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EFFECTS OF ON-RAMP AND OFF-RAMP METERING ON QUEUE FORMING IN URBAN TRAFFIC NETWORKS

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AbstractTo control the traffic flows near on-ramps and off-ramps, ramp metering installations can be used. We compare on-ramp metering and off-ramp metering, with respect to queue forming and total time spent. Both control measures are used to improve traffic flow on freeways, and both have influence on the route choice of the drivers. Although the two measures are very similar, there are some major differences. The use of ramp metering installations can change the traffic assignment in the network because the inflows or outflows of the freeways are limited. This will result in a change in travel times in the network. And since drivers make a route choice based on these travel times, the route choice (and thus the traffic assignment) can change as well. This can lead to a relocation of queues in the network. With a case study we illustrate the differences between on-ramp and off-ramp metering, with three different control methods: fixed time control, ALINEA and a model predictive control-based method.

Keywords: Traffic control, Model predictive control, Ramp metering

1. INTRODUCTION

The amount of traffic on the roads has increased during the last years. This has led to an increase of congestion, mainly located on the freeways. This congestion leads to longer travel times, and as a result it has become more attractive for drivers to leave the freeway, use a shorter route through the urban network, and then enter the freeway again downstream of the congestion (rat-running). This causes an increase of long distance traffic on the urban network. The long distance vehicles in the urban network slow down the local traffic, decrease the safety due to higher speeds and less knowledge of the local situation, and generate more pollution and noise. This change in route choice can be prevented with static measures, e.g. lower speed limits on the urban network, closing lanes during peak hours, placing route guidance signs,

etc. Also some dynamic measures are available, e.g. creating 'red waves', providing information on variable message signs, or using ramp metering installations. These measures influence the route choice of the drivers by increasing the travel times in the urban network, or by guiding unfamiliar drivers only along the freeway. In this paper we will focus on the effect of ramp metering on the route choice of the drivers.

Originally, on-ramp metering installations were used to prevent congestion on freeways (Papageorgiou and Kotsialos, 2002; Cassidy and Rudjanakanoknad, 2005; Chen *et al.*, 1990; Zhang *et al.*, 2001). When the on-ramp metering installations were actually implemented, it became clear that they also influenced the route choice of the drivers (Taale and Middelham, 2000; Haj-Salem and Papageorgiou, 1995). The explanation for this phenomenon is that ramp meter-

ing changes the travel times of the routes, and since route choice is mainly based on these travel times, some drivers will select another route when a ramp metering installation is placed. These ideas lead to research on corridor control where on-ramp metering installations are used to influence route choice (Bellemans, 2003; Karimi *et al.*, 2004; Yang and Yagar, 1994).

A problem with the use of on-ramp metering installations is that on-ramp metering creates longer queues on the on-ramps, which can spill-back in the urban network. This results in more noise and pollution in the urban network, causing problems for the inhabitants of the cities. To solve these problems, off-ramp metering can be used. This method limits the flow that can leave the freeway, and so decreases the number of vehicles in the urban network. This improves the traffic condition in the urban network, but since the vehicles stay on the freeway, it has a negative impact on the situation on the freeway.

This paper is organized as follows. We first describe on-ramp and off-ramp metering, and give some theoretical (dis-)advantages. Next, we present some control methods that can be used to determine the settings of the ramp metering installations. At last, to investigate the differences between on-ramp and off-ramp metering, we perform a case study in which we simulate traffic in a small network with two possible routes. We use the Metanet model developed by Papageorgiou (Messmer and Papageorgiou, 1990) to describe the evolution of the traffic flows. This model is a discrete time discrete space model that divides the freeway network into links m, which are again divided into segments i. For each segment three state variables (density $\rho_{m,i}(k)$, velocity $v_{m,i}(k)$, and flow $q_{m,i}(k)$) are computed every time step k. As a route choice model we use the model we described in (van den Berg *et al.*, 2005). We compare different methods to control the ramp metering installations: fixed time control, ALINEA (Papageorgiou *et al.*, 1991), and a model predictive control based method (Bellemans, 2003).

2. RAMP METERING

Ramp metering is a control method that limits the flow on ramps connected to a freeway. On-ramp metering limits the flow that enters the freeway, off-ramp metering limits the flow that leaves the freeway. Ramp metering is implemented with traffic signals, which allow only one vehicle to drive on during each green period.

The ramp metering rate gives the percentage of the capacity flow that is allowed to drive on. The ramp metering rate can vary between a maximum and a minimum value: $r_{\min} \leq r(k) \leq r_{\max}$.

2.1 On-ramp metering

On-ramp metering limits the flow that can enter the freeway via the metering rate:

$$q_{o,f}^{\text{real}}(k) = \min\left(r(k)Q_{\text{cap},f}, q_{o,f}^{\text{int}}(k)\right)$$

where $q_{o,f}^{\text{int}}(k)$ is the flow that intends to enter freeway f via on-ramp o, $r(k)$ is the ramp metering rate, $Q_{\text{cap},f}$ is the capacity flow, and $q_{o,f}^{\text{real}}(k)$ is the flow that really enters the freeway.

On-ramp metering can influence the route choice of drivers, but only when queues are formed that become long enough to influence the travel time significantly. When drivers have experienced a long queue on the urban network during previous trips, they will select the freeway route during a next trip. But the long queue that is required to obtain this change in route choice spills back through the total urban network. As a result the urban traffic is totally blocked, and the local traffic is also delayed.

2.2 Off-ramp metering

Off-ramp metering limits the flow that can leave the freeway:

$$q_{f,o}^{\text{real}}(k) = \min\left(r(k)Q_{\text{cap},f}, q_{f,o}^{\text{int}}(k)\right)$$

where $q_{f,o}^{\text{real}}(k)$ is the flow that really leaves freeway f toward off-ramp o, and $q_{f,o}^{\text{int}}(k)$ the flow that intends to leave the freeway. The part of the flow that intends to leave the freeway but that is not allowed to is given by

$$q_{f,o}^{\text{over}}(k) = q_{f,o}^{\text{int}}(k) - q_{f,o}^{\text{real}}(k).$$

This flow will result in an increase of the density on the segment upstream of the off-ramp:

$$\rho_{f,N_m}^{\text{tot}}(k) = \rho_{f,N_m}(k) + \frac{T}{l\lambda}q_{f,o}^{\text{over}}(k) - \frac{T\gamma}{l\lambda}q_{f,o}^{\text{over}}(k-1)$$

where $\rho_{f,N_m}^{\text{tot}}(k)$ is the total density (including the vehicles that want to leave toward the off-ramp) on the last segment N_m of freeway f, $\rho_{f,N_m}(k)$ is the density on this segment as computed with the Metanet model (without the extra waiting vehicles), T the simulation time step, l the length of a segment, λ the number of lanes, and γ a parameter explained below. The waiting vehicles of the previous time step are used to compute the vehicles that intend to leave the freeway during the current time step:

$$q_{f,o}^{\text{int}}(k) = \gamma q_{f,o}^{\text{over}}(k-1) + q_{f,o}(k)$$

where $q_{f,o}(k)$ is the flow that wants to leave the freeway according to the Metanet model. When the number of vehicles that waits to enter the off-ramp becomes too high, some of these vehicles will change their route and stay on the freeway. The percentage of drivers that keeps waiting is given by γ.

Off-ramp metering can be used to prevent rat running by creating visible queues at the off-ramp, which

will discourage drivers to leave the freeway. A disadvantage of off-ramp metering is that the queues can become too long for the off-ramp, and spill back on the freeway. This can decrease the throughput on the freeway, and decrease the safety since large speed-differences are created between the traffic on the first lane and on the second lane of the freeway.

3. CONTROL METHODS

There are different methods to control ramp metering installations. A fixed ramp metering rate can be selected off-line. Other methods determine the ramp metering rate on-line, like ALINEA (Papageorgiou *et al.*, 1991) and the method described in (Taale and Middelham, 2000). The traffic flow or density on the freeway is measured, and this value is used to determine the ramp metering rate. Cooperation of different ramp metering installations is also possible (Bellemans, 2003; Kotsialos *et al.*, 1999). Objectives of this kind of systems are for example maximizing throughput on the freeway, maximize the mean speed, reducing the shock waves to improve safety, minimize the queue length and waiting time on the ramps, or minimize the total time spent in the network.

In this paper we compare on-ramp and off-ramp metering. For each of them, we compare three different methods, which are described below.

3.1 Fixed rate control

With fixed rate control the ramp metering installations are operating with a fixed ramp metering rate. This rate is determined off-line, but is selected in such a way that it is the most optimal setting for the whole simulation period.

3.2 ALINEA

ALINEA is a method for on-ramp metering developed by Papageorgiou (Papageorgiou *et al.*, 1991). It is developed for on-ramp metering. The ramp metering rate is determined based on the density downstream of the on-ramp:

$$r(k) = r(k-1) + K_r(\rho_{\mathrm{crit},f} - \rho_{f,1}(k))$$

The controller tries to keep this density near a set-point value, which is often selected around the critical density $\rho_{\mathrm{crit},f}$, to allow as much flow as possible without creating a traffic jam. K_r is a positive constant, and $\rho_{f,1}$ is the density on the freeway downstream of the on-ramp.

For off-ramp metering we have also measured the density downstream of the on-ramp, because this is the location where the problems start. A disadvantage of this is the long delay between the control action

at the off-ramp and the measurable effects of this action downstream of the on-ramp. This can lead to oscillations in the control signal. These oscillations can be decreased by selecting a smaller K_r, but this makes the controller less effective. A second problem with the distance between the measurement and the ramp metering installation is that the measured density can be influenced by traffic that does not pass the ramp metering installation. When this effect is large, the influence of the ramp metering installation decreases.

3.3 Model Predictive Control (MPC)

Ramp metering installations can also be controlled using MPC (Maciejowski, 2002), which works as follows (Bellemans, 2003). At a given time $t = k_c T_c = k_f T_f$ the MPC controller uses a prediction model and numerical optimization (e.g. SQP (Boggs and Tolle, 1995)) to determine the optimal ramp metering rate sequence $r^*(k_c), \ldots, r^*(k_c + N_p - 1)$ that minimizes a given performance indicator $J(k_c)$ over the time period $[k_c T_c, (k_c + N_p)T_c)$ based on the current state of the traffic network and on the expected demands over this period, where N_p is called the prediction horizon, and T_c the controller time step. The prediction horizon should be long enough to show all the effects of a control action. This can be reached by choosing it larger than or equal to the time that is needed by a vehicle to drive through the longest route of the network. Furthermore, a receding horizon approach is used in which at each control step only the first ramp metering input sample $r^*(k_c)$ is applied to the system during the period $[k_c T_c, (k_c + 1)T_c)$. For the next control time step the optimization procedure is started again.

4. CASE STUDY

Let us now compare on-ramp and off-ramp metering using a case study. The network used for the case study consists of two roads: a long two lane freeway, and a short-cut through an urban area, see Figure 1(a). The demand starts at 4000 veh/h, increases to 8000 veh/h, and then decreases again to 4000 veh/h. The set-up of the case study is simple, but contains all required features.

The parameters in the Metanet model are selected as in (Kotsialos *et al.*, 1999), and those of the route choice model as in (van den Berg *et al.*, 2005). We compare the simulations based on the total time spent (TTS) and on the mean urban density (MUD). The TTS is the total time all vehicles spent in the network. The MUD is an indicator for the undesired effects of a queue forming in the urban area, e.g. pollution and noise.

4.1 No control

The first simulation is done without any control. The results can be seen in Figures 1(b) and 1(c). Figure

1(b) shows the density which is experienced when the route via the urban network is selected, and Figure 1(c) shows the density on the freeway route. The y-axis represents the segments, with the origin at 0. The off-ramp is located after segment 4, the on-ramp after freeway segment 13 and urban segment 10. The time is given at the x-axis, and the color represents the density. The congestion starts to appear at the location downstream of the on-ramp, and spills back in the urban as well as in the freeway network. The TTS in the network is 11205 veh h, and the MUD is 33.6 veh/km/lane.

4.2 Fixed time control

The second simulation contains fixed time on-ramp metering. The optimal metering rate is 0.78, which only limits the flow during the peak in the demand. The results are shown in Figures 2(a) and 2(d). The on-ramp metering prevents the congestion on the freeway, but results in a queue on the urban network. The TTS is 10987 veh h, and the MUD is 41.1 veh/km/lane.

The results of the simulation with fixed time off-ramp metering are shown in Figures 3(a) and 3(d). The optimal metering rate is 0.45. The congestion is prevented for some time, but appears at the end of the simulation. The TTS is 11065 veh h, and the MUD is 13.8 veh/km/lane. This low value is mainly due to the fact that nearly all traffic is kept on the freeway during the beginning of the simulation, which compensates for the congestion at the end.

4.3 ALINEA

Figures 2(b) and 2(e) show on-ramp metering with ALINEA. For the gain K_r 0.015 is selected, after testing different gains between 0.01 and 0.1. The TTS is 10966 veh h, and the MUD 35.7 veh/km/lane. The ALINEA controller performs better than the fixed time controller when looking at the MUD. The TTS is nearly the same as with fixed time control. This is due to the fact that the fixed time controller is tuned for the given demand, and leaves not much room for improvement. The fixed time controller will perform worse when another demand is used, while the ALINEA controller will react on the changed demand. The ALINEA controller performs better when looking at the MUD.

ALINEA for off-ramp metering does not lead to congestion on the urban network, see Figures 3(b) and 3(e). The oscillations due to the delay between action and measuring the effect can be seen clearly. The TTS is 10982 veh h, which is again nearly the same as previous simulations. The MUD however is lower: 11.0 veh/km/lane.

4.4 MPC

Since we compare the systems based on the TTS and the MUD, the performance indicator for MPC is selected as a combination of those:

$$J(k_c) = \alpha_1 \text{TTS} + \alpha_2 \text{MUD}$$

where α_1 and α_2 are weighting factors, with $\alpha_1 = 0.01$ and $\alpha_2 = 1$.

The results of MPC on-ramp metering are shown in Figures 2(c) and 2(f). The TTS is 10955 veh h, and the MUD 35.7 veh/km/lane. A small improvement in the TTS is obtained with respect to the ALINEA controller, without increasing the MUD.

At last, Figures 3(c) and 3(f) shows the results with MPC based off-ramp metering. The TTS is 10956 veh h, and the MUD 9.8 veh/km/lane. The TTS for off-ramp metering is nearly the same as for on-ramp metering. The off-ramp metering performs better with respect to the MUD. The MUD for off-ramp metering is a factor three lower than the MUD for on-ramp metering.

5. CONCLUSION

Congestion on freeways has an effect on the route choice of drivers. They tend to leave the freeway, use an urban road, and enter the freeway again (rat-running), which leads to an increase of the number of vehicles on the urban road, which has a negative impact on the safety, noise and pollution. To improve the environmental conditions in the urban area it is useful to prevent rat-running. This can be done via speed limitations, restrictions on road use, and placing static route guidance signs. Dynamic control methods are also possible, for example ramp metering.

Lately, the attention payed to environmental issues is increasing. The queues in the urban area, induced by on-ramp metering, became a problem, as well as the resulting noise and pollution. To relocate this queue to the freeway network the idea of off-ramp metering was introduced. In this paper we have used a case study to compare on-ramp and off-ramp metering, using three different control algorithms, e.g. fixed time control, ALINEA, and an MPC-based method. We have compared the different approaches based on the total time spent and the mean density in the urban network. An overview of the results is given in Table 1. When each of the control methods is used the TTS (for on-ramp as well as off-ramp metering) decreases compared to the no control situation. The differences between the control approaches are small. The main difference between on-ramp and off-ramp control is the MUD. For off-ramp control the MUD is a factor three lower than for on-ramp control.

MPC is the best algorithm of the three, for on-ramp as well as off-ramp metering. It results in the lowest total
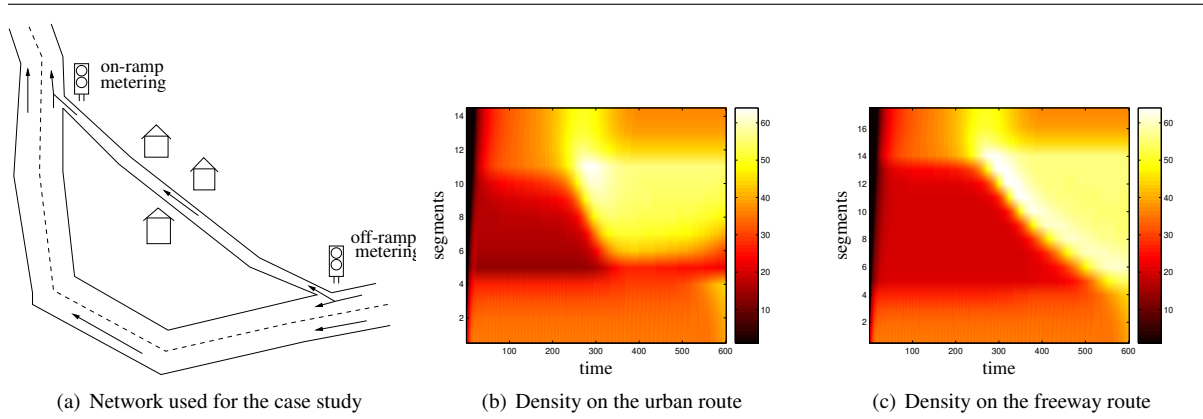
(a) Network used for the case study

(b) Density on the urban route

(c) Density on the freeway route

Figure 1. Network for the case study, and simulation results when no control is applied

(a) Density on the urban route with fixed time control

(b) Density on the urban route with ALINEA

(c) Density on the urban route with MPC

(d) Density on the freeway route with fixed time control

(e) Density on the freeway route with ALINEA

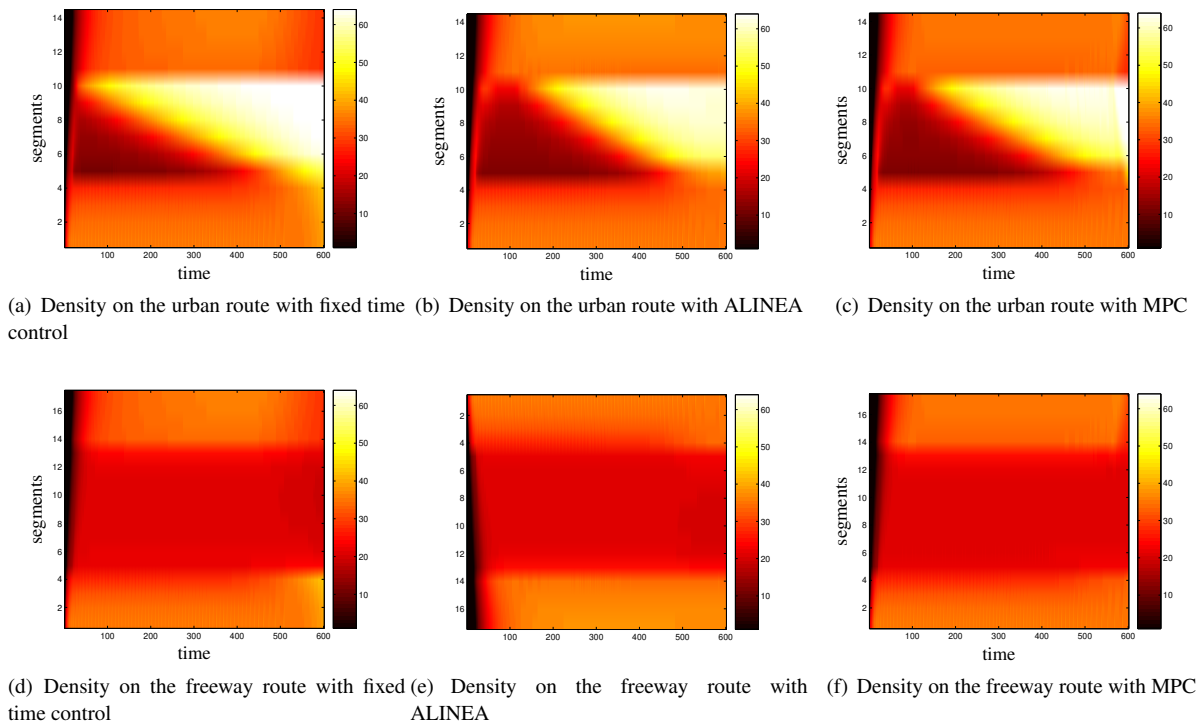(f) Density on the freeway route with MPC

Figure 2. Simulation results for on-ramp metering

Table 1. TTS (in veh h) and MUD (in veh/km/lane) for on-ramp and off-ramp metering, using various control methods.

	On-ramp		Off-ramp	
	TTS	MUD	TTS	MUD
no control	11205	33.0	11205	33.0
fixed time	10987	41.1	11065	13.8
ALINEA	10966	35.7	10982	11.0
MPC	10955	35.7	10956	9.8

time spent, without resulting in high urban densities. A disadvantage of the method is the required computational effort, but it still runs faster than real time.

Further research includes extending the urban network to investigate the effect of disturbances caused by local traffic on the performance, and improving the control algorithms for off-ramp metering. Also some attention should be paid to the safety on the freeways related to the decrease in speed due to the off-ramp metering.

(a) Density on the urban route with fixed time control (b) Density on the urban route with ALINEA (c) Density on the urban route with MPC

(d) Density on the freeway route with fixed time control (e) Density on the freeway route with ALINEA (f) Density on the freeway route with MPC
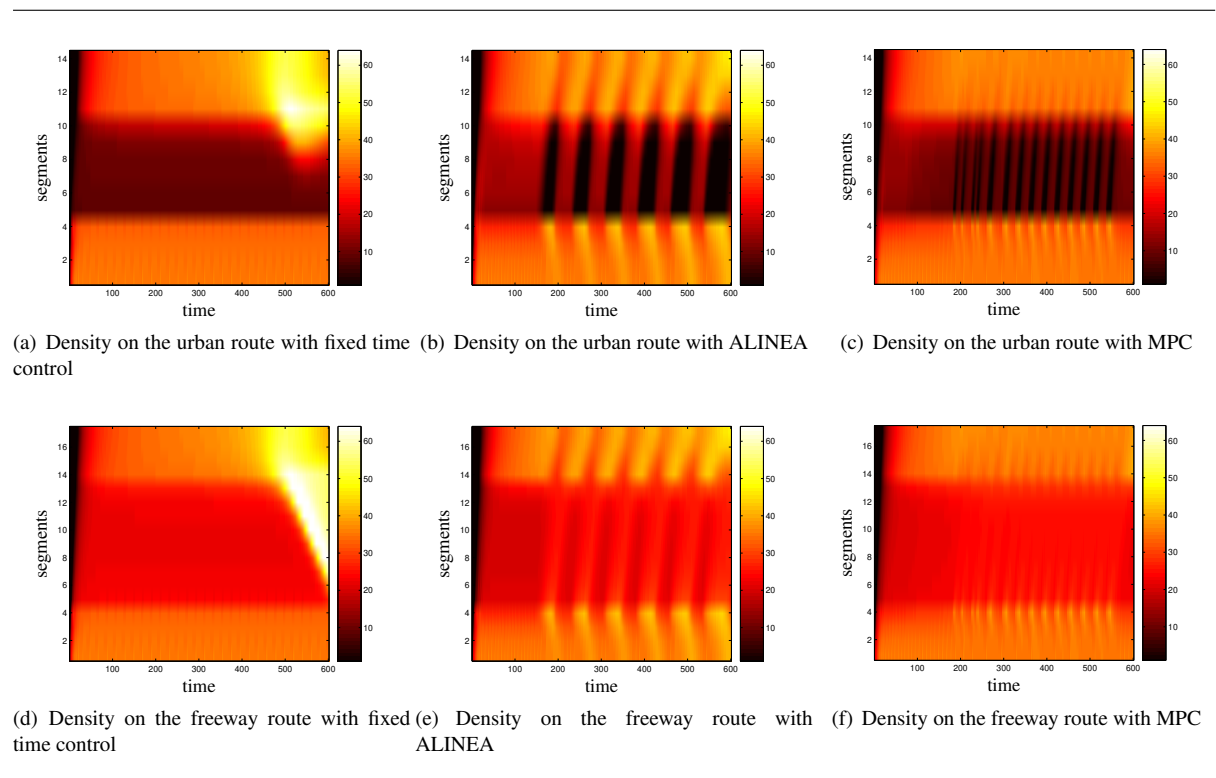
Figure 3. Simulation results for off-ramp metering

REFERENCES

Bellemans, T. (2003). Traffic Control on Motorways. PhD thesis. Faculty of Applied Sciences, K.U.Leuven. Leuven, Belgium.

Boggs, P.T. and J.W. Tolle (1995). Sequential quadratic programming. *Acta Numerica* **4**, 1–51.

Cassidy, M.J. and J. Rudjanakanoknad (2005). Increasing the capacity of an isolated merge by metering its on-ramp. *Transportation Research Part B: Methodological* **39**, 896–913.

Chen, L.L., A.D. May and D.M. Auslander (1990). Freeway ramp control using fuzzy set theory for inexact reasoning. *Transportation Research Part A* **24**, 15–25.

Haj-Salem, H. and M. Papageorgiou (1995). Ramp metering impact on urban corridor traffic: Field results. *Transportation Research A* **29**(4), 303–319.

Karimi, A., A. Hegyi, B. De Schutter H. Hellendoorn and F. Middelham (2004). Integration of dynamic route guidance and freeway ramp metering using model predictive control. In: *Proceedings of the 2004 American Control Conference (ACC 2004)*. Boston, MA, USA. pp. 5533–5538.

Kotsialos, A., M. Papageorgiou and A. Messmer (1999). Optimal coordinated and integrated motorway network traffic control. In: *Proceedings of the 14th International Symposium of Transportation and Traffic Theory (ISTTT)*. Jerusalem, Israel. pp. 621–644.

Maciejowski, J.M. (2002). *Predictive Control with Constraints*. Prentice Hall. Harlow, England.

Messmer, A. and M. Papageorgiou (1990). METANET: A macroscopic simulation program for motorway networks. *Traffic Engineering and Control* **31**, 466–470.

Papageorgiou, M. and A. Kotsialos (2002). Freeway ramp metering: An overview. *IEEE Transactions on Intelligent Transportation Systems* **3**(4), 271–280.

Papageorgiou, M., H. Hadj-Salem and J.M. Blosseville (1991). ALINEA: A local feedback control law for on-ramp metering. *Transportation Research Record* (1320), 58–64.

Taale, H. and F. Middelham (2000). Ten years of ramp-metering in The Netherlands. In: *Proceedings of the 10th International Conference on Road Transport Information and Control*. IEE Conference Publication No. 472. London, UK. pp. 106–110.

van den Berg, M., B. De Schutter and J. Hellendoorn (2005). Information providing as a control measure in an integrated traffic control approach. In: *Proceedings of the 8th International IEEE Conference on Intelligent Transportation Systems (ITSC '05)*. Vienna, Austria. pp. 91–96.

Yang, H. and S. Yagar (1994). Traffic assignment and traffic control in general freeway-arterial corridor systems. *Transportation Research Part B* **28**(6), 463–486.

Zhang, H.M., S.G. Ritchie and R. Jayakrishnan (2001). Coordinated traffic-responsive ramp control via nonlinear state feedback. *Transportation Research Part C* **9**(5), 337–352.