REAL-TIME ROUTE GUIDANCE IN LARGE-SCALE URBAN EXPRESS RING-ROADS

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Abstract: The paper addresses real-time feedback route guidance in large-scale urban express ring-roads. Feedback routing strategies of bang-bang, P, and PI types as well as an ideal iterative strategy of the Frank-Wolfe type are applied to this end, with the aid of the macroscopic traffic flow modelling tools METANET and METANET-DTA. The investigation results indicate that real-time route guidance can help alleviate and dissolve heavy non-recurrent congestion, and establish dynamic user equilibrium.

Keywords: Transportation, urban express ring-roads, dynamic user equilibrium, route guidance, traffic control.

1. INTRODUCTION

Traffic networks typically include a high number of network-node couples each connected with multiple routes. Under user-equilibrium conditions, all alternative routes for any node couple that are actually utilized should have equal travel times that are not greater than the travel times on non-utilized routes. User-equilibrium traffic conditions usually improve the network performance (although they do not actually correspond to system-optimum conditions) without disadvantaging any part of the driver population. For this reason, most modern route guidance systems aim at **dynamic user equilibrium** (**DUE**) conditions within traffic networks (Papageorgiou, 1990).

The strategies for route guidance may be classified as feedback strategies or iterative strategies. Feedback strategies may be employed to approximate DUE in traffic networks. This is achieved via simple reaction to real-time traffic measurements with the explicit aim of equalizing instantaneous travel times along alternative utilized routes, despite the impact of various disturbances including incidents, weather conditions, demands, OD rates, compliance rate, etc. On the other hand, iterative strategies may be applied to establish exact DUE in traffic network models. This is achieved by running a traffic network model repeatedly over a future time horizon, based on real-time measured initial conditions and disturbance prediction, in order to equalize experienced travel times along alternative utilized routes.

At present many metropolitan areas are encircled by large-scale express ring-roads, which often act as hubs to serve local, regional, and inter-regional traffic. With the sharp increase of the number of passenger vehicles, urban express ring-roads are playing an increasingly important role within their corresponding overall urban traffic systems. A dual-direction urban express ring-road normally offers two route choices between various locations along the ring, i.e, an inner and an outer route. Without real-time route guidance, commuters make their route decisions based on past experiences, which may be sufficient under recurrent traffic congestion. However, daily demand variations, special events, and most importantly incidents may change traffic conditions in a non-predictable way. This may lead to an underutilization of the overall capacity of the ring-road, i.e. one direction of the ring is heavily congested while capacity reserves are available in the other direction. This paper investigates real-time route guidance in large-scale urban express ring-roads, with a special attention to the routing performance in the cases of incidents.

2. THE ROUTE GUIDANCE PROBLEM

Route guidance aims to establish dynamic user equilibrium in a traffic network by guiding vehicles among alternative routes over a given time horizon. The attribute **dynamic** emphasizes the fact that traffic demands, OD rates, traffic states, and travel times vary over time (and space). This section briefly introduces some necessary notions; for more details, see (Wang, *et al*., 2001).

With the aid of virtual nodes and dummy links (Papageorgiou, 1990), any bifurcation node in a network may be decomposed into several nodes so that each resulting bifurcation node has only one entering link and two leaving links (a primary and a secondary). Consider such a bifurcation node n and a destination j that may be reached via both leaving links of node n. There is exactly one **splitting rate** $\beta_{n,j}$ for such a **(n,j)-couple**, which determines the portion of j-bound traffic that leaves node n via its primary leaving link. For a couple (n, j), the directions to j via both leaving links of n are accordingly referred to as the primary and secondary directions. **Instantaneous** travel time along a route (including several links) is an ideal travel time spent by an ideal vehicle travelling along that route under the currently prevailing traffic conditions. **Experienced** (**predictive**) travel time along a route is the real travel time that vehicles will actually experience along the route. For each discrete time period k, let $\tau^{p}_{n,j}(k)$ and $\tau^{s}_{n,j}(k)$ be (instantaneous or experienced) **shortest** travel times along the primary and secondary directions of a couple (n, j), respectively. **Travel time difference** of the couple is defined as $\Delta\tau_{n,j}(k) = \tau^{s}_{n,j}(k) - \tau^{p}_{n,j}(k)$. With these notions, the DUE condition can be formulated as

$$\begin{aligned}
&\Delta\tau_{n,j}(k) \geq 0 \qquad \text{if} \qquad \beta_{n,j}(k) = 1\\
&\Delta\tau_{n,j}(k) = 0 \qquad \text{if} \qquad 0 < \beta_{n,j}(k) < 1\\
&\Delta\tau_{n,j}(k) \leq 0 \qquad \text{if} \qquad \beta_{n,j}(k) = 0
\end{aligned} \tag{1}$$

for all considered (n, j)-couples. When eq. (1) holds, travel times along both directions are equal if both directions are utilized, i.e. if $0 < \beta_{n,j}(k) < 1$. Thus the objective of routing control is to keep $\Delta\tau_{n,j}(k)$ close to zero so long as the splitting rate does not hit the bounds.

Suitable splitting rates may be calculated in real time by a variety of routing strategies. Feedback strategies attempt to keep the instantaneous travel time differences close to zero. A PI controller may be employed as a feedback strategy:

$$\begin{aligned}
\beta_{n,j}(k) = \beta_{n,j}(k-1) + K_p[\Delta\tau_{n,j}(k) - \Delta\tau_{n,j}(k-1)]\\
+ K_i\Delta\tau_{n,j}(k).
\end{aligned} \tag{2}$$

Iterative algorithms run a traffic network model (with suitable disturbance predictions) over a future time horizon repeatedly. At each iteration, the splitting rate trajectory calculated in the last iteration is updated in a suitable way and then applied to the model to produce the experienced travel times of the current iteration, and so forth, until the predictive DUE condition is satisfied with sufficient accuracy. The $\beta_{n,j}(k)$ resulting from both strategies are truncated if they exceed the admissible region [0, 1]. The disbenefit criterion (veh·h) is used to assess the degree of approximation to the exact DUE over the whole time horizon. It reflects the total vehicle-hours wasted on time-longer routes due to non-DUE routing. If the total disbenefit value is zero, the DUE condition is fully established.

3. A TEST EXAMPLE OF URBAN EXPRESS RING-ROAD

The Amsterdam Orbital Motorway A10 is considered as the test example, which is modelled by use of the macroscopic traffic flow modelling tools METANET and METANET-DTA (Wang, *et al*., 2001). The reader is referred to (Kotsialos, *et al*., 2002) for the METANET-based modelling of A10 and the related model calibration. The model of A10 is reflected in Fig. 1. The central dual-direction ring-road is A10, to which four other motorways (A1, A2, A4, and A8) are connected. The length of A10 is 32 km for each direction (A1-A2: 5 km, A2-A4: 5 km, A4-A8: 10.5 km, A8-A1: 11.5 km). Except A1, A2, A4, A8, there are 16 on-ramps and 16 off-ramps along the inner ring; 17 on-ramps and 16 off-ramps along the outer ring. The ring-road has 3 or 4 lanes in each direction, except at its northwestern part, where the Coen Tunnel lies with 2 lanes. The whole motorway system is modelled with 104 links (each representing a motorway stretch), which are separated by a number of nodes at the locations where on/off-ramps are situated or lane number changes. Each link is further sub-divided into several segments with an average length of 400 m.

A number of investigations have been conducted in simulation (each with a duration of 24 hours) to test the performance of the routing strategies with regard to this test example. As shown in Fig. 1, N_O_A1/2/4/8 refer to the bifurcation nodes immediately downstream of the A1/2/4/8 stretches towards A10, while D_A1/2/4/8 refers to the destinations of A10 at A1/2/4/8. Only 12 (n,j)-couples between A1, A2, A4, and A8 are considered in the investigation, each of which has two alternative routes via, respectively, the inner and outer rings. For example the three (n,j)-couples originating at A1 are (N_O_A1, D_A2), (N_O_A1, D_A4), and (N_O_A1, D_A8); the splitting rate for each (n,j)-couple is always defined for the outer ring direction. The utilized traffic demands are based on the real traffic inflows measured at A1, A2, A4, A8, and at all other on-ramps on June 6 1996. The traffic

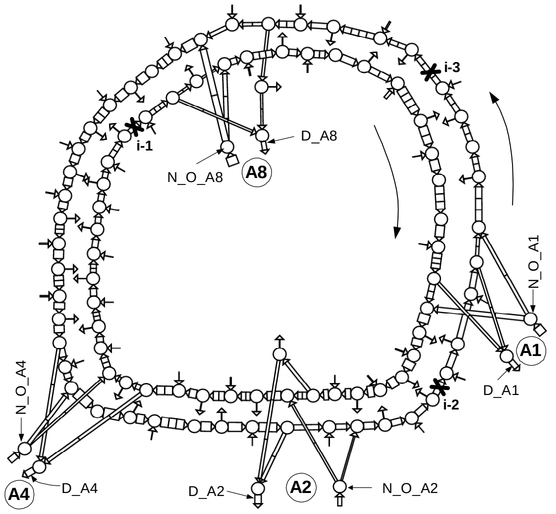

Fig. 1. Network topology of A10.

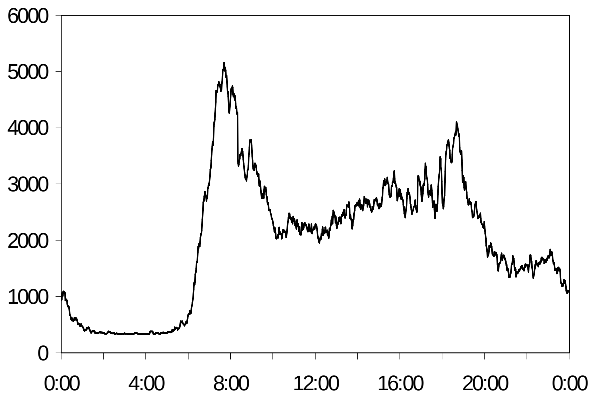

Fig. 2. 24-hour traffic demand at A4 (veh/h).

demands during the morning peak period are generally heavier than those during the afternoon peak period (see e.g. Fig. 2 for the A4 demand). The utilized OD matrix is based on reasonable assumptions. The adopted simulation time step is 10 s. Two simulation scenarios are considered: **recurrent scenario** with the aforementioned demands and OD; and **incident scenario** with three incidents i-1/2/3 occurring, respectively, at 7:00 AM/5:20 PM/5:40 PM with severities of 0.5/0.4/0.45 (representing the percentage of lost capacity) and with identical durations of 30 min. The three incident locations are marked with crosses in Fig. 1.

4. SIMULATION INVESTIGATIONS

The investigations were conducted for two cases: **non-routing case** and **routing case**. The former case means that no route guidance is performed in real time, and each commuter makes the route choice individually based on his past experiences, while the latter case means that real-time route guidance is conducted via feedback or iterative strategies. Both recurrent and incident scenarios are considered for the non-routing case, while only the incident scenario is considered for the routing case. All investigations were conducted using the default traffic assignment capabilities of METANET and METANET-DTA. Some representative investigation results are shown in Figs. 3-12. The performance indices (total disbenefit and total travel time spent; both in veh·h) and further comparative results are presented in Tables 1 and 2.

4.1 Non-routing case

This investigation aims to (1) re-construct the DUE conditions under recurrent traffic congestion; and (2) demonstrate that such DUE conditions cannot be kept in the case of non-recurrent traffic congestion (caused e.g. by incidents).

Recurrent scenario: For any given traffic network, the commuters adjust their route choices based on their past experiences. The overall impact of all commuters' independent decisions of route choices is believed to approximate a user-equilibrium of the network under recurrent traffic conditions. For the test ring-road, this DUE condition is emulated by applying the iterative algorithm of the Frank-Wolfe type (Wang *et al.*, 2001) to the ring-road model (based on METANET-DTA) under the recurrent scenario. Recurrent traffic congestion is observed inside the ring-road during both morning and afternoon peak periods. More specifically, the traffic congestion in the inner ring occurs first at the northwestern part (where the Coen Tunnel lies with a bottleneck) and the whole queue moves gradually to the upstream to cover fully or partially the southern part of the ring-road, while traffic congestion in the outer ring arises first at the southeastern and/or southwestern parts of the ring-road and propagates upstream to cover the western part of the ring. All congestions fully dissolve at the end of the corresponding peak periods. The disbenefit evaluated over 24 hours is only 2 veh·h, indicating that the DUE is almost fully achieved. Therefore, the resulting splitting rates (for the 12 (n,j)-couples) can be viewed as the commuters' nominal splitting rates.

Incident scenario: Due to lack of real-time traffic information, when non-predictable events (e.g. incidents) take place, most commuters are unable to make correct route choices; in most cases, they follow the same routes as under recurrent traffic situations. To investigate to what extent the DUE can be jeopardized in this case, a simulation was conducted (based on METANET) under the incident scenario but with the nominal splitting rates (perfect under the recurrent scenario) applied. It is observed that after each incident, the incident-related ring is getting seriously congested, while traffic on the alternative ring is free-flowing during that period, see Figs. 3 and 4 for the two most congested moments[1].

[1] In the network plots (produced by METANET or METANET-DTA), the width of a segment represents the

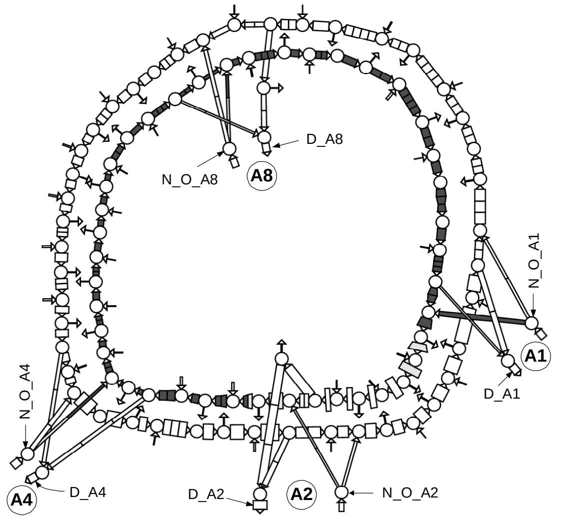

Fig. 3. Non-routing case at 9:55 AM.

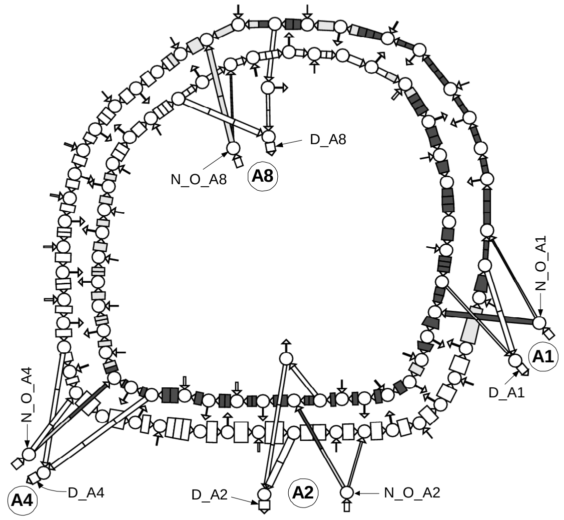

Fig. 5. PI-routing result at 9:55 AM.

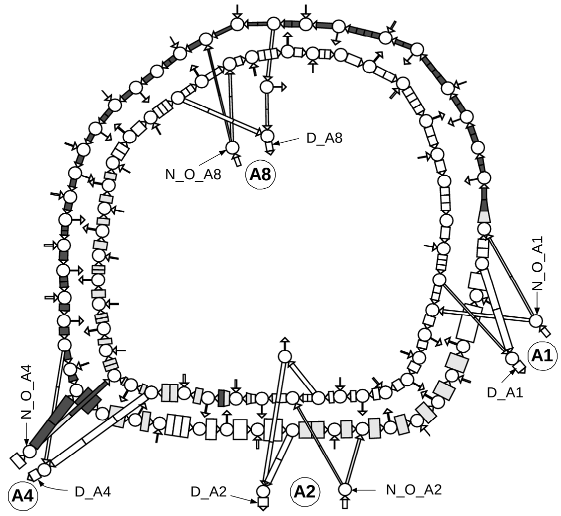

Fig. 4. Non-routing case at 7:30 PM.

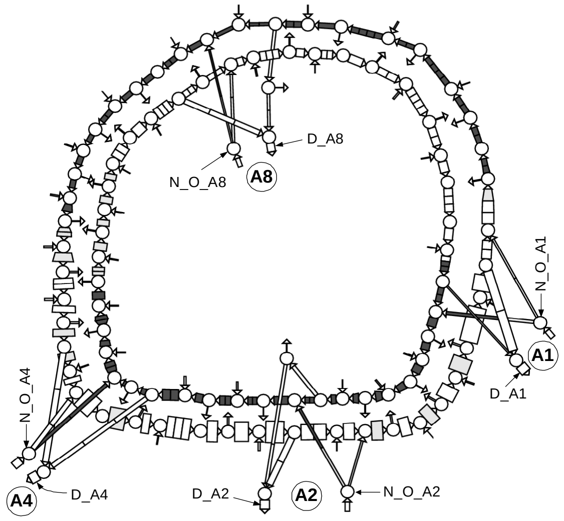

Fig. 6. PI-routing result at 7:30 PM.

Obviously, the DUE is destroyed, which is also indicated by the corresponding indices in Table 1. It is noted that all congestions are fully dissolved at the end of the corresponding peak periods.

4.2 Routing case

This investigation shows how the DUE can be approximated by the feedback routing strategies and exactly established by the iterative strategies even under the incident scenario.

General results: The feedback and iterative routing suitably divert traffic demands from the ring that is seriously congested to the alternative ring with capacity reserves. Consequently, DUE is achieved approximately (with real-time feedback routing) or exactly (with the ideal iterative routing); see Table 1 for the corresponding disbenefit values. Figures. 5/6 and Figs. 7/8 may be compared with Figs. 3/4 for the overall traffic situation at the same moments; it may be seen that the traffic load is much more balanced between the inner and outer rings via route guidance. A more systematic comparison is presented in Table 2 between the non-routing case and the routing case to further illustrate the performance of route guidance. In Table 2, "REC", "INC", "PI", and "ITER" refer to "recurrent scenario", "incident scenario", "PI strategy", and "iterative algorithm", respectively, while "to appear", "most congested", and "dissolved" refer to the time instants that "the congestion appears in the ring-road", "the ring-road is most congested", and "the congestion is fully dissolved in the ring-road". Clearly, without route guidance, as compared to the recurrent scenario, each direction of the ring with the incident(s) (the inner in the morning and the outer in the afternoon) needs 3 more hours (in average) to dissolve the congestion, while the incident-free directions experience only the recurrent congestion, which dissolves at the same

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traffic volume (veh/h), while the grey scale of the segment represents the corresponding traffic conditions (white for free flow, grey for dense, and dark for congested traffic). With the plots, the dynamic evolution of overall traffic conditions can be displayed at any user-specified time step.

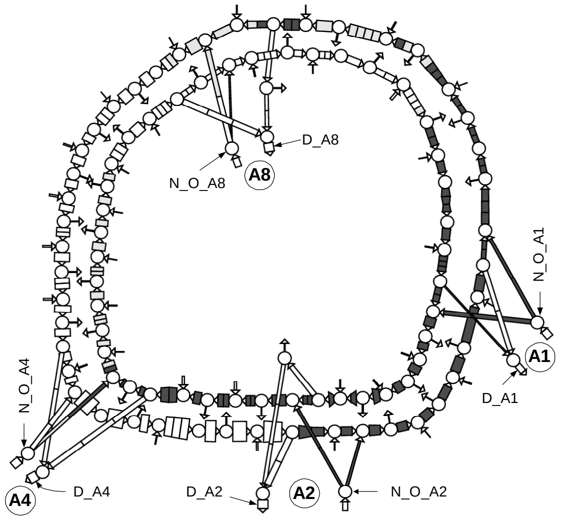

Fig. 7. Iterative-routing result at 9:55 AM.

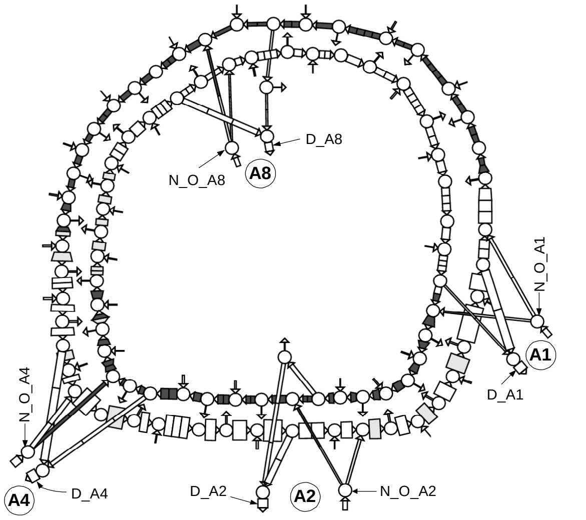

Fig. 8. Iterative-routing result at 7:30 PM.

moments as under the recurrent scenario. On the other hand, with route guidance applied, the congestion in the incident directions is dissolved much earlier, while the congestion in the incident-free directions, to which more traffic loads are diverted, is dissolved relatively later. Totally, the routing has reduced the congestion duration of the whole ring road by about 2.5 hours a single day. Moreover, with route guidance, both directions return to the free-flow condition at similar time instants. The resulting TTS (Table 1) is consistently improved via route guidance in the incident case by some 16%.

PI-routing results: The real-time splitting rate for (N_O_A2, D_A1) is kept constant at 1, i.e. the traffic demand with this OD is always routed to the outer ring, while the resulting splitting rates for (N_O_A2, D_A4) and (N_O_A4, D_A2) are only slightly changed during the after peak period. On the other hand, the splitting rates of the other nine (n,j)-couples are significantly modified during both peak periods. The splitting rate and predictive travel time differences for (N_O_A8, D_A2) and (N_O_A2, D_A8) are displayed in Figs. 9-12. Note that the distances between A8 and A2 in both directions are similar (15.5 and 16.5 km for the outer and inner directions). As shown in Fig. 9, since 0:00 AM the outer direction is utilized for the traffic of (N_O_A8, D_A2) until about 7:00 AM, when the first incident occurs at the inner ring. As a result of the routing control, more traffic demand at A4, A2, and A1 are diverted to the outer ring after 7:00 AM, which renders the inner direction more competitive for (N_O_A8, D_A2), and hence the inner ring is chosen (the corresponding splitting rate becomes zero). With the progressing time, the congestion queue at the inner ring moves upstream, while the congestion

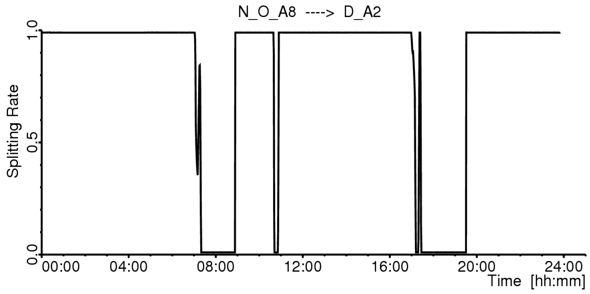

Fig. 9. Real-time splitting rate for (N_O_A8, D_A2).

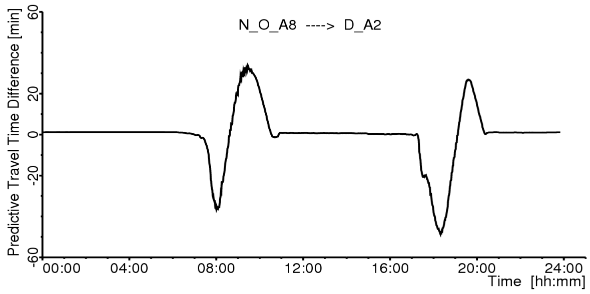

Fig. 10. Travel time difference for (N_O_A8, D_A2).

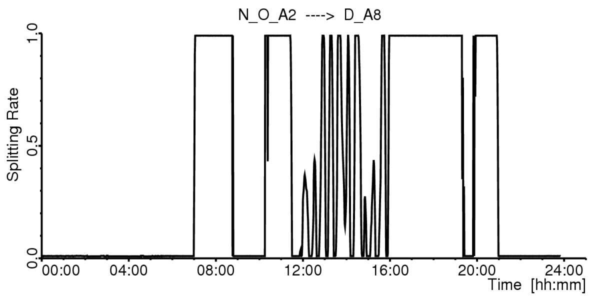

Fig. 11. Real-time splitting rate for (N_O_A2, D_A8).

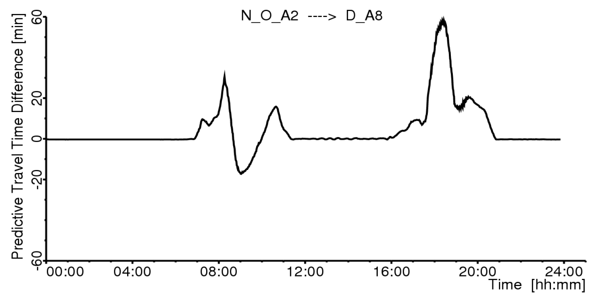

Fig. 12. Travel time difference for (N_O_A2, D_A8).

queue at the outer ring moves to the eastern side of the ring. Consequently, the outer direction for (N_O_A8, D_A2) becomes competitive again at about 8:50 AM (see Fig. 5 for a later moment but with a similar situation). At 5:20 PM, due to the incident at the outer ring, the inner direction becomes competitive until 7:30 PM (Fig. 6). Clearly, the corresponding predictive travel time differences (Fig. 10) match the splitting rates in the sense of approximate DUE. A similar interpretation applies to couple (N_O_A2, D_A8); see Figs. 11 and 12.

4.3 Practical applicability

The feedback route guidance investigated via simulation employs only readily available real-time traffic measurements; hence the obtained simulation results are deemed comparable to what would be achievable for the real traffic flow. In contrast, if the iterative algorithm would be realistically employed for real-time route guidance, a rolling-horizon (model-predictive) control procedure should be employed, whereby the achieved results would be critically dependent upon a number of potentially serious uncertainties, e.g. traffic composition (by destination), demands, OD, driver compliance, incidents, etc. These uncertainties are likely to deteriorate the routing quality and complicate the real-time route guidance. The presented iterative routing was performed under ideal conditions only to deliver an optimal reference case for comparison with the feedback routing results. In addition, the utilized control interval to activate the feedback routing strategies was set equal to the simulation time step (10 s). In the field, a control interval is normally not less than 1 min, but in fact the feedback routing strategies are rather insensitive to longer control intervals. For the test example, when the control interval of the PI-strategy is gradually increased from 10 s to 5 min, the total disbenefit was found to monotonically increase from 495 to 606 veh·h. The drivers' compliance rate is another important factor that may have an impact on the routing performance. Full compliance rate has been assumed in the presented investigations, but it is known from previous investigations that the impact of partial driver compliance on the routing performance is quite moderate.

5. CONCLUSIONS

The real-time feedback route guidance for large-scale urban express ring-road has been investigated in simulation and compared to ideal DUE conditions. The investigation results demonstrate that

- The daily travelling experiences are far insufficient for the commuters to deal with non-recurrent traffic situations (due to e.g. incidents).
- Real-time feedback route guidance is very efficient in handling non-recurrent traffic situations and establishing the DUE condition within the road network.

Further work including the OD estimation and real-data based testing of the routing strategies for the Amsterdam ring road is currently under way.

ACKNOWLEDGEMENT

The first author wishes to thank Dr. Apostolos Kotsialos, Technical University of Crete, for his help at the early stage of this work. Dr. Albert Messmer's contribution to METANET and METANET-DTA is also acknowledged.

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Table 1 Disbenefit and TTS (veh·h) over 24 hours

	Non-routing case		Routing case (incident scenario only)			
	Normal	Incident	Bang-bang	P	PI	Iterative
Disbenefit	2	5484	516	521	495	3
TTS	57802	96720	81405	81395	81572	80651

Table 2 Key time instants of congestions for the non-routing and routing cases

		Morning peak period (AM)					Afternoon peak period (PM)				
		To appear		Most congested	Dissolved		To appear		Most congested	Dissolved	
		Outer	Inner		Outer	Inner	Outer	Inner		Outer	Inner
Non-routing	REC	7:30	7:35	8:27	9:30	10:15	17:10	16:15	19:10	19:45	20:15
	INC	7:30	7:00	9:55	9:30	13:50	17:10	16:15	19:30	22:30	20:15
Routing	PI	7:20	7:00	9:00	10:50	11:20	17:10	16:05	19:00	20:20	20:50
	ITER	7:20	7:00	8:40	10:40	11:10	17:10	16:05	19:00	20:30	20:52