OVERVIEW OF MOTORWAY NETWORK TRAFFIC CONTROL STRATEGIES

Apostolos Kotsialos, and Markos Papageorgiou
Dynamic Systems and Simulation Laboratory
Technical University of Crete, Greece
E-mail: appie@dssl.tuc.gr, markos@dssl.tuc.gr

1 INTRODUCTION

The efficient, safe, and less polluting transportation of persons and goods on motorways calls for an optimal utilisation of the available infrastructure via suitable application of a variety of traffic control measures. The recent developments and advances in the areas of computation and communications may support this effort, but it is evident that the efficiency of traffic control depends on the efficiency and relevance of the employed control methodologies. The goal of this paper is to provide an overview of advanced traffic control strategies for motorway networks.

2 THE CONTROL LOOP

Controlling the motorway traffic flow process is a highly complicated task which may involve a variety of spatially distributed control measures such as ramp metering, route guidance, variable speed limits, etc. The way the control measures behave and act on the traffic process stems from the specific design of the control strategy used. The control strategy employed determines the control actions, and the specific response to the prevailing traffic conditions, through the available control actuators, is based on its design and on pre-specified goals.

Figure 1 depicts the general control loop for the motorway network traffic process which includes all technical and physical phenomena that should be influenced according to the specific goals. The evolution of the traffic process depends upon the control inputs and the process disturbances. The control inputs are directly related to corresponding control devices such as traffic lights, variable message signs, variable direction signs, etc., and may be selected from an admissible control region subject to technical, physical, and operational constraints. The process disturbances cannot be manipulated, but may possibly be measurable (e.g. demand) or detectable (e.g. incident) or predictable over a future time horizon with appropriate algorithms. Typical disturbances in motorway traffic are traffic
demands, origin-destination patterns, the drivers' compliance to variable message signs, environmental conditions, and incidents.

The process outputs are quantities chosen to represent the performance aspects of interest, e.g. total time spent, queue lengths, etc. The estimation of the traffic state and the prediction of the various traffic quantities are performed based on real-time measurements taken from the traffic process, and are subsequently fed to the control strategy. The control strategy determines, based on the measured, estimated and predicted quantities, the appropriate control inputs which are fed to the traffic process so as to meet the specified goals despite the impact of various disturbances.

Figure 1. Motorway traffic flow process under control.

3 MOTORWAY NETWORK TRAFFIC MODELS

When developing a control system, a mathematical model of the process, deduced from suitable laws or induced from experimental results, is necessary. In the case of motorway network traffic models, a combination of both approaches is used. Traffic flow models may be categorised into microscopic, mesoscopic, and macroscopic, depending on the adopted level of detail. The main disadvantages of microscopic and mesoscopic models from the traffic control point of view are their complexity, their non-analytic character (they are simulation tools rather than mathematical models), and their demand on computation time. Due to these drawbacks, the suitability of microscopic and mesoscopic models for the design of real-time control strategies is limited, although they may provide a background for the off-line evaluation of developed control strategies. Contrary to the microscopic and mesoscopic approaches, macroscopic models are more suitable for the design of control strategies since they describe the traffic flow process analytically and demand lower computational effort.
4 CONTROL STRATEGY DESIGN

4.1 Ramp metering

4.1.1 Fixed time ramp metering strategies
Fixed-time ramp metering strategies are derived off-line for particular times-of-day, based on constant historical demands, without the use of real-time measurements. These formulations lead to linear programming or quadratic programming problems that may be readily solved by use of broadly available computer codes.

4.1.2 Reactive ramp metering strategies
Reactive ramp metering strategies are employed at a tactical level, i.e. in the aim of keeping the motorway traffic conditions close to pre-specified set values, based on real-time measurements. Local ramp metering strategies make use of traffic measurements in the vicinity of a ramp to calculate suitable ramp metering values. Strategies that have applied in the field include the demand-strategy, which is an open-loop disturbance-rejection policy, and the feedback control strategy ALINEA. Multivariable regulator strategies for ramp metering pursue the same goals as local ramp metering strategies: They attempt to operate the motorway traffic conditions near some pre-specified set (desired) values. While local ramp metering is performed independently for each ramp, based on local measurements, multivariable regulators make use of all available mainstream measurements on a motorway stretch, to calculate simultaneously the ramp volume values, for all controllable ramps included in the same stretch.

4.1.3 Nonlinear optimal ramp metering strategies
Reactive ramp metering strategies may be helpful to a certain extent, but, first they need appropriate set values, and, second, their character is more or less local. What is needed for motorway networks or long stretches is a superior coordination level that calculates in real time optimal set values from a proactive, strategic point of view. Such a comprehensive dynamic optimal control problem may be formulated and solved with moderate computation time by use of suitable solution algorithms.

4.2 Link control strategies
Link control may include one or a combination of the following actions: variable speed limitation, changeable message signs with indications for “keep lane”, or congestion warning, or environmental warning (e.g. information about the pavement state), lane control, incident warning, reversible flow lanes (tidal flow). Very few systematic studies have been conducted to quantify the impact of these control measures and corresponding validated mathematical models are currently lacking. This is one the reasons why the corresponding control strategies of operating systems are of a heuristic character.
4.3 Route guidance control strategies

A route guidance system may be viewed as a traffic control system in the sense of Figure 1. Based on real-time measurements, sufficiently interpreted and extended within the surveillance block, a control strategy decides about the routes to be recommended (or the information to be provided) to the road users. This, on its turn, has an impact on the traffic flow conditions in the network, and this impact is reflected in the performance indices. Depending on the use of real time measurements and the use of traffic prediction methods, route guidance strategies may be classified to reactive, predictive, iterative, and one-shot strategies. Route guidance strategies may aim at either system-optimal or user-optimal traffic conditions.

4.4 Integrated motorway network traffic control

As mentioned earlier, modern motorway networks may include different types of control measures. The corresponding control strategies are usually designed and implemented independently, thus failing to exploit the synergistic effects that might result from coordination of the respective control actions. An advanced concept for integrated motorway network control, results from the optimal control approach. Such an approach was implemented in the integrated motorway network control tool AMOC (Advanced Motorway Optimal Control) where ramp metering and route guidance are considered simultaneously with promising results.

5 AN ADVANCED EXAMPLE

The efficiency and the amelioration potential of non-linear optimal ramp metering strategies may be demonstrated by means of simulation for a large-scale network with the use of the AMOC generic motorway network control tool.

For the purposes of our study the counter-clockwise direction of the A10 ring-road of Amsterdam, The Netherlands, which is about 32 km long, is considered. There are 21 on-ramps on this motorway, including the connections with the A8, A4, A2, and A1 motorways, and a total number of 20 off-ramps, including the junctions with A4, A2, A1, and A8. It is assumed that ramp metering may be performed at each on-ramp. The ring-road was studied for a time horizon of 4 hours. In absence of any control measures, the ring-road is subject to recurrent congestion that is formed downstream of the junctions of A10 with A2 and A1 in A10-South. Figure 3 depicts the density propagation along the motorway segments (segment 0 is the first segment of A10-West after the junction of A10 with A8), and Figure 4 the on-ramp queue formation. (on-ramp 0 corresponds to A8). As a result, the total time spent over the 4h-horizon is equal to 13,226 veh*h. When ramp metering is performed at all on-ramps, the congestion is virtually lifted from the network (Figure 5).
The control strategy succeeds in establishing optimal uncongested traffic conditions. In Figure 6, the queues formed are depicted. The control trajectories are depicted in Figure 7. The resulting total time spent is 8833 veh*h, which is a 33.2% improvement compared to the no-control case.

6 FUTURE DIRECTIONS
As in many other engineering disciplines, only a small portion of the significant methodological advancements in motorway network control have really been exploited in the field. It is beyond our scope to investigate and discuss the reasons behind this theory-practice gap, but administrative inertia, little competitive pressure in the public sector, the complexity of traffic control systems, limited realisation of the improvement potential
behind advanced methods by the responsible authorities, and limited understanding of practical problems by some researchers may have a role in this. Whatever the reasons, the major challenge in the coming decade is the deployment of advanced and efficient traffic control strategies in the field.