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Integrated model predictive control for mixed urban and freeway networks*

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Integrated Model Predictive Control for Mixed Urban and Freeway Networks

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Abstract

We develop a control method for networks containing both urban roads and freeways. Existing control systems often target only one of the two road types. In urban areas intersections are optimized locally, and on the freeways only the freeway traffic is taken into account. But the two are closely connected: congestion on the freeway often causes spill back of urban queues, slowing down the urban traffic, and vice versa. As a consequence, control measures taken in one of the two areas can have significant influence on the other area.

The method that we develop integrates the control for urban roads and freeways, to prevent the negative influences as much as possible, and to be able to exploit the positive influences. The method is based on model predictive control, and requires a model of the traffic. So we first present a model that is able to describe the urban traffic, the freeway traffic, and the interface in between. Next we develop the control structure that is used for the integrated control. The differences between integrated control and local optimized control are shown with a synthetic case study.

Keywords

Urban traffic control, freeway traffic control, model predictive control, integrated control, coordinated control

1 Introduction

The frequency of traffic jams in and around cities keeps increasing. The traffic jams do not only delay the urban traffic, but have a severe influence on the long distance traffic too. The amount of congestion on a freeway can be influenced by traffic control measures, but measures that allow a better flow, higher speeds or higher throughput on the freeways can lead to queues at the on-ramps which may spill back and block the urban roads. On the other hand, many cities try to get the vehicles out of the urban road network as soon as possible, thereby displacing the congestion to the neighboring ring roads and freeways, and thus causing delays for the long distance traffic.

In this paper we consider traffic control for networks containing both urban roads and freeways. By considering an integrated and coordinated approach, the performance of the overall network can be significantly improved (taking into account the trade-off between the often conflicting objectives and interests of different traffic management bodies). In this paper we present an integrated traffic control approach for coordinated control of mixed urban and freeway networks that prevents a shift of problems from urban roads to freeways and vice versa.

For urban traffic networks, systems such as UTOPIA/SPOT described in Peek Traffic Scandinavia (2002) and SCOOT described by Robertson & Bretherton (1991) use an integrated approach that optimizes the operation of several traffic signal set-ups in a city to obtain a smoother flow and/or a better circulation. For freeway traffic networks several authors e.g. Haj-Salem & Papageorgiou (1995); Kotsialos et al. (2002); Papageorgiou et al. (1990a,b) have considered a coordinated approach in which many different control measures (such as ramp metering, route guidance, variable speed limits, etc.) are coordinated on a larger scale, which results in a better overall performance. However, up to now little attention has been paid to integrated control of networks consisting of both urban and freeway roads, For some work in this area see Chen et al. (2000). In this paper we develop a method for the integrated control of networks containing both urban roads and freeways, and compare this method to a general local control method.

We propose to use a model predictive control (MPC) approach as presented in Camacho & Bordons (1995); Maciejowski (2002), which has already been successfully applied to coordinated control of freeway networks by Breton et al. (2002); Hegyi et al. (2002); Bellemans (2003). MPC requires a model to predict the future evolution of the traffic flow. Then, a first requirement is a model that describes the evolution of the traffic in a mixed urban/freeway traffic network. We use a macroscopic traffic model based on the extended version of the METANET model for the freeways described by Messmer & Papageorgiou (1990); Papageorgiou & Messmer (2000), and on a modified and extended version of the Kashani model given in Kashani & Saridis (1983) for the urban roads. The total model, also including the interface between the two models, is given in Section 2.

In Section 3 the use of this model in the controller is explained, and the structure of the controller is given.

To illustrate the effects of the MPC approach we perform a synthetic case study in Section 4. A small network is simulated with five different traffic scenarios. The MPC controller for the total network is compared with a structure where each urban intersection is optimized, which is often the case in currently implemented traffic control strategies. The importance of coordinating control measures of freeways and urban roads is demonstrated.

2 Macroscopic model for mixed urban/freeway networks

To model the evolution of the traffic flows on the mixed urban/freeway network we have selected the METANET macroscopic traffic flow model developed by Messmer & Papageorgiou (1990); Papageorgiou & Messmer (2000), together with an extended version of the Kashani model described in Kashani & Saridis (1983). This model provides a balanced trade-off between accuracy (Papageorgiou et al. (1990b)) and computational complexity. Note that as the MPC strategy discussed in Section 3 involves on-line simulation and optimization, we require a model that can be simulated sufficiently fast. The proposed model satisfies this requirement. The variables used to describe the model are given in Appendix A.

Remark 1:

As we will explicitly make a difference between the simulation time step T_f for the freeway part of the network, the simulation time step T_u for the urban part of the network, and the controller sample time T_c , we will also use three different counters for the freeway network model (k_f), the urban model (k_u), and the controller (k_c). For the sake of simplicity, we assume that T_u is an integer divisor of T_f , and that T_f is an integer divisor of T_c :

$$T_f = T T_u, \quad T_c = L T_f = L T T_u ,$$

with T and L integers. ◇

2.1 Freeway part of the model

In the METANET model the freeway network is divided in links, which are stretches that have the same characteristics. Each freeway link is further divided in segments, see Figure 1.

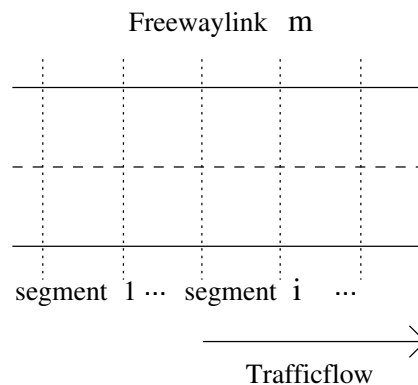


Figure 1: A freeway link divided in segments

The traffic state in segment i of link m at time $t = k_f T_f$ is described with the macroscopic variables density $\rho_{m,i}(k_f)$, speed $v_{m,i}(k_f)$, and flow $q_{dep,m,i}(k_f)$. These

variables evolve as follows:

$$\rho_{m,i}(k_f + 1) = \rho_{m,i}(k_f) + \frac{T_f}{L_m n_m} [q_{m,i-1}(k_f) - q_{m,i}(k_f)] \quad (1)$$

$$q_{m,i}(k_f) = \rho_{m,i}(k_f) v_{m,i}(k_f) n_m \quad (2)$$

$$v_{m,i}(k_f + 1) = v_{m,i}(k_f) + \frac{T_f}{\tau} (V(\rho_{m,i}(k_f)) - v_{m,i}(k_f)) + \frac{T_f}{L_m} v_{m,i}(k_f) [v_{m,i-1}(k_f) - v_{m,i}(k_f)] - \frac{\nu T_f [\rho_{m,i+1}(k_f) - \rho_{m,i}(k_f)]}{\tau L_m [\rho_{m,i}(k_f) + \kappa]} \quad (3)$$

where T_f , L_m , $V(\rho_{m,i}(k_f))$ and n_m are respectively the time step for freeway simulation, the length of the segments of freeway link m , the desired speed of the drivers on segment i of freeway link m , and the number of lanes of freeway link m , while τ , ν and κ are parameters. The desired speed $V(\rho_{f,m}(k))$ is given by:

$$V(\rho_{m,i}(k_f)) = v_{\text{free},m} \exp \left[-\frac{1}{a_m} \left(\frac{\rho_{m,i}(k_f)}{\rho_{\text{crit},m}} \right)^{a_m} \right]$$

where $v_{\text{free},m}$ is the free flow speed, $\rho_{\text{crit},m}$ the critical density, and a_m a parameter.

Origins are described with a flow that enters and a queue waiting to enter:

$$q_{\text{dep},m,\text{origin}}(k_f) = \min \left[d_{\text{origin},m}(k_f) + \frac{w_m(k_f)}{T_f}, Q_m \frac{\rho_{\text{max}} - \rho_{m,1}(k_f)}{\rho_{\text{max}} - \rho_{\text{crit},m}} \right]$$

$$w_m(k_f + 1) = w_m(k_f) + T_f (d_{\text{origin},m}(k_f) - q_{\text{dep},m,\text{origin}}(k_f)) .$$

Here $q_{\text{dep},m,\text{origin}}(k_f)$ is the flow departing from the origin (veh/h), $d_{\text{origin},m}(k_f)$ the number of vehicles arriving at the end of the queue at the origin, $w_m(k_f)$ the queue at the origin, Q_m the capacity of the freeway, and ρ_{max} the maximal density.

2.2 Urban part of the model

Our model to describe the traffic in the urban parts of the network is based on the Kashani model given in Kashani & Saridis (1983), but it is extended with horizontal queues, turning-direction-dependent queues and a shorter cycle-time, as further explained in van den Berg et al. (2004). Two intersections connected by an urban link are shown in Figure 2.

The new model is formulated as follows. The traffic leaving the link $l_{o_i,s}$ towards destination d_j is given by

$$m_{\text{dep},o_i,s,d_j}(k_u) = \begin{cases} 0 & \text{if } g_{o_i,s,d_j}(k_u) = 0, \\ \min(x_{o_i,s,d_j}(k_u) + m_{\text{arr},o_i,s,d_j}(k_u), S_{s,d_j}(k_u), T_u Q_{o_i,s,d_j}) & \text{if } g_{o_i,s,d_j}(k_u) = 1 \end{cases} \quad (4)$$

where $x_{o_i,s,d_j}(k_u)$ is the queue length, $m_{\text{arr},o_i,s,d_j}(k_u)$ the arriving traffic, $S_{s,d_j}(k_u)$ the free space on the link l_{s,d_j} , and Q_{o_i,s,d_j} the capacity of intersection s for traffic coming from origin o_i going to destination d_j . During the optimization the green time is given as a percentage of the cycle time. In the simulation program this percentage is translated in the signal $g_{o_i,s,d_j}(k_u)$.

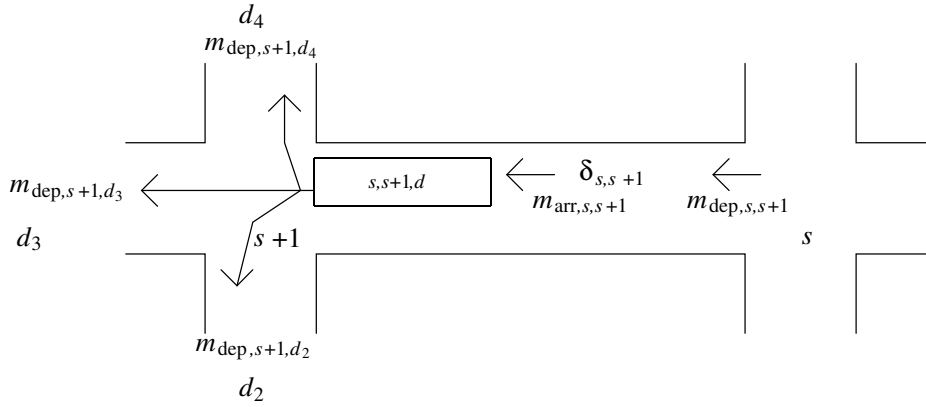


Figure 2: Two urban intersections connected by a link

The free space S_{s,d_j} in link l_{s,d_j} is equal to the number of vehicles that can enter the link. The free space is an implicit constraint on the number of vehicles that can depart towards each link, m_{dep,o_i,s,d_j} , and it can never be larger than the link length. It is computed as

$$S_{s,d_j}(k_u + 1) = S_{s,d_j}(k_u) - m_{\text{dep},s,d_j}(k_u) + \sum_{o_i \in O_s} m_{\text{dep},o_i,s,d_j}(k_u) . \quad (5)$$

The total flow towards one destination consists of several flows from different origins. These different flows do not have to have the same value. To illustrate how the effective values of $m_{\text{dep},o_i,s,d_j}(k_u)$ can be computed let us assume that there are two origins, and so two queues from which vehicles want to drive into the same link. Let $m_{\text{dep,int},1}(k_u)$ and $m_{\text{dep,int},2}(k_u)$ denote the number of vehicles wishing to enter the link l_{s,d_j} from respectively origin 1 and origin 2. If we assume without loss of generality that $m_{\text{dep,int},1}(k_u) \leq m_{\text{dep,int},2}(k_u)$, then the effective values for $m_{\text{dep},1}(k_u)$ and $m_{\text{dep},2}(k_u)$ can be computed as follows:

- if $m_{\text{dep,int},1}(k_u) + m_{\text{dep,int},2}(k_u) \leq S_{s,d_j}(k_u)$, then

$$m_{\text{dep},1}(k_u) = m_{\text{dep,int},1}(k_u) \quad \text{and} \quad m_{\text{dep},2}(k_u) = m_{\text{dep,int},2}(k_u) .$$

- if $m_{\text{dep,int},1}(k_u) + m_{\text{dep,int},2}(k_u) \geq S_{s,d_j}(k_u)$, then

$$\begin{cases} m_{\text{dep},1}(k_u) = m_{\text{dep,int},1}(k_u) \quad \text{and} \quad m_{\text{dep},2}(k_u) = S_{s,d_j}(k_u) - m_{\text{dep,int},1}(k_u) & \text{if } m_{\text{dep,int},1}(k_u) \leq \frac{1}{2}S_{s,d_j}(k_u), \\ m_{\text{dep},1}(k_u) = m_{\text{dep},2}(k_u) = \frac{1}{2}S_{s,d_j}(k_u) & \text{if } m_{\text{dep,int},1}(k_u) \geq \frac{1}{2}S_{s,d_j}(k_u). \end{cases}$$

The extension to a link with more queues with vehicles waiting to enter it is straightforward.

The traffic arriving at link l_{s,d_j} can be computed as

$$m_{\text{dep},s,d_j}(k_u) = \sum_{o_i \in O_s} m_{\text{dep},o_i,s,d_j}(k_u)$$

with m_{dep,o_i,s,d_j} the arriving traffic from origin o_i going toward the destination d_j via intersection s , $m_{\text{dep},s,d_j}(k_u)$ all the arriving traffic at link l_{s,d_j} , and O_s the set of origins connected to intersection s .

These vehicles drive from the beginning of the link l_{s,d_j} towards the tail of the queue waiting on the link. This gives a time delay $\delta_{s,d_j}(k_u)$:

$$\delta_{s,d_j}(k_u) = \text{ceil} \left(\frac{S_{s,d_j}(k_u) L_{\text{vehicle}}}{v_{s,d_j}} \right) \quad (6)$$

where L_{vehicle} is the length of a vehicle, and v_{s,d_j} the speed on link l_{s,d_j} .

The amount of traffic arriving at the tail of the queue is added to the traffic that arrived in the link in earlier time steps but required more time to reach the tail of the queue. This results in:

$$m_{\text{arr},s,d_j}(k_u + \delta_{s,d_j}(k_u))_{\text{new}} = m_{\text{arr},s,d_j}(k_u + \delta_{s,d_j}(k_u))_{\text{old}} + m_{\text{dep},s,d_j}(k_u)$$

where $m_{\text{arr},s,d_j}(k_u + \delta_{s,d_j}(k_u))$ is the traffic arriving at the end of the queue, and $m_{\text{dep},s,d_j}(k_u)$ the traffic entering link l_{s,d_j} .

The traffic reaching the tail of the queue in link l_{s,d_j} divides itself over the sub-queues according to the turning rates $\beta_{o_i,s,d_j}(k_u)$:

$$m_{\text{arr},o_i,s,d_j}(k_u) = \beta_{o_i,s,d_j}(k_u) m_{\text{arr},o_i,s}(k_u) .$$

Finally, the sub-queue lengths are updated as follows:

$$x_{o_i,s,d_j}(k_u + 1) = x_{o_i,s,d_j}(k_u) + m_{\text{arr},o_i,s,d_j}(k_u) - m_{\text{dep},o_i,s,d_j}(k_u) .$$

2.3 Model for the interface between the urban and freeway models

Now we connect the freeway model and the urban model as described above by presenting a model of the interface that is between them. This interface consists of two parts: on-ramps and off-ramps. In this section we first present the model for the evolution of the traffic flows on on-ramps, and next for the evolution of the flows on off-ramps.

2.3.1 Model of an on-ramp

Consider an on-ramp o that connects intersection s of the urban network to node n of the freeway network, see Figure 3. The traffic that enters the on-ramp from the urban network is given by $m_{\text{dep},s,o}(k_u)$. This traffic has a delay given by $\delta_{s,o}(k_u)$, and is determined similarly as in (6).

The vehicles arrive at the tail of the on-ramp queue. The queue length $w_{s,o,n}(k_u)$ is computed as

$$w_{s,o,n}(k_u + 1) = w_{s,o,n}(k_u) + m_{\text{arr},s,o,n}(k_u) - m_{\text{dep},s,o,n}(k_u)$$

where $m_{\text{arr},s,o,n}(k_u)$ is the arriving traffic, and $m_{\text{dep},s,o,n}(k_u)$ the departing traffic.

The number of departures at the front of the on-ramp queue depends on the available space on the freeway, which depends on the density on the first segment of freeway m downstream of node n . This results in a maximum flow that can leave the on-ramp:

$$q_{\text{dep},\text{max},o,n}(k_f) = \begin{cases} Q_m \left(1 - \frac{\rho_{m,1}(k_f) - \rho_{\text{crit},m}}{\rho_{\text{max}} - \rho_{\text{crit},m}} \right) & \text{if } \rho_{m,1}(k_f) > \rho_{\text{crit},m} , \\ Q_m & \text{otherwise.} \end{cases}$$

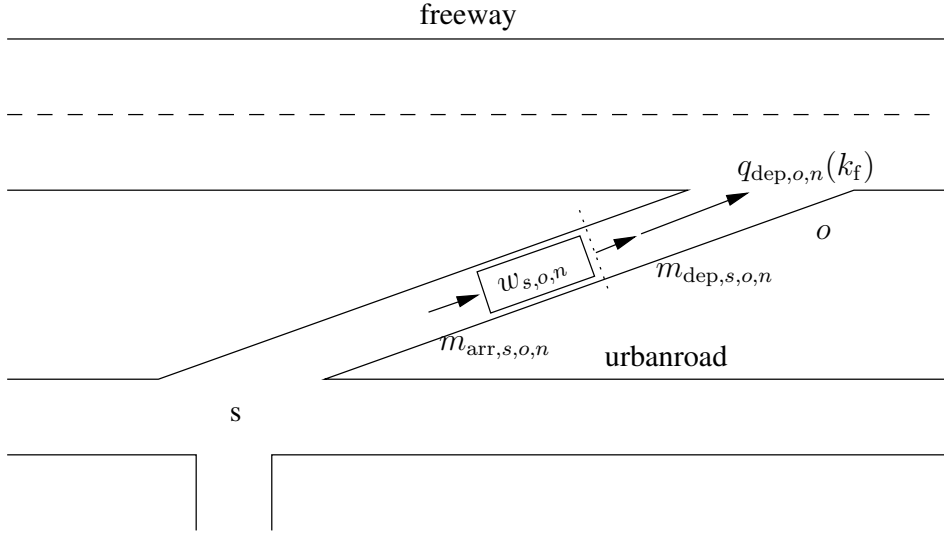


Figure 3: Layout of an on-ramp

The flow $q_{\text{dep},o,n}(k_f)$ that enters the freeway is then given by

$$q_{\text{dep},o,n}(k_f) = \min \left(\frac{1}{T_f} \left[w_{s,o,n}(k_f T) + \sum_{k_u=k_f T}^{(k_f+1)T-1} m_{\text{arr},s,o,n}(k_u) \right], q_{\text{dep,max},o,n}(k_f) \right) .$$

This flow should be translated into the number of vehicles that leaves the on-ramp. This is done by distributing the flow equally over the urban time step:

$$m_{\text{dep},s,o,n}(k_u) = \frac{q_{\text{dep},o,n}(k_f) T_f}{T} \quad \text{for } k_u = T k_f, \dots, T(k_f + 1) - 1 .$$

The free space $S_{s,o}(k_u)$ is also computed using (5).

2.3.2 Model of an off-ramp

Now consider the off-ramp o that connects freeway node n to urban intersection s , see Figure 4. We assume that T_f is short enough so that no vehicle can enter and leave the link in one time freeway step, so the departing traffic does not depend on the arriving traffic. Therefore, the departing traffic from intersection s can be computed first, and afterwards the traffic entering the link $l_{o,s}$ can be computed.

The flow leaving the freeway cannot be larger than allowed by the free space on the off-ramp. This free space depends on the length of the off-ramp, on the queue currently waiting on it, and on the traffic that is going to leave the link $l_{o,s}$ during the period $k_f T_f, (k_f + 1) T_f$. The flow that wants to enter the off-ramp is a fraction of the flow on the freeway:

$$q_{\text{dep,demand},n,s}(k_f) = \beta_{n,s}(k_f) q_{\text{dep},m,N_m}(k_f) ,$$

where $\beta_{n,s}(k_f)$ denotes the turning fraction, and $q_{\text{dep},m,N_m}(k_f)$ the flow arriving at the freeway node n from the last segment N_m of freeway link m . This flow is not always able to enter the off-ramp, due to the maximum capacity of the off-ramp, $Q_{n,o,s}$, and the free space on the off-ramp, $S_{o,s}$. This free space in fact varies over the time interval

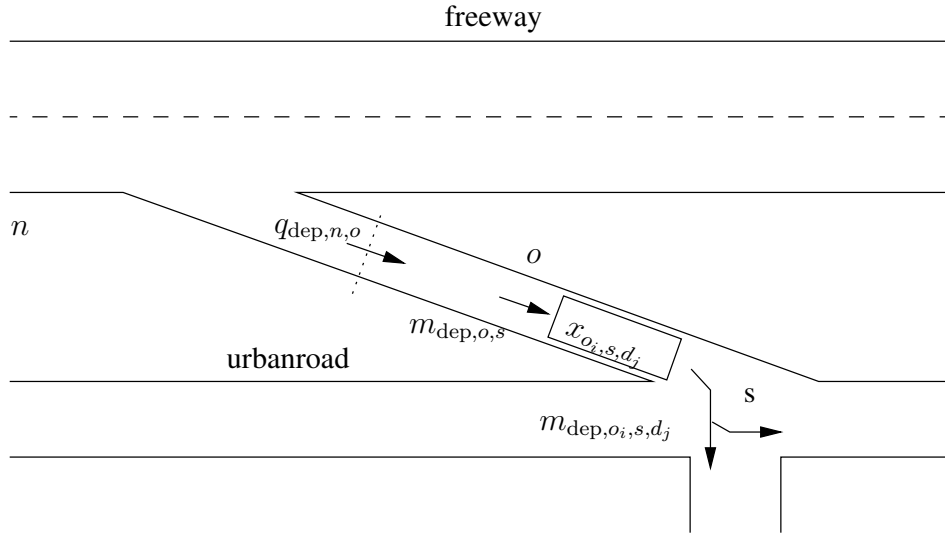


Figure 4: Layout of an off-ramp

$[k_f T_f, (k_f + 1)T_f)$, as vehicles are leaving at the front of the queue during the time interval, and so the free space grows. This results in the following expression for the actual flow that arrives at the off-ramp from the freeway:

$$q_{\text{dep},n,o}(k_f) = \min \left(q_{\text{dep,demand},n,s}(k_f), Q_{n,o,s}, \frac{1}{T_f} \left[S_{o,s}(k_u) + \sum_{\ell=k_u}^{k_u+T-1} \sum_{d_j \in D_s} m_{\text{dep},o,s,d_j}(\ell) \right] \right).$$

The flow entering the off-ramp is translated into the number of vehicles per urban time step:

$$m_{\text{dep},o,s}(k_u) = \frac{q_{\text{dep},n,o}(k_u)T_f}{T} \quad \text{for } k_u = k_f T + 1, \dots, (k_f + 1)T.$$

This traffic undergoes a delay $\delta_{o,s}(k_u)$ and then arrives at the tail of the queue in the urban network.

A constraint for the leaving flow in METANET can be implemented by adjusting the flow of the incoming traffic. The flow is computed using Equation (2). A way to influence the flow is changing the speed that is used to compute this flow. This speed can be adapted as follows:

$$v_{m,N_m}(k_f)_{\text{new}} = \begin{cases} v_{m,N_m}(k_f)_{\text{old}} & \text{if } q_{\text{dep,demand},n,s}(k_f) \leq q_{\text{dep},n,o}(k_f), \\ v_{m,N_m}(k_f)_{\text{old}} \frac{q_{\text{dep},n,o}(k_f)}{q_{\text{dep,demand},n,s}(k_f)} & \text{otherwise,} \end{cases}$$

where $v_{m,N_m}(k_f)_{\text{old}}$ is the value originally computed using (3). The density of the off-ramp is computed with:

$$\rho_{\text{off},o}(k_f) = \frac{L_{o,s} - S_{o,s}((k_f + 1)T - 1)}{L_{\text{km},o,s}} \quad (7)$$

where $L_{o,s}$ is the length of the off-ramp in vehicles, $S_{o,s}((k_f + 1)T - 1)$ the free space on the off-ramp, and $L_{\text{km},o,s}$ the length of the off-ramp in km.

3 Model Predictive Control

We will apply a model predictive control (MPC) strategy for traffic control of mixed urban and freeway networks. MPC described in Camacho & Bordons (1995); Maciejowski (2002) is an on-line optimization-based controller design procedure. In Breton et al. (2002); Hegyi et al. (2002); Bellemans (2003), MPC has already been extended to coordinated control of traffic on freeway networks. Below we will describe how MPC can be used for the local control of urban intersections and for the integrated control of mixed urban/freeway traffic networks.

The goal of MPC is to find the control signal that minimizes a cost function over a given prediction period. The cost function should give an indication for the performance of the system. To compute the control signal that minimizes this cost function, a model is used to predict of the behavior of the traffic. We use the integrated urban/freeway traffic model described in Section 2 as prediction model. Note, however, that the MPC approach is generic so that we could also work with other traffic flow models.

The MPC approach proceeds as follows. Assume we are at time $t = k_c T_c$ where T_c is the controller time step (typically 1 to 5 min). Now a model of the system is used to predict the behavior of the system for the period $[k_c T_c, (k_c + N_p) T_c]$ defined by the prediction horizon N_p . The optimal control signal is computed that minimizes the cost criterion over the period $[k_c T_c, (k_c + N_p) T_c]$ using e.g. numerical optimization. When the optimal control signal is determined, the first step of it is applied to the system. Then a new situation arises, and the whole process is started again, with the horizons shifted one step ahead. This is called the receding horizon principle.

Below two control structures using MPC are explained. One for local urban intersection control, and one for integrated control of mixed urban and freeway networks. The control signal contains the offsets of the phases of each intersection, the durations of the green times and the cycle time. In a separate control module the offsets and durations of the green times will be translated into the binary signals g_{o_i,s,d_j} , which are used in the prediction model. Speed limits and ramp metering signals can also be added to the control signal, when they are formulated as described in Hegyi et al. (2002).

3.1 MPC for local intersection traffic control

In this section we describe a control structure that optimizes each intersection separately.

For the intersections we choose the total time spent (TTS) in the queue as a cost function. Note, however, that the MPC approach works equally well for other objective functions (or (weighted) combinations of objective functions). The cost function is then given by:

$$\text{TTS}_{\text{urban},s}(k_c) = \sum_{k_u=LTk_c}^{LT(k_c+N_p)} \sum_{o_i \in O_s} x_{o_i,s,d_j}(k_u) T_u ,$$

where $\text{TTS}_{\text{urban},s}(k_c)$ is the TTS predicted at $t = k_c T_c$ for the period $[k_c T_c, (k_c + N_p) T_c]$, and $x_{o_i,s,d_j}(k_u)$ the queue at intersection s with traffic arriving from origin o_i going to destination d_j at time $t = k_u T_u$.

To be able to optimize for each intersection separately the arriving traffic on each intersection must be determined. This is done using the past evolution of the traffic and the available measurements.

3.2 MPC for integrated control of mixed urban and freeway networks

This section proposes an integrated control method that optimizes the total network.

We choose the total time spent as a cost function for the freeway part of the network. It is computed using the density of the segments:

$$\text{TTS}_{\text{freeway}}(k_c) = T_f \sum_{k_f=Lk_c}^{L(k_c+N_p)} \sum_{m \in M} \left(L_m n_m \sum_{i \in I_m} \rho_{m,i}(k_f) + \sum_{o \in O_m} n_{\text{vehicles,origin},m,o}(k_f) \right),$$

where M is the set of freeway links in the network, I_m the set of segments of freeway link m , O_m the set of origins of freeway link m , and $n_{\text{vehicles,origin},m,o}(k_f)$ the number of vehicles waiting at the origin of freeway link m .

The urban cost function is the same as described in the previous section, but now optimized for all the intersections together. The total cost function is given by the sum of the urban and freeway cost functions:

$$\text{TTS}(k_c) = \alpha_1 \text{TTS}_{\text{freeway}}(k_c) + \sum_{s \in S} \text{TTS}_{\text{urban},s}(k_c)$$

with S the set of intersections in the network. The positive weighting factor α_1 is added to give more or less importance to one of the two parts.

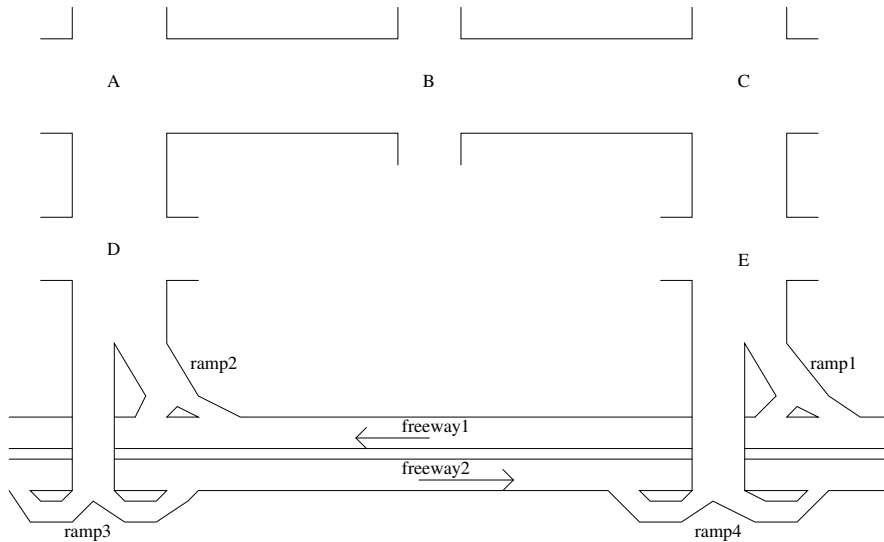


Figure 5: Mixed urban/freeway network used in the case study.

4 Case study

To compare the two control methods we present a case study. A network is simulated with different traffic scenarios. For each scenario both control methods are applied, and the results are compared.

4.1 Set up of the case study

For the case study a simple test network is used (see Figure 5), that contains some essential elements of mixed urban and freeway networks. The test network consists of a two-way freeway with two on-ramps and two off-ramps. Furthermore, there are two urban intersections, which are connected to the freeway and to each other. Between these intersections and the freeways there are some crossing roads, where there is only crossing traffic that does not turn into other directions (e.g., pedestrian traffic, bicycles, etc.). The traffic that arrives at the origins of the network is given as a flow, with a demand $d_{\text{origin},s}(k) = 1000$ veh/h for urban origins and 3600 veh/h for freeway origins. We assume that at the beginning of the simulation the network is completely empty, so all the traffic enters it from the origins.

4.2 Traffic scenarios

The performance of the controllers will be shown for five different traffic scenarios:

Scenario 1: Capacity of the network reached This is the required situation that all the traffic that enters the network can pass through nearly undelayed. The traffic demand is so that nearly all the queues can clear during the green times, and no congestion on the freeway occurs.

Scenario 2: Morning rush hour, traffic into the city During the morning rush hour, many traffic wants to enter the city. This results in long queues on the off-ramps,

which can spill back and cause a congestion at the freeway.

Scenario 3: Evening rush hour, traffic leaving the city The evening rush hour is the opposite of the morning rush hour. Traffic wants to leave the city, causing congestion near the on-ramps. The on-ramps can not handle the large amount of traffic, which can result in congestion on the freeway or in blocking of the urban roads connected to the on-ramp.

Scenario 4: Congestion at urban intersection In this scenario intersection D is blocked. The traffic that has to pass this intersection cannot drive on. This results in long queues, which spill back on nearby intersections that then are blocked also.

Scenario 5: Congestion at freeway The congestion exists downstream of the network. As a result the traffic cannot leave the freeway, which leads to a congestion in the network. When the freeway is congested less traffic can leave the on-ramps, resulting in longer queues in the urban area.

4.3 Results of the case study

The results of the simulations are shown in Table 1. To be able to compare the two control structures the performance of the network is computed according to the cost function used for the integrated approach. This means that the total time spent is given for each simulation.

The improvements reached with the integrated control method can better be seen when we look at the total time spent in the urban part and in the freeway part separately. Table 2 shows the performance index split up in the freeway and urban parts. It can be seen that the integrated control method reaches better performance in the urban area by slightly decreasing the performance on the freeways in scenario 1 and 2. In scenario 3 the problems are due to the current implementation. The intersection control method is able to do 'double cycling' while the implementation of the integrated method prevents this. This implies that the integrated method can perform better (maybe also for the other scenario's) when the implementation will be adapted to include double cycling.

Blocking one intersection in scenario 4 makes less control measures effective, so only minor results can be reached. The MPC method can reach small improvements on

Table 1: Performance of the network for different scenarios

Scenario	intersection control	integrated control	improvement
1. Capacity of the network reached	611.2	595.9	2.6%
2. Morning rush hour, traffic into the city	633.2	601.4	5.1%
3. Evening rush hour, traffic leaving the city	662.4	670.8	-1.3%
4. Congestion at urban intersection	1068.0	1061.2	0.7%
5. Congestion at freeway	920.1	901.1	2.1%

Table 2: Performance of freeway and urban network separately

Scenario	intersection control	integrated control	improvement
1. urban	224	208.3	7.1%
freeway	386.3	387.7	-0.4%
2. urban	294.9	259.9	11.9%
freeway	338.3	341.5	-0.9%
3. urban	276.1	284.4	-3.0%
freeway	386.3	386.5	-0.5%
4. urban	634.3	628.9	0.9%
freeway	433.6	432.1	0.4%
5. urban	234.8	222.3	5.4%
freeway	709.4	697.7	1.7%

the freeway as well as on the urban roads. In scenario 5 the problem is on the freeway. The urban intersection control method cannot do anything here, and will also not detect the problem. The MPC method sees the problem, and is able to solve a part of it by delaying traffic that wants to enter the freeways via the on-ramps.

The effects of integrating the control of the intersections can be seen in Figures 6 and 7. A queue waiting for intersection D is shown for both types of control. Figure 6 shows the queue when local control is applied. The controller on the intersection reacts on the arriving traffic and adapts its control signal. This causes a change in the arriving traffic for the next intersection, where the controller also changes its control signal, etc. This causes a continuously changing traffic situation, with a lot of changes in the control signal, and thus in the queue lengths. Figure 7 the same queue is shown for the situation where integrated control is used. Because the actions of neighboring intersections are taken into account, it is known longer in advance when the traffic will arrive, so a less varying control signal can be selected.

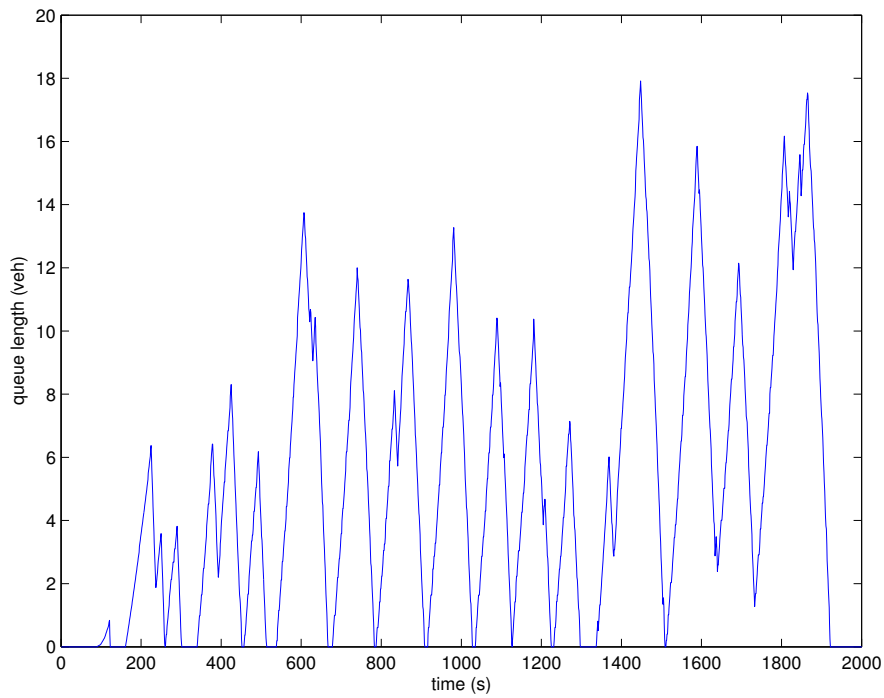


Figure 6: Queue length on intersection D with local control

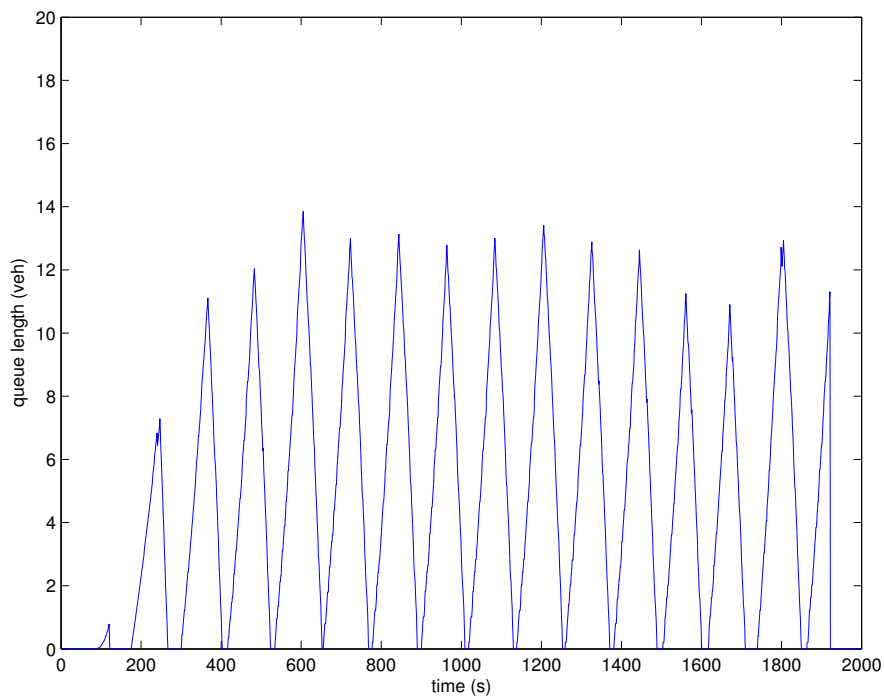


Figure 7: Queue length on intersection D with integrated control

5 Conclusion

Traffic congestion in urban networks and in freeway networks can not be seen as separate problems. Solving a problem in one of the two areas often leads to more congestion in the other. Therefore an integrated approach is required for the traffic control strategy.

We have developed a control structure based on model predictive control. The method predicts the traffic over a certain period, and then uses this prediction to determine the optimal control settings. This is done every time step, so the system is able to cope with changes in the traffic demands.

For the predictions we have developed a model that describes freeway as well as urban traffic. The model is based on METANET and a model developed by Kashani. These two models are combined by modeling the traffic on on-ramps and off-ramps.

A case study is done where an urban optimization control method that optimizes each intersection separately and does not take the freeway into account is compared with the integrated control structure. The integrated control method leads to improvements up to 5%.

Further research will include a case study where control measures on the freeway are added. We will perform a comparison of our method with control structures that are currently used, such as SCOOT and UTOPIA. Validation and calibration of the model and robustness tests of the controller will be done to be able to use the model for a real-life case study. The trade-off between computational complexity and accuracy will also be assessed thoroughly. Some attention will be paid to the scalability of the method for larger networks, and the effect of route choice will be evaluated.

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A Variables used in the model

	Freeway variables
m	index of the freeway link
i	segment index
T_f	time step of the freeway simulation (h; a typical value is about $10 \text{ s} \approx 0.0028 \text{ h}$)
k_f	freeway time step counter
N_m	number of segments in freeway link m
n_m	number of lanes in freeway link m
L_m	length of the segments in link m (km)
τ, κ, a_m, η	constant parameters reflecting street geometry, vehicle characteristics, drivers' behavior, etc.
$\rho_{\text{crit},m}$	critical density (veh/km/lane) in link m
ρ_{max}	maximum density (veh/km/lane)
$v_{\text{free},m}$	speed that the vehicles tend to drive at under free flow conditions (km/h/lane) in link m
Q_m	capacity of the segments of freeway link m (veh/h)
$\rho_{m,i}(k_f)$	density of segment i of freeway link m at time $t = k_f T_f$ (veh/km/lane)
$v_{m,i}(k_f)$	speed in segment i of freeway link m at time $t = k_f T_f$ (km/h)
$w_o(k_f)$	length of the queue waiting on on-ramp o at time $t = k_f T_f$ (veh)
O_n	set of freeway links entering node n
D_n	set of freeway links leaving node n
$q_{\text{arr},n}(k_f)$	total flow arriving at freeway node n during period $[k_f T_f, (k_f + 1) T_f)$ (veh/h)
$\beta_{n,m}(k_f)$	turning rate from freeway node n towards link m during period $[k_f T_f, (k_f + 1) T_f)$
$q_{\text{arr,orig},m}(k_f)$	flow that enters freeway link m on the mainstream origin in the time interval $[k_f T_f, (k_f + 1) T_f)$ (veh/h)
$q_{\text{dep},m,i}(k_f)$	flow leaving segment i of freeway link m in $[k_f T_f, (k_f + 1) T_f)$ (veh/h)
$d_{\text{origin},m}(k_f)$	flow arriving at the origin of freeway link m in $[k_f T_f, (k_f + 1) T_f)$ (veh/h).

	Urban variables
s	index of the intersection
T_u	time step of the urban simulation (h; a typical value is about 1 s)
k_u	urban time step counter
$d_{s,j}$	urban destination number j of intersection s
D_s	set of urban destinations of intersection s
$x_{o_i,s,d_j}(k_u)$	queue length at time $t = k_u T_u$ of the queue at intersection s , for traffic that goes from origin o_i to destination d_j (veh)
$l_{s,\sigma}$	link connecting intersections s and σ
$\beta_{o_i,s,d_j}(k_u)$	relative fraction of the traffic arriving from urban origin o_i on intersection s that wants to go to urban destination d_j in the time interval $[k_u T_u, (k_u + 1) T_u)$
$L_{s,\sigma}$	length of urban link $l_{s,\sigma}$ in number of vehicles
$L_{\text{km},s,\sigma}$	length of urban link $l_{s,\sigma}$ (km)
$S_{s,\sigma}(k_u)$	available free space of urban link $l_{s,\sigma}$ at time $t = k_u T_u$ in number of vehicles (i.e., the buffer capacity $L_{s,\sigma}$ minus the number of vehicles that are already present at time $t = k_u T_u$)

$m_{arr,s,d_j}(k_u)$	number of vehicles arriving at the tail of the queue in link l_{s,d_j} during $[k_u T_u, (k_u + 1)T_u)$
$m_{arr,o_i,s,d_j}(k_u)$	number of vehicles coming from intersection o_i arriving at the tail of the queue in link l_{s,d_j} during $[k_u T_u, (k_u + 1)T_u)$
$m_{dep,o_i,s,d_j}(k_u)$	number of vehicles departing from link $l_{o_i,s}$ towards destination d_j in $[k_u T_u, (k_u + 1)T_u)$
$m_{dep,s,d_j}(k_u)$	number of vehicles departing from intersection s towards link l_{s,d_j} in $[k_u T_u, (k_u + 1)T_u)$
$g_{o_i,s,d_j}(k_u)$	indicates whether the traffic sign at intersection s for the traffic going from o_i to d_j is green (1) or red (0) during $[k_u T_u, (k_u + 1)T_u)$
Q_{o_i,s,d_j}	capacity of intersection s for traffic arriving from o_i and turning to d_j (veh/s)
$v_{s,\sigma}$	mean speed for the urban traffic in link $l_{s,\sigma}$ (km/h)
$\delta_{s,\sigma}(k_u)$	time required to reach the end of the queue waiting in link $l_{s,\sigma}$ at time $t = k_u T_u$ (s)
$L_{vehicle}$	average length of the vehicles (m)

	On-ramp and off-ramp variables
o	index of the on-ramp or off-ramp
n	index of freeway node connected to on-ramp or off-ramp
$w_{s,o,n}(k_u)$	queue length in number of vehicles on on-ramp o coming from intersection s waiting to depart towards freeway node n at time $t = k_u T_u$
$m_{dep,s,o}(k_u)$	traffic entering on-ramp o connected to intersection s of the urban network at time $t = k_u T_u$ (veh)
$\delta_{s,o}(k_u)$	time required to reach the end of the queue on ramp o at time $t = k_u T_u$ (s)
$m_{arr,s,o,n}(k_u)$	traffic leaving on-ramp o connected to intersection s towards the freeway node n at time $t = k_u T_u$ (veh)
$m_{dep,s,o,n}(k_u)$	traffic arriving at the end of the queue on on-ramp o coming from intersection s going to freeway node n at time $t = k_u T_u$ (veh)
$q_{dep,max,o,n}(k_f)$	maximum flow that can leave from on-ramp o toward freeway node n during the period $[k_f T_f, (k_f + 1)T_f)$ (veh/h)
$q_{dep,o,n}(k_f)$	flow that leaves from on-ramp o toward freeway node n during the period $[k_f T_f, (k_f + 1)T_f)$ (veh/h)
$S_{s,o}(k_u)$	available free space at ramp o connected to intersection s at time $t = k_u$ (veh)
$q_{dep,demand,n,s}(k_f)$	flow willing to leave freeway node n toward intersection s during period $[k_f T_f, (k_f + 1)T_f)$ (veh/h)
$\rho_{off,o}(k_f)$	density of off-ramp o during the period $[k_f T_f, (k_f + 1)T_f)$ (veh/km/lane)

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