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Chapter 73
Departure Rates Optimization and Perimeter Control: Comparison and Cooperation in a Multi-region Urban Network

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Abstract With the renewed interest in the Macroscopic Fundamental Diagram (MFD) in the last decade, studies on network-level urban traffic control have increased in popularity. A popular urban traffic control approach is perimeter control, in which vehicle accumulation is kept below some critical accumulation value. An alternative control strategy is to optimize time series of departure rates as a means to limit inflows into the (sub)network. In this paper we test how these approaches compare in terms of minimizing total time spent (TTS), and whether network performance can be improved by combining these two approaches. To the best of the authors' knowledge, answers to these two questions are still missing. Our findings indicate that—for a particular multi-region network under a specific demand profile—optimizing departure rates outperforms perimeter control. Particularly, we find that the combination of perimeter control and departure rates optimization may even have adverse effects on minimizing TTS, compared to optimizing departure rates only. We also show that properly over-saturating part of a network could result in less TTS than under the application of a perimeter control, which keeps the accumulation under the critical accumulation.

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73.1 Introduction

The Macroscopic Fundamental Diagram (MFD), which describes an inverse-U shaped relationship between traffic flow and density on a network level, offers a parsimonious approach to model and study urban traffic dynamics and control in a large-scale network [1, 2].

A popular urban traffic control approach is perimeter control, in which vehicle accumulation is kept below some critical accumulation value. An alternative to perimeter control is to optimize departure rates, for example by means of pricing strategies [3]. In this paper we test how these approaches compare in terms of minimizing total time spent (TTS), and whether network performance can be improved by combining these two approaches. To the best of the authors' knowledge, answers to these two questions are still missing.

We formulate the research question as a comparison among four study cases. This research offers two main findings: (i) departure rates optimization outperforms perimeter control in minimizing TTS in a multi-region urban network; (ii) perimeter control may even have adverse effects on the performance of departure rates optimization when combining the two measures. The second finding also indicates that partial over-saturation could result in less TTS than fully under-saturation under the application of perimeter control. We believe our work contributes to the research of applying departure time control (by whatever means) in combination with perimeter control in more complex (multi-region) networks.

This paper is organized as follows: Sect. 73.2 describes the network transmission model and the genetic algorithm. Section 73.3 formulates the optimization problem, and conduct four case studies. Finally, we end this paper with conclusions in Sect. 73.4.

73.2 Methodology

This section describes methods for addressing the research questions. The traffic dynamics are described by a MFD-based model in Sect. 73.2.1. Section 73.2.2 describes the optimization of control measures.

73.2.1 Network Transmission Model: MFD-based Traffic Dynamics

This section introduces the MFD-based network transmission model. This model is used for describing the traffic dynamics on network level. The MFD function is expressed as $Q_i(N_i) = N_i \cdot v_{i,f} \cdot e^{-\frac{1}{2}(N_i/N_{i,c})^2}$ where $v_{i,f}$ and $N_{i,c}$ are the free-flow speed and the critical number of vehicles, $Q_i(N_i)$ is the potential outflow of zone i pertaining to N_i.

According to [4], the traffic dynamics of zone i are given by

$$N_i(t+1) = N_i(t) + [I_i(t) - O_i(t)] \cdot \Delta t \tag{73.1}$$

where

$$I_i(t) = \lambda_i(t) + \sum_{i \neq j, j \in \mathcal{U}_i} \min\left(\frac{N_{j\to i}}{N_j} Q_j(N_j), \frac{N_{i \leftarrow j}}{N_i} \tilde{Q}_i(N_i)\right) \tag{73.2a}$$

$$O_i(t) = \sum_{i \neq j, j \in \mathcal{D}_i} \min\left(\frac{N_{i\to j}}{N_i} Q_i(N_i), \frac{N_{j \leftarrow i}}{N_j} \tilde{Q}_j(N_j)\right) + \frac{N_{ii}}{N_i} Q_i(N_i) \tag{73.2b}$$

$I_i(t)$ is the number of vehicles entering region i per unit of time, while $O_i(t)$ is the number of vehicles leaving the region i per unit of time. $\mathcal{U}_i$ and $\mathcal{D}_i$ are the set of adjacent zones in the upstream and downstream of zone i, respectively. $N_{i \leftarrow j}$ means the number of vehicles in zone i that originating from zone j. $N_{i \to j}$ is the number of vehicles in zone i whose destination is zone j. $Q_i(N_i)$ represents the aggregated demand (shaped by the MFD function) of zone i when the vehicle accumulation is N_i, and $\tilde{Q}_i(N_i)$ is the aggregated supply of zone i whose accumulation is N_i. Remark here the term "aggregated" means all vehicle in the corresponding region are counted regardless their origins and destinations. $\lambda_i(t)$ indicates how many vehicles are generated per time unit within the region i at time t.

When perimeter control is off, the aggregated supply in one region is formulated as:

$$\tilde{Q}_i(N_i) = \begin{cases} Q_i(N_{i,c}) & \text{if } N_i \leqslant N_{i,c}, \\ Q_i(N_i) & \text{if } N_i > N_{i,c}. \end{cases} \tag{73.3}$$

When perimeter control is on, a feed-back controller is designed to limit the aggregated supply (73.3). The feed-back controller is expressed as:

$$\tilde{Q}_i(N_i(t+1)) = \tilde{Q}_i(N_i(t)) + K_1 \cdot (N_{i,c} - N_i(t+1))/L)) \tag{73.4}$$

where L is the network distance in every region. K_1 is a coefficient for the proportional term. When the perimeter controlled is on, the aggregated supply of each region will be the minimum value between (73.3) and (73.4).

73.2.2 *Optimization: A Genetic Algorithm*

We specify the demand profile along time as a vector over the monitored period. A genetic algorithm is used to find an optimal demand profile (or solution). Each solution corresponds to a cost pertaining to the total time spent (TTS), which is given by running simulations. We rank the solutions by the corresponding costs from low to high.

We repeatedly select two solutions (parents) to generate two new solutions (children) by crossover. In the selection, only a number of highly ranked solutions (named as the sample size) will be chosen to ensure the chosen 'parents' have the best 'gene'. From the top 75 out of 2000 solutions, a choice is made using a logit model. Before generating children from two parents, this crossover will take place for a random number of times. This study has a challenge to this with a constraint on the fixed total number of trips, that is, interchanging elements of any two solutions would immediately violate this constraint. Hence, after the crossover, the difference between the total number of trips in the solution and the desired total number of trips N will be added/subtracted from the very last element of the solution. If this value turns out negative after the crossover, we discard the solution and replace it with a new (random) one. The final step in the genetic algorithm is the mutation. We perform an iteration-dependent mutation by adding/subtracting a value from a random amount of elements of the parents. The repetition of generating two new solutions will end when the population size in the next generation is reached. The whole process is one iteration. In every iteration, the best solution in one generation will be recorded as the solution of the final generation. After finite iterations, the top ranked solution in the final generation would be the optimal solution.

73.3 Problem Formulation and Case Study

This section describes the studied urban network, and how we formulate the optimization problem. A particular case study is given.

Consider an urban network, which is divided into $R = 6$ regions; see Fig. 73.1. Each region ($i = 1, 2, ..., R$) is characterized by a well-defined MFD. In this network, during peak hours citizens in region 1 and 4 need to drive to region 3 and 6, respectively. This OD matrix structure illustrated in Fig. 73.1, where two directions of traffic streams intersect each other in region 2. The same MFD is applicable from region 1 to region 5; the MFD in the region 6 has a lower capacity and free-flow speed. In Fig. 73.2, the area of each region indicates its capacity.

In this study, the departure rates at every time window from region 4 was fixed; while the departure rate time series via region 1 is controllable by using some prospective traffic measures, e.g., time-specific trade-able peak permits [3]. This study uses $\lambda_i(t)$ to denote the expected departure rate via region i at time t per unit of time. As a result, region 6 can be a bottleneck for vehicles from region 4. Congestion could occur in region 5 due to the bottleneck. When the perimeter control is on, congestion will be prohibited from occurring in the region 5 by holding vehicles in its upstream.

The goal of the departure rates optimization is to minimize the cost pertaining to TTS, U. The cumulative number of vehicles entering and exiting the network at time t are denoted by $N_{\text{in}}(t)$ and $N_{\text{out}}(t)$. The cost function is formulated as:

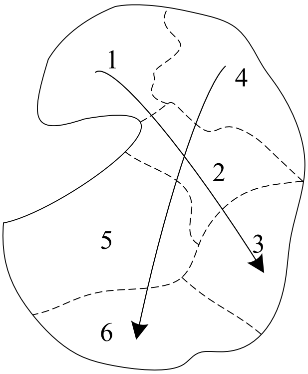


Fig. 73.1 Studied urban network structure

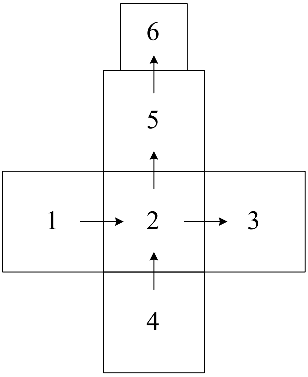


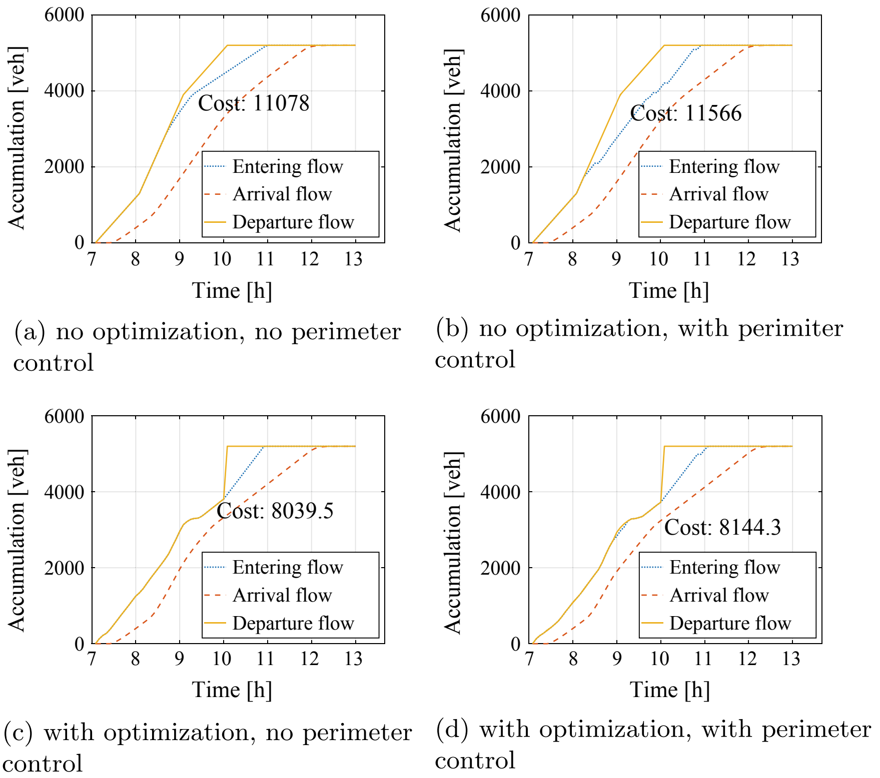
Fig. 73.2 A representation of the network

$U = \alpha \int_0^T ([N_{out}(t) - N_{in}(t)]\,dt$. Here, the total simulation time is denoted as T. α is the marginal cost of total time spent on roads.

For all simulations we consider a peak-period of three hours (from 7:00 am to 10:00 am) and a simulation time of six hours: three more hours following the peak duration for emptying the network.

As described in Sect. 73.3, two different exogenous flows enter our network: from zone 1–3; and from zone 4–6. Consider two demands: from 8:00 to 9:00, 1300 vehicles would like to take the path $1 \rightarrow 2 \rightarrow 3$; while 3900 vehicles take $4 \rightarrow 2 \rightarrow 5 \rightarrow 6$ during the 3-hour peak duration.

Four different cases are categorized regarding to whether the departure rate time series $\lambda_4(t)$ is optimized and whether perimeter control is active: : (Case 1) Without any control measure: The aggregated departure rate in every time window is the same. The perimeter control is off; (Case 2) Perimeter control: The aggregated departure rate in every time window is the same. The perimeter control is on; (Case 3) Departure rates optimization: The time series of departure rates is optimized through the genetic algorithm. The perimeter control is off; (Case 4) Combining perimeter control and the departure rates optimization: The time series of departure rates is optimized through the genetic algorithm. The perimeter control is on.



(a) no optimization, no perimeter control

(b) no optimization, with perimiter control

(c) with optimization, no perimeter control

(d) with optimization, with perimeter control

Fig. 73.3 Cumulative curves of departure, entering and arrival flow in four study cases. The cost in each case is put in each sub-figure

The departure rates tell how many vehicles depart in every time windows. Due to the traffic dynamics (e.g., low supply in the downstream zone) or perimeter control, some vehicles will be kept waiting out of the monitored network (before entering region 1 or 4). Hence, another term “entering rate" is used to indicate the number of vehicles entering into region 1 and 4 per unit of time.

Figure 73.3 shows the cumulative curves of departure rates, entering rates and arrival rates. The cost estimated using for each case is shown in the corresponding sub-figure. The cost is α times the area between the departure (solid line) and arrival (dashed line) cumulative curve. In Fig. 73.3, the area between the cumulative curve of entering and arrival rates indicates the total time spent in the monitored network, excluding the waiting time out of the network.

The case with departure rates optimization and without perimeter control has the lowest cost (8039) among four cases. In the case of combination of the departure rates optimization and perimeter control, the cost reaches 8144. Since the only difference in these two cases is whether the perimeter control is on, we can conclude that perimeter control adds *adverse* effects to the congestion mitigation performance of the departure rates optimization in this study. Comparing the cases without optimization, i.e., Case 1 and Case 2, we can find a slightly lower cost in the case without perimeter control. When the optimization is used in Case 3 and Case 4, the case with perimeter control has higher cost. All show that perimeter control will slightly increase total cost, and that departure rates optimization will decrease total cost.

73.4 Conclusions

In this paper we compared different combinations of perimeter control and departure rates optimization. To this end we used an MFD network traffic flow model and a genetic optimization algorithm to do the optimization.

This research offered two main findings: (i) departure rates optimization outperforms perimeter control in minimizing TTS in a multiregion urban network—given of course our assumptions on the supply dynamics; (ii) perimeter control may even have adverse effects on the performance of departure rates optimization when combining the two measures. The second finding also indicates that partial over-saturation could result in less TTS than fully under-saturation under the application of perimeter control. In the future, authors will explore whether the findings and conclusions can be generalised in a more complex but realistic city.

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