HIERARCHICAL NONLINEAR MODEL-PREDICTIVE RAMP METERING CONTROL FOR FREEWAY NETWORKS

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Abstract: A nonlinear rolling-horizon model-predictive hierarchical coordinated ramp metering scheme is presented. The hierarchical control structure consists of three layers: the estimation/prediction layer, the optimization layer and the direct control layer. The second layer incorporates the previously designed optimal control tool AMOC while the local feedback strategy ALINEA is used in the third layer. Simulation results are presented for the Amsterdam ring-road. It is shown that control of all on-ramps including freeway intersections leads to the optimal utilization of the available infrastructure. *Copyright © 2006 IFAC*

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1. INTRODUCTION

Ramp metering aims at improving the traffic conditions by appropriately regulating the inflow from the on-ramps to the freeway mainstream and is deemed as one of the most effective control measures for freeway network traffic. One of the most efficient local ramp metering strategies is the ALINEA feedback strategy and its variations (Papageorgiou, *et al.*, 1991, 1998; Smaragdis and Papageorgiou, 2003; Smaragdis, *et al.*, 2004). A number of design approaches have been proposed for coordinated ramp metering. These include multivariable control (Diakaki and Papageorgiou, 1994) and optimal control (Bellemans, *et al.*, 2002; Hegyi, *et al.*, 2003; Gomes and Horowitz, 2004). Kotsialos *et al*. (2002b) presented AMOC, an open-loop control tool which combines a nonlinear formulation with a powerful numerical optimization algorithm and is able to consider coordinated ramp metering, route guidance as well as integrated control combining both control measures. In (Kotsialos and Papageorgiou, 2001, 2004) the results from AMOC's application to the problem of coordinated ramp metering at the Amsterdam ring-road are presented in detail. A more detailed overview of ramp metering algorithms may be found in (Papageorgiou and Kotsialos, 2002).

Due to various inherent uncertainties, the open-loop optimal solution becomes suboptimal when directly applied to the freeway traffic process. In this paper, the optimal results are cast in a model-predictive frame and are viewed as targets for local feedback regulators which leads to a hierarchical control scheme.

The rest of this paper is structured as follows. In section 2 the freeway network traffic flow model used for both simulation and control design purposes is briefly described. Section 3 introduces the formulation of the optimal control problem for ramp metering. The hierarchical control structure is described in section 4 while the results of applying ALINEA, as a stand-alone strategy, and the proposed hierarchical strategy are presented in section 5. Finally, conclusions and directions for future work are outlined in section 6.

2. TRAFFIC FLOW MODELLING

A validated second-order traffic flow model is used for the description of traffic flow on freeway networks and provides the modeling part of the optimal control problem formulation. In fact, the same model is used in this paper for the traffic flow simulator (METANET) (Messmer and Papageorgiou, 1990) and for the control strategy (AMOC) albeit with different external disturbances.

The network is represented by a directed graph whereby the links of the graph represent freeway stretches. Each freeway stretch has uniform characteristics, i.e., no on-/off-ramps and no major changes in geometry. The nodes of the graph are placed at locations where a major change in road geometry occurs, as well as at junctions, on-ramps, and off-ramps.

The time and space arguments are discretized. The discrete time step is denoted by T (typically $T \approx 10s$). A freeway link m is divided into N_m segments of equal length L_m (typically $L_m \approx 500m$), such that the stability condition $L_m \geq T \cdot \upsilon_{f,m}$ holds, where $\upsilon_{f,m}$ is the free-flow speed of link m. This condition ensures that no vehicle traveling with free speed will pass a segment during one simulation time step. Each segment i of link m at time $t = kT$, $k = 0,...,K$, where K is the time horizon, is macroscopically characterized via the following variables: the *traffic density* $\rho_{m,i}(k)$ (veh/lane/km) is the number of vehicles in segment i of link m at time $t = kT$ divided by L_m and by the number of lanes Λ_m; the *mean speed* $\upsilon_{m,i}(k)$ (km/h) is the mean speed of the vehicles included in segment i of link m at time $t = kT$; and the *traffic volume* or *flow* $q_{m,i}(k)$ (veh/h) is the number of vehicles leaving segment i of link m during the time period $\left[kT,(k+1)T\right]$, divided by T. The evolution of traffic state in each segment is described by use of the interconnected state equations for the density and mean speed respectively (Kotsialos and Papageorgiou, 2001, 2004). Roughly speaking, the flow increases with increasing density until a density critical value is reached, at which flow becomes maximum ($q_{\mu,cap}$). After this critical density, congestion sets on and the flow decreases reaching virtually zero at a jam density value.

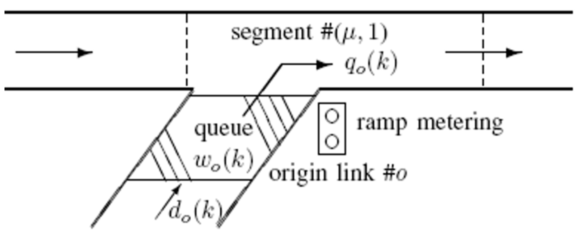

Fig. 1. The origin-link queue model.

For origin links, i.e., links that receive traffic demand d_o and forward it into the freeway network, a simple queue model is used (Fig. 1). The outflow q_o of an origin link o depends on the traffic conditions of the corresponding mainstream segment (μ,1), the ramp's queue length w_o (veh) and the existence of ramp metering control measures. If ramp metering is applied, then the outflow $q_o(k)$ that is allowed to leave origin o during period k, is a portion $r_o(k)$ of the maximum outflow that would leave in absence of ramp metering. Thus, $r_o(k) \in \left[r_{\min,o},1\right]$ is the metering rate for the origin link o, i.e., a control variable, where $r_{\min,o}$ is a minimum admissible value; typically, $r_{\min,o} > 0$ is chosen in order to avoid ramp closure. If $r_o(k) = 1$, no ramp metering is applied. A similar approach applies to freeway-to-freeway (ftf) interchanges. The evolution of the origin queue w_o is described by an additional state equation (conservation of vehicles). Note that the freeway flow $q_{\mu,1}$ in merge segments is maximized if the corresponding density $\rho_{\mu,1}$ takes values near the critical density $\rho_{\mu,cr}$.

Freeway bifurcations and junctions (including on-ramps and off-ramps) are represented by nodes. Traffic enters a node n through a number of input links and is distributed to the output links. The percentage of the total inflow at a bifurcation node n that leaves via the outlink m is the turning rate β_n^m.

3. FORMULATION OF THE OPTIMAL CONTROL PROBLEM

The overall network model has the state-space form

$$\mathbf{x}(k+1) = \mathbf{f}\left[\mathbf{x}(k),\mathbf{u}(k),\mathbf{d}(k)\right] \qquad (1)$$

where the state of the traffic flow process is described by the state vector $\mathbf{x} \in \mathbb{R}^N$ and its evolution depends on the system dynamics and the input variables. Input variables are distinguished into control variables $\mathbf{u} \in \mathbb{R}^M$ and external disturbances $\mathbf{d} \in \mathbb{R}^D$. In this case, vector $\mathbf{x}$ consists of the densities $\rho_{m,i}$ and mean speeds $\upsilon_{m,i}$ of every segment i of every link m as well as the queues w_o of every origin o. The control vector $\mathbf{u}$ consists of the ramp metering rates r_o of every on-ramp o under control, with $r_{o,\min} \leq r_o(k) \leq 1$. Finally, the disturbance vector consists of the demands d_o at every origin of the network and the turning rates β_n^m at the network's bifurcations. The disturbance trajectories $\mathbf{d}(k)$ must be known over the time horizon K_P for optimal control. For practical applications, these values may be predicted more or less accurately based on historical data or on real-time estimations (Wang *et al*., 2003).

The coordinated ramp metering control problem is formulated as a discrete-time dynamic optimal control problem with constrained control variables and can be solved numerically over a given optimization horizon K_P (Papageorgiou and Marinaki, 1995). The chosen cost criterion is the Total Time Spent (TTS) of all vehicles in the network (including the waiting time experienced in the ramp queues) which is a natural objective for the traffic systems considered. Penalty terms are added appropriately to the cost criterion in