longer route. Suppose that there is no inlet or outlet on the routes, and denote by μ_r invariant capacity of the bottleneck on route r; let τ_r be free-flow travel time on route r, and $\tau_r(t)$ be actual travel time at time t on route r; $A(t)$ and $a(t)$ are the cumulative count of vehicles and traffic flow passing the VMS, respectively; $A_r(t)$ and $a_r(t)$ are the cumulative arrival count of vehicles and traffic flow using route r, respectively; $D_r(t)$ is the corresponding cumulative departure count of vehicles.

We briefly introduce applications of the cumulative count curve of vehicles (see, for example, Newell, 1982; Daganzo, 1997; Windover, 2001; Lago and Daganzo, 2007). In a typical queue system, vertical and horizontal distances between cumulative arrival and departure count curves are the queue length and delay of corresponding vehicles, respectively, and the area enclosed by the two curves are total delay and total queue length. In addition, a virtual cumulative arrival curve, which horizontally separates free-flow travel time and queueing delay, is usually introduced as $V_r(t) = A_r(t - \tau_r)$.

To simplify the exposition, we take a network with only two alternative routes as an example, and the dynamic user optimal equilibrium problem can be graphically solved in real time as follows (see Fig. 1):

(1) Let all incoming traffic stay on route 1 until point "a"; starting from t_a, the travel time on route 1 is equal to free-flow travel time τ_2 on route 2;
(2) After point "a" two types of diversion are defined. In type-I diversion, the incoming flow in excess of capacity μ_1 of route 1 should divert to route 2 in order to maintain constant travel time τ_2 on both routes;

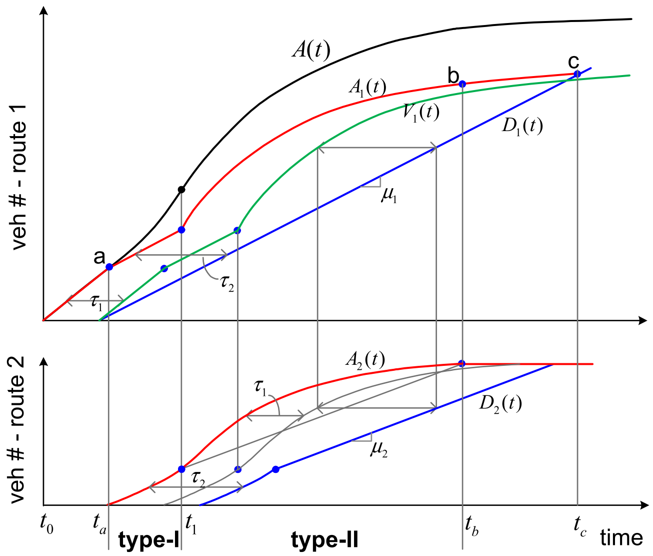


Fig. 1. Queueing diagrams for a network with two alternative routes without inlets or outlets under user optimal equilibrium.

(3) At time t_1 the incoming flow is greater than the sum of the capacities of both routes, i.e., $a(t_1) > \mu_1 + \mu_2$. Type-II diversion splits the incoming flow by following a fraction that is proportional to the capacity of the route;
(4) The diversion will continue up to point "*b*" in the figure where the queue dissipates on route 2. At this point all incoming traffic should use route 1 until the end of the rush hour at point "*c*" where the queue vanishes.

General formulae of type-1 and type-2 diversion are written as follows:
Type-I diversion. In set R of alternative routes, we first determine route $N(t) < N$ by

$$\sum_{k=1}^{N(t)} \mu_k < a(t) < \sum_{k=1}^{N(t)+1} \mu_k. \tag{1}$$

In the real-time solution, $N(t)$ is the longest one of all congested routes at time t. When $\tau_{N(t)}(t) = \tau_{N(t)+1}$ and $a(t) \leqslant \sum_{k\in R}\mu_k$,

$$a_r(t) = \begin{cases} \mu_r, & \text{if } r \leqslant N(t), \\ a(t) - \sum_{k=1}^{N(t)} \mu_k, & \text{if } r = N(t)+1, \\ 0, & \text{otherwise}. \end{cases} \tag{2}$$

Type-II diversion. When $a(t) > \sum_{k\in R}\mu_k$,

$$a_r(t) = \frac{\mu_r}{\sum_{k\in R}\mu_k} a(t). \tag{3}$$

In essence, the diversion maintains a balance between the diverting flow and exit capacity, i.e., equalizing marginal delay $\Delta w_r(t)$ encountered by the diverting flow in each congestion:

$$\Delta w_1(t) = \Delta w_2(t) = \cdots = \Delta w_N(t), \tag{4}$$

where $\Delta w_r(t) = a_r(t)/\mu_r - 1$.

3. A traffic-condition-based route guidance strategy

3.1. A basic strategy

The goal is to steadily divert incoming flow and approximate user optimal equilibrium by only considering traffic conditions. To the end, we propose a route guidance strategy based on free-flow or congested conditions that vehicles will experience on the alternative routes; we thus refer to this strategy as a traffic-condition-based strategy. The following three types of diversion compose the strategy:

- *type-0 diversion*. If vehicles entering any route at time t will experience no congestion, i.e., free-flow conditions where $\tau_r(t) = \tau_r$, we divert all incoming flow onto route 1:

$$a_r(t) = \begin{cases} a(t), & \text{if } r = 1, \\ 0, & \text{otherwise}, \end{cases} \tag{5}$$

- *type-1 diversion*. If vehicles entering at time t will experience congested conditions on some routes but not all, we divert the incoming flow by following Eq. (2);
- *type-2 diversion*. If vehicles entering any route at time t will experience congested conditions on all routes, i.e., $\tau_r(t) > \tau_r$, we divert the incoming flow by following Eq. (3);
The splitting rate can be written as

$$\beta_r(t) = \frac{a_r(t)}{a(t)}. \tag{6}$$

The proposed strategy does not compare travel time on alternative routes, i.e., eliminating the condition that $\tau_{N(t)}(t) = \tau_{N(t)+1}$ in type-I diversion. The three types of diversion are exclusive and cover all situations in the onset and offset of a rush hour, the proposed strategy is thus not necessarily sequential. Since the strategy works based on the capacities of routes, the generated splitting rates would be stable. Moreover, in some situations particularly with a long interval of updating guidance information, it is possible that a longer route might be in congested conditions, whereas a shorter route might be in free-flow conditions. In this situation, the diversion following Eq. (2) is also reasonable, in which vehicles are guided to sufficiently but not excessively use shorter routes.

It is obvious that user optimal equilibrium is compromised in the proposed strategy. Also taking a network with only two alternative routes as an example, we now analyze the trade-off made by the traffic-condition-based strategy; see Fig. 2. In a real-time situation, the traffic-condition-based strategy maintains route 1 in capacity and route 2 in free-flow conditions from time t_0 to t_1, and the travel times are τ_1 and τ_2, respectively. In contrast to the user optimal equilibrium in the travel-time-based strategy, more vehicles, $\Delta n = \mu_1(\tau_2 - \tau_1)$, are diverted to route 2, and the total extra travel time spent on route 2 is

$$\Delta T_2 = \tau_2 \Delta n = \tau_2 \mu_1 (\tau_2 - \tau_1), \tag{7}$$

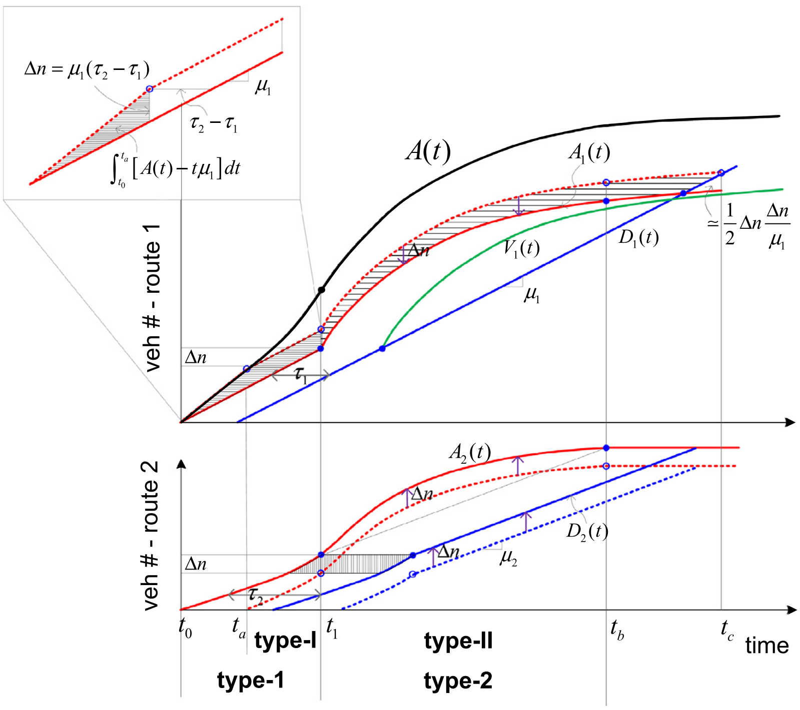


Fig. 2. Queueing diagrams for a network with two alternative routes without inlets or outlets in the traffic-condition-based strategy. (Dotted curves: cumulative count curves in the analytical solution.)

which is constant obviously. The total saving time of vehicles staying on route 1 during the whole period is

$$\Delta T_1 \simeq \int_{t_0}^{t_a} [A(t) - t\mu_1]dt + \Delta n(t_c - t_a) - \frac{\Delta n^2}{2\mu_1}. \tag{8}$$

Normally if the difference between the free-flow travel time is not great and the rush hour is relatively long, ΔT_1 should be greater than ΔT_2. The total travel time under the traffic-condition-based strategy reduces by $\Delta T_1 - \Delta T_2 > 0$. It implies a tendency to achieve system optimal equilibrium.

In addition, the difference between the travel time on the two routes is $\tau_2 - \tau_1$ at the beginning of type-2 diversion. Limited by the way how type-2 diversion splitting flow, the difference will keep in the whole period of type-2 diversion.

At the beginning this paper assumes that drivers completely follow the splitting rate. To relax the assumption (i.e., incorporating the drivers' compliance), one could add a compliance function to represent the drivers' choice between the nominal and recommended route. Although the function is a result of drivers' behavior study, the following simple but efficient formula (see e.g. Papageorgiou, 1990; Pavlis and Papageorgiou, 1999; Deflorio, 2003) is widely used and also suggested here:

$$\hat{\beta}_r(t) = \varepsilon_r\beta_r(t) + (1 - \varepsilon_r)\beta_r^N(t), \tag{9}$$

where $\hat{\beta}_r(t)$ and $\beta_r(t)^N$ are the real and nominal splitting rates at time t, respectively; $\varepsilon_r \in [0,1]$ is the compliance rate.

3.2. An extension for complex networks

Neither the above analytical solution nor the basic traffic-condition-based strategy considers networks with inlets and outlets on alternative routes. To cope with the limitation, this section introduces an extended traffic-condition-based route guidance strategy for complex networks.

We assume that a bottleneck only occurs due to merging maneuvers at the exit of a link connecting with an inlet. The strategy could also be modified for other cases, such as capacity drops occurring at the middlestream of a link.

3.2.1. Notations

There are two types of outflow for a link: one enters a downstream link on the same route, and the other leaves the route via an outlet. We especially indicate the latter one by using "O"; otherwise it is related to the former one. Moreover, "I" and "n" are generally used to indicate the flow related to an inlet and the VMS location, respectively. The following notations are used in the paper:

$i \in S_r = \{1,\ldots,M_r\}$: a link on route r, which denotes link indices from upstream to downstream;
$W_r(t) \subseteq S_r$: a set of congested links on route r at time t;
j^*: the most upstream one of congested links on route r at time t;
$\overline{W}_r(t) = \{j|j \in W_r(t),\ j \neq j^*\}$: a set of congested links except for the most upstream one;
τ_{ri}: free-flow travel time on link i on route r;
$\tau_{ri}(t)$: actual travel time on link i on route r at time t; obviously, $\tau_{ri}(t) \geqslant \tau_{ri}$. For clarity of exposition, let $\pi_{ri} = \sum_{k=1}^{i}\tau_{rk}(t)$;
$A_{ri}(t)$, $a_{ri}(t)$: the cumulative arrival count and inflow of link i on route r at time t, respectively;
$D_{ri}(t)$, $d_{ri}(t)$: the cumulative departure count and outflow of link i on route r at time t;
μ_{ri}: exit capacity of link i on route r;
$\mu_{ri}(t)$: maximum possible outflow of link i on route r at time t as a result of competition with other inflow via an inlet at a downstream merge;
$\mu_{ri}^n(t)$: maximum possible output VMS flow of link i on route r (note that we call the flow coming from the VMS location at time t the VMS flow at time t);
$\mu_r^n(t)$: maximum quantity of the VMS flow at time t that is able to pass route r;
$d_{ri}^I(t)$: inflow via an inlet at the downstream of link i;
$a_{ri}^O(t)$: outflow via an outlet at the downstream of link i;
ϕ_{ri}, $\psi_{ri} = \{0,1\}$: dummy coefficients. If there is an inlet or an outlet at the downstream of link i on route r, the value of ϕ_{ri} or ψ_{ri} is 1, and vice versa. At least an inlet or an outlet exists at the downstream of a link and they cannot co-exist, i.e., $\phi_{ri} + \psi_{ri} = 1$.

3.2.2. A traffic-condition-based route guidance strategy for complex networks

In a simple network without any inlet or outlet on alternative routes, all flow comes from the VMS location, and the basic strategy use the capacity of a route as the maximum quantity of the VMS flow that is able to pass a route. In a complex network in which the flow comes from multiple origins, the VMS flow shares a link with the flow from other origins; this should be considered.

- *type-0 diversion*. If vehicles entering any route at time t will experience no congestion, we divert all incoming flow onto route 1; it is the same with the one in the basic strategy.
- *type-1 diversion*. If vehicles entering at time t will experience congestion on some routes but not all, we divert the incoming flow by the following the equation:

$$a_r(t) = \begin{cases} \mu_r^n(t), & \text{if } r \leqslant N(t), \\ a(t) - \sum_{k=1}^{N(t)} \mu_k^n(t), & \text{if } r = N(t)+1, \\ 0, & \text{otherwise}, \end{cases} \tag{10}$$

that is, substituting μ_r in Eq. (2) with

$$\mu_r^n(t) = \min_{i \in S_r} \{ \mu_{ri}^n(t + \pi_{ri}) \} \tag{11}$$

and $N(t)$ is determined by

$$\sum_{k=1}^{N(t)} \mu_k^n(t) < a(t) < \sum_{k=1}^{N(t)+1} \mu_k^n(t). \tag{12}$$

- *type-2 diversion*. If vehicles entering any route at time t will experience congestion on all routes, we divert the incoming flow by following the same logic of the basic strategy, i.e., Eq. (4). The difference is that the diverting flow might experience several congestion on a route. The marginal delay on a route is thus

$$\Delta w_r(t) = \sum_{j \in W_r(t)} \Delta w_{rj}(t + \pi_{rj}) = \sum_{j \in W_r(t)} \frac{a_{rj}(t + \pi_{r(j-1)})}{\mu_{rj}(t + \pi_{rj})} - |W_r(t)|, \tag{13}$$

where $|W_r(t)|$ is the number of congested links, and the marginal delay on congested link $j \in W_r(t)$ is

$$\Delta w_{rj}(t + \pi_{rj}) = \frac{a_{rj}(t + \pi_{r(j-1)})}{\mu_{rj}(t + \pi_{rj})} - 1. \tag{14}$$

It is obvious that the diverting flow is only able to impact the most upstream one of congested links due to a congested bottleneck working like a filter. All links at the upstream of link j^* are in free-flow conditions, and the relation between the inflow of link j^* and the diverting flow is

$$a_{rj^*}(t + \pi_{r(j^*-1)}) = a_r(t) + F_{rj^*}(t), \tag{15}$$

where

$$F_{rj^*}(t) = \sum_{k=1}^{j^*-1} \phi_{rk} d_{rk}^I(t + \pi_{rk}) - \sum_{k=1}^{j^*-1} \psi_{rk} a_{rk}^O(t + \pi_{rk}), \tag{16}$$

which is the sum of inflow via inlets minus the sum of outflow via outlets at the upstream of link j^* on route r.

Eq. (13) can further be written as

$$\Delta w_r(t) = \frac{a_{rj^*}(t + \pi_{r(j^*-1)})}{\mu_{rj^*}(t + \pi_{rj^*})} + \sum_{j \in \overline{W}_r(t)} \frac{a_{rj}(t + \pi_{r(j-1)})}{\mu_{rj}(t + \pi_{rj})} - |W_r(t)| = \frac{a_r(t)}{\mu_{rj^*}(t + \pi_{rj^*})} + G_r(t), \tag{17}$$

where

$$G_r(t) = \frac{F_{rj^*}(t)}{\mu_{rj^*}(t + \pi_{rj^*})} + \sum_{j \in \overline{W}_r(t)} \frac{a_{rj}(t + \pi_{r(j-1)})}{\mu_{rj}(t + \pi_{rj})} - |W_r(t)|. \tag{18}$$

Combining with constraint $a(t) = \sum_{k \in R} a_k(t)$, we can obtain the diverting flow on route r by simple deduction as follows:

$$a_r(t) = \frac{\mu_{rj^*}(t + \pi_{rj^*})}{\sum_{k \in R} \mu_{kj^*}(t + \pi_{kj^*})} \left[\sum_{k \in R} \mu_{kj^*}(t + \pi_{kj^*}) G_k(t) + a(t) \right] - \mu_{rj^*}(t + \pi_{rj^*}) G_r(t). \tag{19}$$

Since diverting flow can only impact the most upstream one of congested links, Eq. (4) could not be universally guaranteed in a complex network. We sequentially truncate the splitting rate for the shortest route in $[0, 1]$ and those for others in $\left[0, 1 - \sum_{k=1}^{r-1} \beta_k(t)\right]$ where $r > 1$.

3.3. A feedback approximation

Prediction is always needed by the proposed strategy, however it is uneasy to be realized in practice, in particular when the network is complex. To avoid forecast, we consider a feedback concept. Since the traffic is usually stably under free-flow and congested conditions, it is appropriate to replace free-flow or congested conditions in the future with the current ones. The operation is simple, i.e., setting $\pi_{ri} = 0$ in the above equations, and we do not itemize them here due to space limitations.

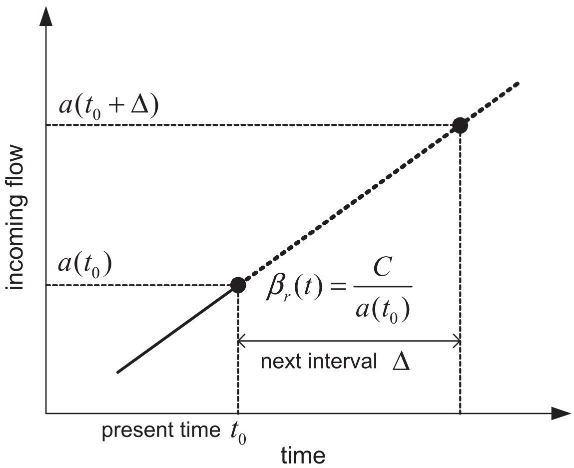


Fig. 3. An example: a fixed splitting rate generated by type-1 diversion cannot effectively divert increasing incoming flow when an update interval is relatively long.

4. Weaknesses of the traffic-condition-based route guidance strategy

The traffic-condition-based route guidance strategy mainly has the following weaknesses:

Errors occur when update intervals are relatively long. (a) Traffic conditions on an alternative route may change within an update interval, while the strategy is not able to update itself accordingly; this generates errors. (b) A constant splitting rate generated by type-1 diversion is not able to maintain a route in capacity when incoming flow increases or decreases dramatically, or the update interval is quite long. We illustrate the weakness in the following example:

Denote by Δ constant length of an update interval; suppose an increasing demand presented in Fig. 3, and constant maximum quantity of the VMS flow that is able to pass route r, i.e., $\mu_r^n(t) = C$. If we determine a splitting rate based on the incoming flow at present, i.e., $\beta_r(t) = C/a(t_0)$, the flow diverting to route r will be $Ca(t)/a(t_0)$, $t \in [t_0, t_0 + \Delta]$. The flow in excess of the maximum quantity is unexpectedly diverted to route r, since $a(t) > a(t_0)$; if we set the splitting rate by using predictive incoming flow, for example, $a(t_0 + \Delta)$, the excessive flow is diverted to longer route $r + 1$. Although route r is held under capacity within the interval, drivers following the guidance information would take longer travel time. Such errors occur considering either present or future demand, which seems to be inevitable under a long update interval. Similarly, time-varying maximum quantity can also produce the kind of errors. The errors would be small if the interval is short or the demand changes slowly.

The traffic-condition-based strategy is incapable of self-regulation. Once unexpected travel time difference among alternative routes occurs, the strategy is not able to regulate itself and mitigate the difference. Instead, the difference will last until congestion dissipates. For example, incoming flow in type-2 diversion is splitted based on the proportion of capacities of the alternative routes; it does not consider the existing time difference, and then the difference will not vanish in the type of diversion.

To increase the robustness of the strategy, disturbance predictions can be considered externally, although accurate predictions are still uneasy. Internally, one can incorporate other route guidance strategy as a calibrator, i.e., the traffic-condition-based strategy provides an interval to maintain stability of diversion, and let other strategies specify the splitting rate within the interval. With the combination, the results of the traffic-condition-strategy could be more accurate, and those of other strategies become more stable and may also overcome its own deficiency.

5. Simulation tests

We only test performances of the feedback approximation, which is more applicable not only in practice but also in simulation because of the simpleness. Two simulation investigations are conducted for two single destination networks with multiple parallel routes.

5.1. A network simulation model

5.1.1. The point-queue, merge and diverge models

5.1.1.1. The point-queue model. The point-queue assumption ignores the physical length of vehicles and allows vehicles drive at the free-flow speed until reaching the point of congestion. It provides a realistic representation of traffic delays and discharging process (although in a simplified fashion), and has been widely used in traffic flow studies, such as the dynamic network loading problem in dynamic traffic assignment (see e.g. Nie and Zhang, 2005; Szeto and Lo, 2006; Nie et al., 2008; Ban et al., 2012), and traffic analysis (see e.g. Newell, 1987; Muñoz and Laval, 2006; Lago and Daganzo, 2007; Laval, 2009). Considering the less importance of traffic flow propagation on a link in the proposed and compared strategies, this paper employs the macroscopic link model to conduct the simulation test. A continuous mathematical form of the model reads

$$\frac{\mathrm{d}l_{ri}(t)}{\mathrm{d}t} = \begin{cases} 0, & \text{if } a_{ri}(t-\tau_{ri}) + l_{ri}(t) < \mu_{ri}(t), \\ a_{ri}(t-\tau_{ri}) - \mu_{ri}(t), & \text{otherwise}, \end{cases} \tag{20}$$

where $l_{ri}(t)$ is the total number of queueing vehicles at time t on link i on route r.

5.1.1.2. The merge model. The exit flow of a link is a result of merging competition among inflow via downstream inlets. To incorporate the changes of exit flow limitation, a merge model pertaining to a configuration with two inlets and an outlet is considered as follows (see e.g. Nie et al., 2008):

$$d_{ri}(t) = p_{ri}\hat{d}_{r(i+1)}(t), \quad d^I_{ri}(t) = p^I_{ri}\hat{d}_{r(i+1)}(t), \tag{21a}$$

$$\hat{d}_{r(i+1)}(t) = \min\left\{\tilde{d}_{ri}(t) + \tilde{d}^I_{ri}(t), \lambda_{r(i+1)}(t)\right\}, \tag{21b}$$

where $\lambda_{ri}(t)$ is entry capacity of link i on route r at time t, and $\tilde{d}_{ri}(t)$ and $\tilde{d}^I_{ri}(t)$ are demand of link i and its connected inlet, respectively. $p_{ri}(t)$ and $p^I_{ri}(t)$ are called distribution ratio, and we follow a demand-based distribution scheme proposed in Jin and Zhang (2003) as follows:

$$p_{ri}(t) = \frac{\tilde{d}_{ri}(t)}{\tilde{d}_{ri}(t) + \tilde{d}^I_{ri}(t)}, \quad p^I_{ri}(t) = \frac{\tilde{d}^I_{ri}(t)}{\tilde{d}_{ri}(t) + \tilde{d}^I_{ri}(t)}. \tag{22}$$

The maximum demand is equal to exit capacity μ_{ri} in the merge model, and maximum possible output flow $\mu_{ri}(t)$ can thus be written by substituting $\tilde{d}_{ri}(t)$ with μ_{ri}, i.e.,

$$\mu_{ri}(t) = p^*_{ri}(t)\hat{d}^*_{r(i+1)}(t), \tag{23}$$

where

$$p^*_{ri}(t) = \frac{\mu_{ri}}{\mu_{ri} + \tilde{d}^I_{ri}(t)}, \tag{24}$$

$$\hat{d}^*_{r(i+1)}(t) = \min\left\{\mu_{ri} + \tilde{d}^I_{ri}(t), \lambda_{r(i+1)}(t)\right\}. \tag{25}$$

5.1.1.3. The diverge model. The model considers an exogenous leaving rate via an outlet at the downstream of link i on route r, $p^O_{ri}(t)$. The formulae are

$$a_{r(i+1)}(t) = \left[1 - p^O_{ri}(t)\right]d_{ri}(t), \quad a^O_{ri}(t) = p^O_{ri}(t)d_{ri}(t). \tag{26}$$

5.1.2. Proportion of traffic flow coming from different origins

In the simulation model, we assume that the proportion of vehicles coming from different origins keeps the same throughout a link; the flow leaving a route via an outlet also follows the proportion. Therefore, we have the following relation:

$$\vartheta_{ri}(t + \pi_{r(i-1)}) = \theta_{ri}(t + \pi_{ri}), \tag{27}$$

where $\vartheta_{ri}(t)$ and $\theta_{ri}(t)$ are proportion of the VMS flow at time t at the entrance and exit of link i on route r, respectively.

Before entering link i, some flow leaves or enters route r via an outlet or an inlet, i.e.,

$$a_{r(i+1)}(t + \pi_{ri}) = d_{ri}(t + \pi_{ri}) + \phi_{ri}d^I_{ri}(t + \pi_{ri}) - \psi_{ri}a^O_{ri}(t + \pi_{ri}). \tag{28}$$

In exit flow $d_{ri}(t + \pi_{ri})$, the VMS flow is

$$d^n_{ri}(t + \pi_{ri}) = \theta_{ri}(t + \pi_{ri})d_{ri}(t + \pi_{ri}). \tag{29}$$

Then, we have

$$\vartheta_{r(i+1)}(t + \pi_{ri}) = \frac{d^n_{ri}(t + \pi_{ri})}{a_{r(i+1)}(t + \pi_{ri})}. \tag{30}$$

We can thus obtain the proportion of the VMS flow by iterating the equations from the beginning of a route. Under the assumption, $\mu^n_{ri}(t)$ can be obtained as follows: If the link is congested,

$$\mu^n_{ri}(t) = \theta_{ri}(t)d_{ri}(t) = \theta_{ri}(t)\mu_{ri}(t). \tag{31}$$

If the link is free-flow,

$$\mu^n_{ri}(t) = \mu_{ri}(t) - [1 - \theta_{ri}(t)]d_{ri}(t), \tag{32}$$

that is, maximum possible outflow minus the flow coming from all other origins.

5.2. Scenario 1

In this scenario, we test type-1 and type-2 diversion separately to look at more details of the strategy. To the end, we consider a simple network shown in Fig. 4, and first set the exit capacity of route *B* 3500 veh/h, with which the strategy is using type-1 diversion most of time; then set the exit capacity 1500 veh/h, and the strategy is using type-2 diversion most of time. In the network, the free-flow speed on all links is 80 km/h, and the number in the bracket in the figure is the length of the link in km. Obviously, the free-flow travel time on route *A* is shorter than that on route *B*. The update interval is chosen as 300 s.

Fig. 5 presents the simulation results when the exit capacity of route *B* is 3500 veh/h. The strategy is using type-1 diversion most of time. The splitting rates are stable, which are applicable in practice. However, more delay occurs on route *A*, and user optimal equilibrium is thus not well achieved. It is because more incoming flow is diverted to route *A* with an increasing

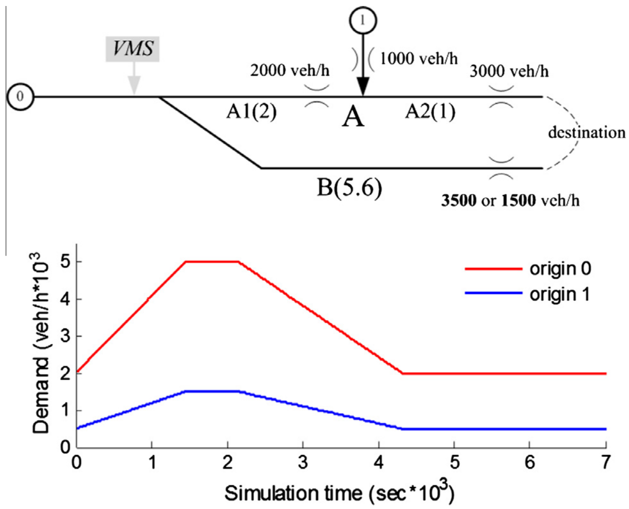


Fig. 4. A single destination road network with two alternative routes.

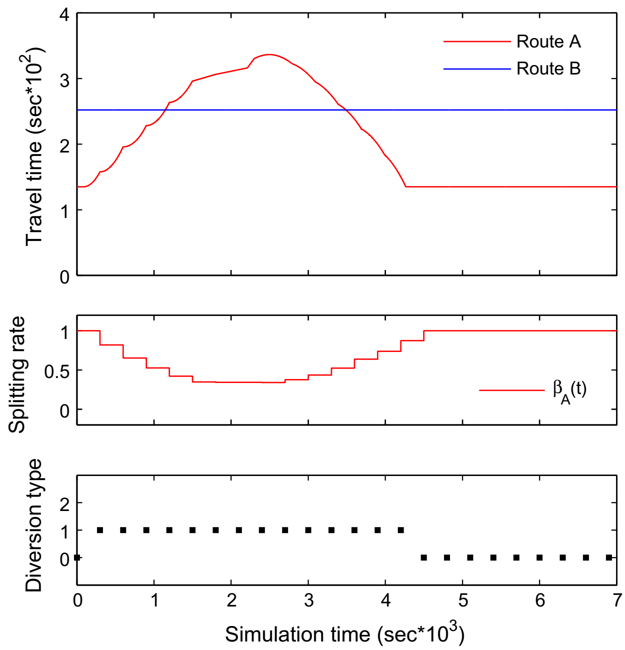


Fig. 5. Simulation results in scenario 1 with exit capacity 3500 veh/h of route *B*.

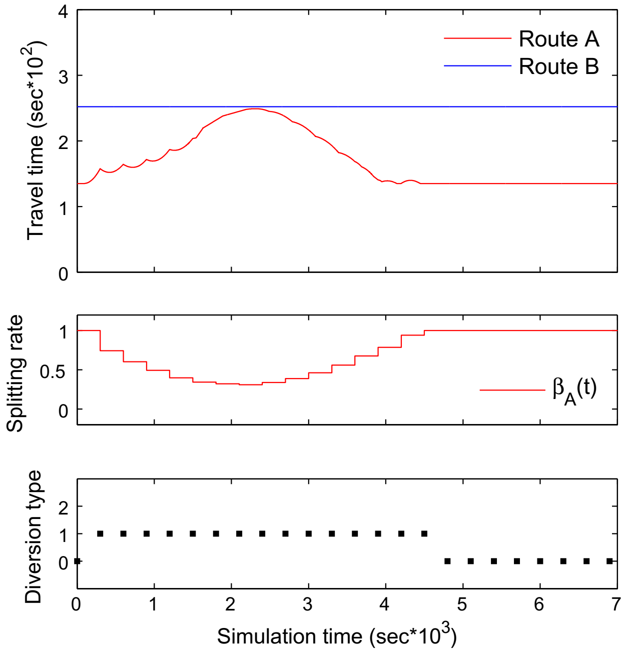


Fig. 6. Simulation results with a predictive demand in scenario 1 with exit capacity 3500 veh/h of route *B*.

demand during a long update interval, i.e., the weakness under a long update interval (see Section 4). When we replace the current demand with a predictive demand at 40% of the next update interval (i.e., the demand in 120 s later), the errors are reduced; see the results in Fig. 6.

Fig. 7 presents the simulation results when the exit capacity of route *B* is 1500 veh/h. The strategy is using under type-2 diversion most of time, i.e., two alternative routes are in congestion. It can be seen that type-2 diversion approximately equalizes travel time on two alternative routes, and thus achieves user optimal equilibrium. Fig. 8 shows that multiple con-

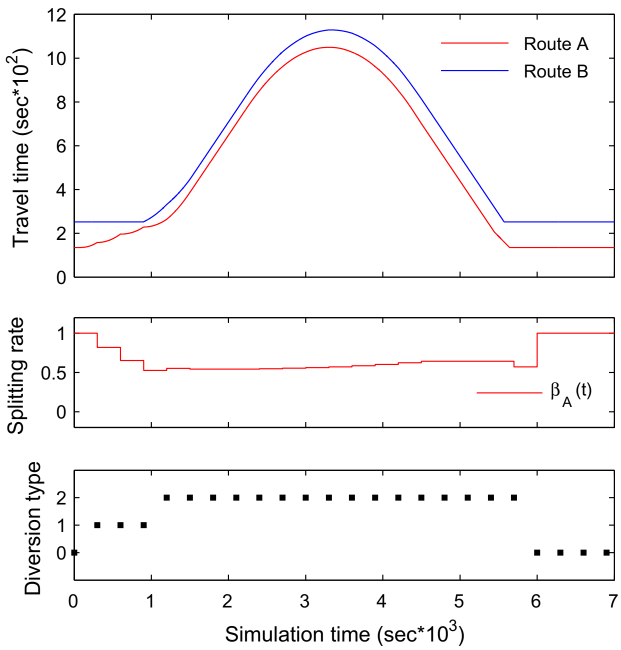


Fig. 7. Simulation results in scenario 1 with exit capacity 1500 veh/h of route *B*.

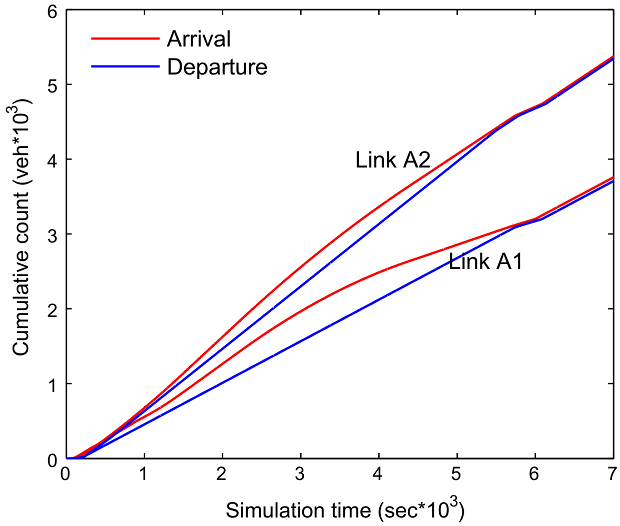
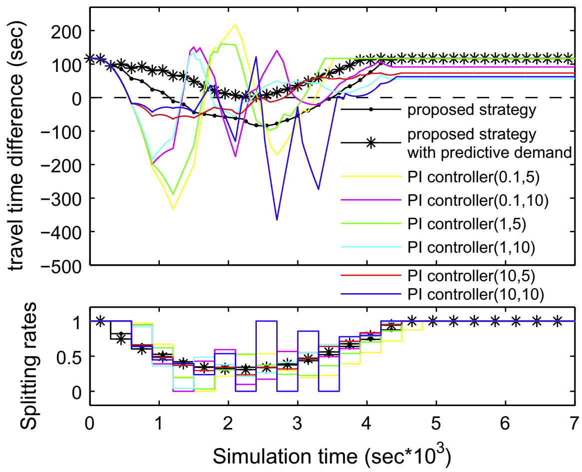
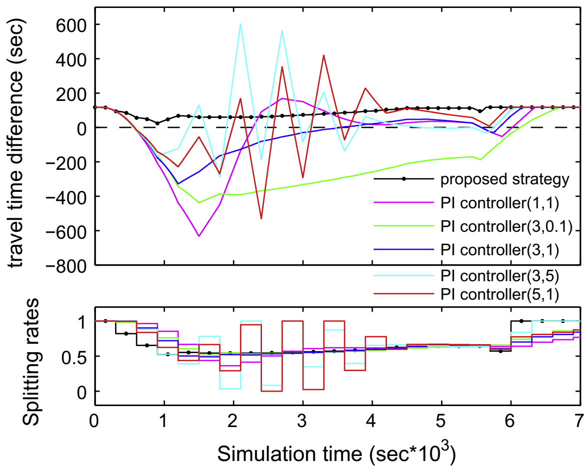


Fig. 8. Traffic conditions on route *A* in scenario 1 with exit capacity 1500 veh/h of route *B*.



(a) Scenario 1 with exit capacity 3500 veh/h of route B



(b) Scenario 1 with exit capacity 1500 veh/h of route B

Fig. 9. A comparison between the traffic-condition-based strategy and the feedback strategy with a PI controller (The travel time difference is the travel time on route *B* minus that on route *A*, and the numbers in the bracket are the proportional and integral parameters, respectively.)

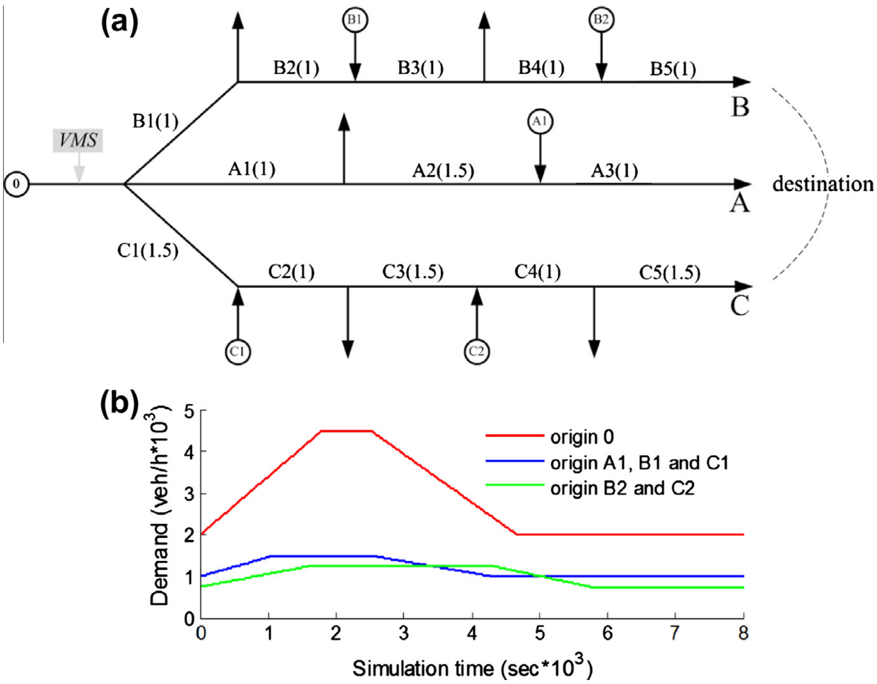


Fig. 10. A single destination road network with three alternative routes.

gestion occurs on route A; it implies the soundness of considering the total marginal delay in the extended strategy when more than one link are congested.

To better exhibit the advantage of the proposed strategy, we compare the strategy with the feedback strategy with a PI controller (Pavlis and Papageorgiou, 1999); see Fig. 9 for the results. Obviously, the diversion results from the feedback strategy are greatly influenced by the proportional and integral parameters, which clearly shows the difficulty of tuning parameters. Moreover, we even do not find proper parameters for the case that the exit capacity of route B is 3500 veh/h (see Fig. 9a). In contrast, the proposed strategy does not have the concern, and both the provided splitting rates and travel time difference are quite stable.

5.3. Scenario 2

In the scenario, we employ a complex network to test the strategy and the performances of the strategy with different update intervals; see Fig. 10. In the network, both entry and exit capacity of all links on all alternative routes are 3000 veh/h; those of an inlet or an outlet are 2000 veh/h. The free-flow speed on all links are 80 km/h, and the number in a bracket in the figure is the length of the link in km. Route A and C obviously have the shortest and longest free-flow travel time, respectively. All leaving rates via outlets are set as 10%.

It can be seen from the results in Fig. 11 that the strategy approximates user optimal equilibrium under a more complicated condition, and that it performs stably and effectively under different lengths of update intervals ranging from 1 s to 900 s. The error in equalizing travel time is caused by eliminating comparing travel time, and it makes the results tend to achieve system optimal equilibrium as discussed in Section 3.1.

6. Conclusions

A route guidance strategy is proposed based on traffic conditions (i.e., free-flow and congested conditions) instead of travel time. An extension for complex networks and a feedback approximation for avoiding forecast are also explored. Simulation investigations conducted on two road networks (see Figs. 4 and 10) demonstrate that the proposed strategy behaves stably and is able to approximate user optimal equilibrium under different conditions (see Figs. 9 and 11), in particular when traffic demand is high (see Fig. 7).

Nevertheless, in return for eliminating travel time comparison the strategy partially compromises user optimal equilibrium in type-1 diversion (see Fig. 5). Considering the occurrence only under the condition of medium traffic demand, as well as the tendency to achieve system optimal equilibrium (see Fig. 2), the trade-off might be acceptable in practice.

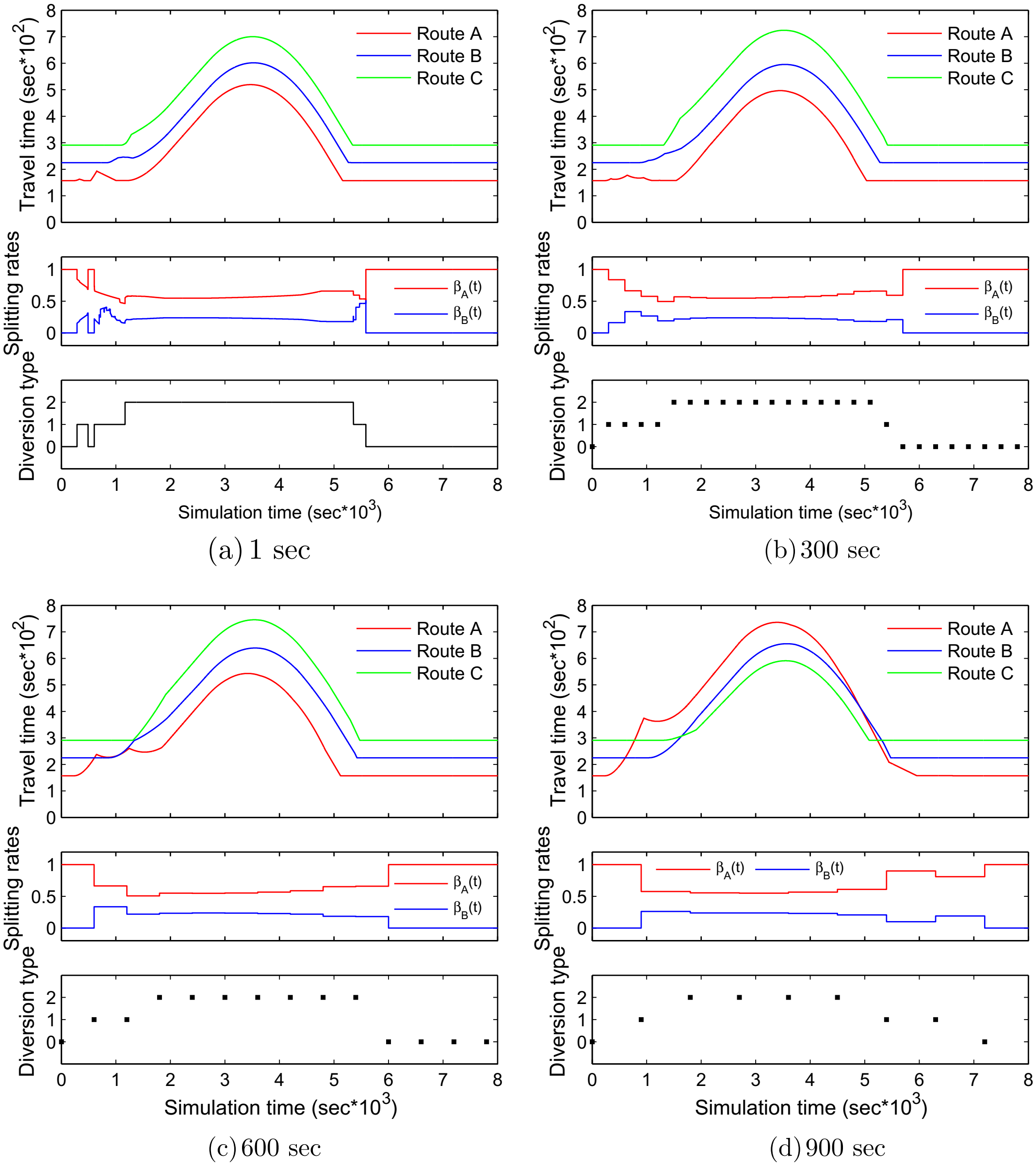


Fig. 11. Simulation results with different update intervals in scenario 2.

We conclude that the strategy has the following features:

- The strategy is simple. The strategy is based on an analytical solution, and the basic diversion rules are straightforward. The setting might be easy in deployment due to no exogenous parameters;
- The input data are easy to obtain. The input data of the strategy mainly include traffic conditions (i.e., free-flow and congested conditions), inflow and outflow of a link, and network configurations. These data are easy to obtain in an urban area except for outflow components of a route to compute the maximum output VMS flow.
- The strategy is able to stably and effectively approximate user optimal equilibrium under different conditions, in particular when the traffic demand is high. Moreover, when changing update intervals, no parameter is required to be tuned.

To finally apply the strategy in urban areas in practice, the following works still need to be considered in the future: extending the strategy to a network with multiple destinations and relaxing the restriction of parallel routes; incorporating traffic signals in order to suit urban areas; importantly, testing the strategy on a microscopic simulation model with the consideration of more practical details, etc.

Acknowledgements

The authors are grateful to the anonymous reviewers for their constructive comments. This research has been funded by 973 Program (2012CB725403), the National Science Foundation of China (71131001) and the Fundamental Research Funds for the Central Universities (2012JBM064).

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