Available online at www.sciencedirect.com
SCIENCE DIRECT
Control Engineering Practice 14 (2006) 757–767
CONTROL ENGINEERING PRACTICE
www.elsevier.com/locate/conengprac

Model predictive control for ramp metering of motorway traffic: A case study

T. Bellemans[a,*], B. De Schutter[b], B. De Moor[a]

[a] ESAT-SCD (Signals, Identification, System Theory and Automation), Katholieke Universiteit Leuven, Kasteelpark Arenberg10, B-3001 Leuven, Belgium
[b] Delft Center for Systems and Control, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands

Received 15 November 2002; accepted 15 March 2005
Available online 10 May 2005

Abstract

A real-life motorway in Belgium is studied and a comparison is made between a simulation of a morning rush hour situation without control and a simulation of a morning rush hour situation with ramp metering implemented. Two types of controllers are compared: a traditional ALINEA based controller and a model predictive control based ramp metering controller. In order to evaluate the controllers in a realistic framework, the simulations presented in this paper are based on real-life traffic measurements, and constraints on the maximal allowed queue lengths at the on-ramps are imposed. The presented simulations are indicative for the reduction in the total time spent (on the studied motorway and on the on-ramps) that can be achieved by ramp metering during a typical morning rush hour.

Keywords: Model predictive control; Traffic control; Ramp metering

1. Introduction

Many countries around the world invest large amounts of resources in attempts to reduce the occurrence of congestion and as such its negative impact on e.g., traffic safety, the environment (air pollution, wasted fuel) and the quality of life (health problems, noise, stress). Since the construction of new roads is not always a viable option due to economical and environmental issues, other solutions are needed. One solution that can be implemented in the short term is dynamic traffic control. Dynamic traffic control is a traffic responsive control method that takes the variations of the traffic situation over time into account. These variations in the traffic state can result from a changing traffic demand during rush hours, accidents, manifestations, ... The research on and implementation of dynamic traffic control systems is aimed at increasing the traffic operation efficiency without building new roads.

This paper focuses on increasing the efficiency of traffic operations on motorways using dynamic control. One way to control traffic on a motorway is ramp metering or admission control. The control signals or metering rates can be obtained by using traditional PID-like control (ALINEA) or they can be optimized in a receding horizon framework as will be presented later.

This paper is organized as follows: First, the concept of ramp metering for control of motorway traffic is presented followed by two methods to calculate dynamic or traffic responsive metering rates. The method presented first consists of a traffic regulator ALINEA while the second method relies on a receding horizon framework. In the third section a motorway in Belgium is considered as a real-life case study. Traffic simulations

*Corresponding author. Tel.: +32 16 32 17 09; fax: +32 16 32 19 70.
E-mail addresses: Tom.Bellemans@esat.kuleuven.ac.be (T. Bellemans), b.deschutter@dcsc.tudelft.nl (B. De Schutter), Bart.DeMoor@esat.kuleuven.ac.be (B. De Moor).

0967-0661/$ - see front matter
doi:10.1016/j.conengprac.2005.03.010

of the case study illustrate the positive impact of ramp metering on the traffic situation and allow for a comparison of the performance of an ALINEA based controller with a controller based on model predictive control.

2. Motorway control using ramp metering

This section deals with ramp metering as a means to control traffic operations on a motorway. Before discussing ramp metering, the fundamental diagrams from traffic theory are presented in order to get a better understanding of the concept behind ramp metering. As far as determining the appropriate control signals is concerned, the ALINEA controller is presented followed by a presentation of the model predictive control approach.

2.1. The fundamental diagrams

Observations and measurements of traffic on motorways show that traffic behaves approximately according to what are known as the fundamental diagrams in traffic flow theory (May, 1990). The fundamental diagrams plot the relations between the traffic density, the average speed, and the traffic flow. A typical flow-density fundamental diagram is presented in Fig. 1. In low traffic conditions, the traffic flow increases in a nearly proportional way with increasing traffic density. If the traffic density keeps increasing, the traffic flow starts saturating until a maximal flow is reached at the critical density ρ_{cr}. The maximal flow associated with the critical density ρ_{cr} is called the capacity q_{cap} of the motorway. A typical value of ρ_{cr} is 34 vehicles per kilometer and per lane. The capacity q_{cap} of a three-lane motorway is typically around 6000 vehicles per hour. Once the critical density is reached, traffic breakdown occurs and the traffic flow starts decreasing with further increasing traffic density. As soon as breakdown of the traffic flow at ρ_{cr} occurs, congestion sets in and traffic starts operating in a congested regime. This congested regime is unstable in the sense that a perturbation that momentarily increases the density on the motorway section will cause the traffic flow to decrease, thus giving rise to an even larger traffic density. The traffic density in congested regime where the average traffic speed is zero or, in other words, where the traffic comes to a stand-still is called the jam density ρ_{jam} (see Fig. 1). A typical value of ρ_{jam} is 180 vehicles per hour and per lane. The values of ρ_{cr}, ρ_{jam} and q_{cap} depend on the motorway characteristics such as e.g., the curvature, the speed limits, the slope, ... Stable, free flowing traffic operation can only occur at densities below the critical density.

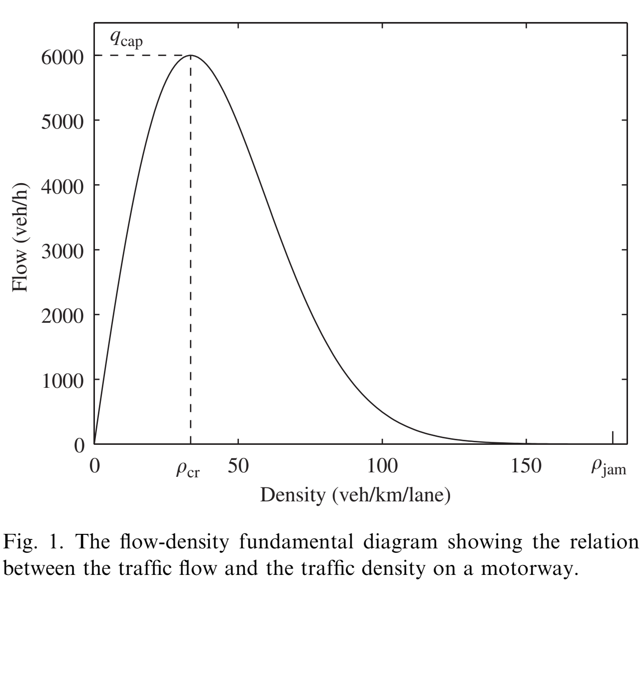

Fig. 1. The flow-density fundamental diagram showing the relation between the traffic flow and the traffic density on a motorway.

2.2. Ramp metering

A ramp metering set-up consists of a traffic light that is placed at the on-ramp of a motorway as schematically represented in Fig. 2. The traffic light alternates between the red and the green phase. During the green phase only one vehicle is allowed to enter the motorway using the on-ramp. By varying the timing of the red and the green phases, the number of vehicles that enters the motorway through the on-ramp is controlled. When the traffic density on the motorway tends to exceed the critical density, the ramp metering set-up limits the inflow of vehicles onto the motorway in order to keep the traffic density below the critical density, thus avoiding traffic breakdown and congestion. Whenever the traffic demand is larger than the number of cars that is allowed to enter the motorway, a waiting queue of vehicles is formed at the on-ramp.

By keeping the traffic state on the motorway in the region of stable operation, ramp metering tries to

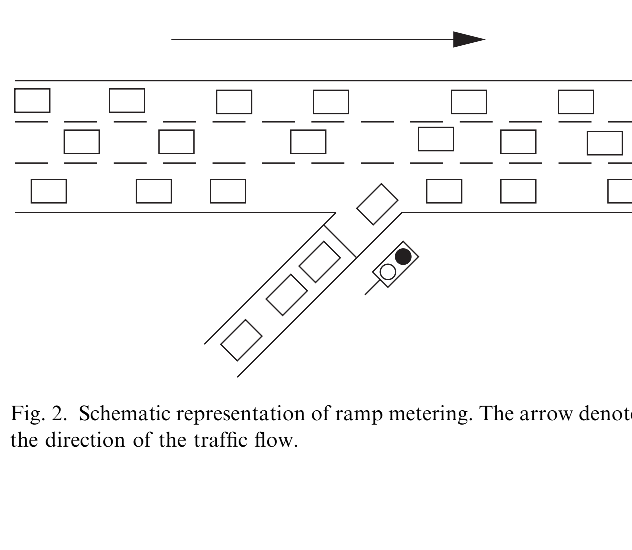

Fig. 2. Schematic representation of ramp metering. The arrow denotes the direction of the traffic flow.