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Model predictive traffic control for green mobility*

Tutorial session on traffic control – Extended abstract

Bart De Schutter¹

Abstract—This tutorial provides a short overview of model-based predictive control approaches for traffic management using multiple performance criteria, including green mobility performance measures such as reduction of emissions and reduction of fuel consumption. In this paper we will briefly discuss the most important aspects of the topic, while also providing the interested reader with a non-exhaustive list of references that provide a more in-depth treatment of the subject.

We start with a brief description of traffic management. Next, we discuss traffic flow and emission models, with an emphasis on macroscopic models, as they are well suited for on-line model-based predictive traffic control, highlighting the importance of the balance between accuracy and control performance. Next, we focus on the use of model-based predictive control (MPC) for coordinated control of various traffic control measures in small-scale freeway networks. Finally, we discuss various ways to improve the computation speed when solving the MPC optimization problem.

I. TRAFFIC MANAGEMENT

Traffic jams and congestion do not only cause considerable costs due to unproductive time losses; they also increase the probability of accidents and they have a negative impact on the environment (air pollution, increased fuel consumption) and on the quality of life (health problems, noise, stress). In principle, there are several ways to address this problem, such as constructing new roads or missing links, promoting public transportation, reducing or shifting the demand, adopting pricing or reward mechanisms, etc. However, on the short term, dynamics traffic management is probably one of the most promising ways to reduce the effects, frequency, and duration of traffic jams.

Dynamic traffic management involves the use of various traffic control measures such as dynamic speed limits, on-ramp metering, dynamic route guidance, traffic signals, lane closures, tidal flow¹, etc. to optimize and control the traffic flows in urban and freeway networks. For more information on traffic management the interested reader is referred to [1], [2], [3], [4], [5], [6].

In this tutorial we will focus on model-based predictive traffic management for freeways while the companion tutorials [7], [8] will concentrate on respectively speed control

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¹Tidal flow involves reversing the direction of one or more lanes during the morning and evening rush hours.

approaches to improve freeway traffic flow and urban traffic management.

II. TRAFFIC MODELS

Traffic models allow to predict the future behavior of the traffic network and as such they are an important component in predictive traffic control. Here, we consider two types of models: (1) traffic flow models, which describe the movement of vehicles and vehicle flows through the network, and (2) emission and fuel consumption models.

A. Traffic flow models

One can distinguish two major classes of models to describe the movement of vehicles in a traffic network, namely microscopic models and macroscopic models.

In microscopic traffic models the movements of individual vehicles are considered and updated at each time step. On the one hand, microscopic models are in general able to describe various traffic phenomena in a very detailed way, but on the other hand they may be very time-consuming for large-scale networks and in case the network has to be simulated repeatedly on-line as is done in model-based predictive traffic control.

Macroscopic traffic models work at an aggregate level with the network being discretized in space (via the subdivision of freeway stretches into segments with a typical length of 500 m to 1 km) and in time (with a typical time step of 10 s). Macroscopic models then describe the evolution of the traffic network via aggregate variables for each segment such as the vehicle density, the vehicle flow, and the average speed. In general, macroscopic traffic flow models may not be able to capture all the details of various traffic phenomena, but on the other hand they can be simulated very efficiently, which makes them very suitable for use in on-line model-based traffic control. In this context, the trade-off between accuracy and computation speed is very important.

Several macroscopic models have been developed for freeway networks, the most well-known being the first-order² models of Payne [9] and Lighthill-Whitham-Richards (LWR) [10], [11], [12], and the second-order METANET model [13], [14] and its extensions [15].

For an overview of traffic models we refer the interested reader to [16], [17], [18].

²Here, the order refers to the number of independent state variables.

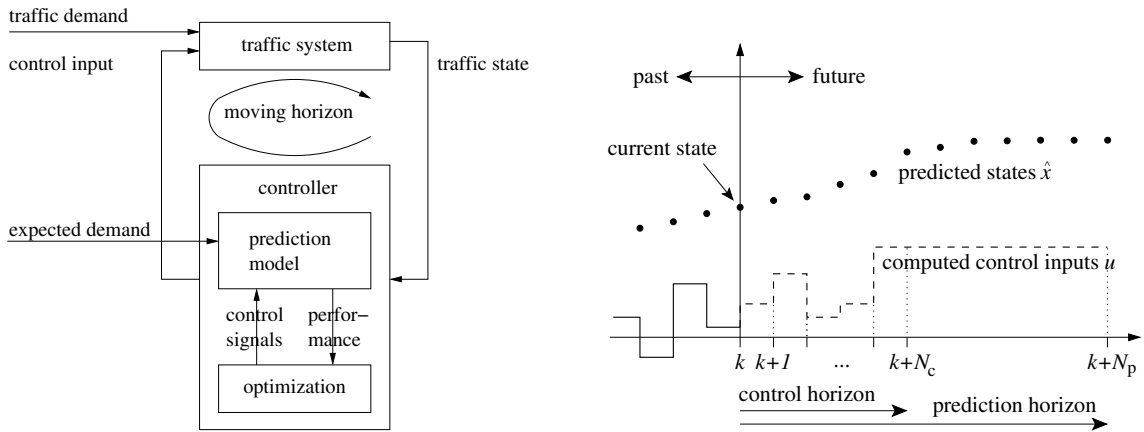


Fig. 1. Model-based predictive traffic control

B. Emission and fuel consumption models

Traditionally, traffic management has mainly focused on the reduction of congestion and on maximizing the throughput of the network or minimizing the total travel time. However, recently sustainability-related performance criteria and constraints such as e.g., reducing emissions of CO, CO₂, HC, NO_x, and reducing fuel consumption have gained increased attention. In order to accommodate these criteria in model-based traffic, one also needs models to describe them.

For emissions, several microscopic models have been developed, most of them using the speed, the acceleration, and the engine load (as well as vehicle type) as input [19] such as the VT-micro model [20], the VERSIT+ model [21], and the models in [22], [23]. For the sake of obtaining a trade-off between accuracy and computation speed, these microscopic models can also be integrated with macroscopic models (see e.g., the VT-macro model of [24]).

Since for fuels like gasoline or diesel, there is a direct, almost affine relation between the amount of fuel consumed and the CO₂ emissions (see, e.g., [25]), the above models can also be used to obtain fuel consumption models.

III. MODEL-BASED PREDICTIVE TRAFFIC CONTROL

Model-based predictive control (MPC) [26], [27], [28] is a control approach that uses a prediction model in combination with (numerical) optimization to determine the control signals that optimize a given performance criterion subject to operational and other constraints over a given prediction horizon. Of the resulting optimal control sequence, only the first sample is then implemented on the system. Next, the horizon is shifted and the whole process is repeated. By adopting this so-called moving horizon or rolling horizon approach, feedback is introduced into the control strategy. A schematic representation of MPC is given in Fig. 1.

In essence, in MPC-based traffic control at each control time step k an optimization problem of the following form

is solved:

$$\min_{\tilde{u}(k)} J(\tilde{u}(k), \tilde{x}(k)) \quad (1)$$

$$\text{subject to } \tilde{x}(k) = \mathcal{M}(\tilde{u}(k), x(k), \tilde{d}(k)) \quad (2)$$

$$\mathcal{C}(\tilde{x}(k), \tilde{u}(k)) \leq 0$$

where J expresses the performance criterion³ (e.g., total time spent, vehicle loss hours, throughput, emissions, etc.) over a time period $[kT, (k+N_p)T]$ with T the sampling time and N_p the prediction horizon; $\tilde{u}(k) = [u^T(k) \ u^T(k+1) \ \dots \ u^T(k+N_p-1)]^T$ contains the control inputs (ramp metering rates, speed limits, splitting rates for route guidance, etc.); $x(k)$ is the state (e.g., average speeds, densities, flows, queue lengths) at time step k ; $\tilde{x}(k) = [\hat{x}^T(k+1) \ \hat{x}^T(k+2) \ \dots \ \hat{x}^T(k+N_p)]^T$ contains the predicted future state of the traffic network; and $\tilde{d}(k)$ contains the future external inputs (e.g., traffic demand). Moreover, the function \mathcal{M} represents the traffic model used, and the function \mathcal{C} describes the various constraints on inputs and states. In order to reduce the number of optimization variables, a control horizon N_c (with $N_c < N_p$) is defined and the control inputs are taken constant from $k+N_c$ on: $u(k+j) = u(k+N_c-1)$ for $j = N_c, \dots, N_p-1$.

The resulting optimization problem is in general a non-linear non-convex optimization problem that can be solved using multi-start local optimization methods (e.g., sequential quadratic programming) or global optimization methods (such as pattern search or genetic algorithms) [29], [30], [31].

In [32], [15] it has been shown how MPC can be used to coordinate various traffic control measures such as on-ramp metering, dynamic speeds limits, route guidance, etc. while minimizing the total time spent subject to e.g., queue length constraints at the on-ramps, maximum speed limit variations of time and space, etc. In [24], [33] this work has been extended to also include green mobility criteria such as point emissions (i.e., emissions directly emitted at the freeway locations) as well as dispersion of emissions (due to e.g., wind).

³In multi-objective context, often a weighted sum of various performance criteria is used.

Model-based control approaches based on optimal control are described in [34], [35], [36], [37]. Other related results for model-based freeway control can be found in [38], [39], [24].

IV. EFFICIENT MPC-BASED TRAFFIC CONTROL

In order to reduce the computation time for solving the MPC optimization problem several approaches can be adopted including reducing the search space [40], approximating the MPC-optimization problem by another problem that can be solved more efficiently [41], or using simplified prediction models [42]. A particularly promising approach is the use of parametrized control [33] where instead of optimizing the sequence $u(k), u(k+1), \dots, u(k+N_p-1)$ a parametrized control law is defined of the form $u(k+j) = f(x(k+j), \theta)$ and subsequently only the parameter θ is optimized, resulting in a significantly smaller number of optimization variables.

For large-scale networks one can also resort to distributed or hierarchical control [43], [44], [45], [46].

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