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Optimisation of dynamic motorway traffic via a parsimonious and decentralised approach

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ABSTRACT

This paper presents an optimisation framework for motorway management via ramp metering and variable speed limit. We start with presenting a centralised global optimal control problem aiming to minimise the total travel delay in a motorway system. Given the centralised global optimal control solutions, we propose a set of decentralised ramp metering and speed control strategies which operate on a novel parsimonious dynamic platform without needing an underlying traffic model. The control strategies are applied to a case on UK M25 motorway. The results show that the proposed set of decentralised control is able to deliver a performance that is close to the global optimal ones with significantly less computational and implementation effort. This study provides new insights to motorway management.

1. Introduction

Efficient use of road infrastructure requires effective traffic control systems (Chow et al., 2008), and a recent empirical study reveals that an effective control scheme can reduce traffic congestion by up to 20–25% of observed congestion in urban areas (Chow et al., 2014). Traffic control systems can be classified into two main categories according to their hierarchies: centralised or decentralised control. Under a centralised and coordinated control system, local measurements collected from different parts (e.g. junctions or links in traffic context) are sent to a central authority or computer. With the received measurements and information, the central authority will generate short-term state predictions of the system and derive corresponding global control plans for the entire system. The state estimation and control derivation processes are typically carried out with the use of an underlying model of the system. Examples of centralised control systems that can be found in the literature include (Gomes and Horowitz, 2006) who present a coordinated ramp metering optimisation model based upon cell transmission model (CTM) (Daganzo, 1994) as a linear program. Chow (2009) presents a global network flow optimizer with consideration of joint route and departure time choices of travellers modelled by a general class of travel time functions. Papamichail et al. (2010) present a model-predictive framework for coordinated ramp metering based upon a high order METANET model which considers transient behaviour of traffic state transition. Formulating and solving these centralised optimisation models can be challenging for practical applications. Challenges include one will need to formulate an underlying traffic model with reasonable accuracy with respect to real world observations, and develop effective algorithms for solving the optimisation model in reasonable time. Considering this, use of parsimonious and decentralised strategies has been receiving increasing attention in recent years (Daganzo et al., 2012).

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Decentralised control, in contrast with its centralised counterpart, refers to control systems that allow local components to derive local control policy based on local information to accomplish global goals without being intervened by the central authority. Such decentralised control reduces significantly the complexity of computation and implementation. A number of existing studies or applications of decentralised control can be found in urban networks (see for examples Geroliminis and Daganzo, 2008; Aboudolas et al., 2010; Haddad and Geroliminis, 2012; Geroliminis et al., 2013; Aboudolas and Geroliminis, 2013). For motorways, we can also find a number of rule-based decentralised controllers including the local ramp controller ALINEA (Papageorgiou et al., 1991), coordinated ramp controller HERO (Papamichail and Papageorgiou, 2008), and others (Zhang and Levinson, 2004). In addition to the control design, there have also been a number of studies attempting to develop a parsimonious paradigm for estimating behaviour of the underlying transport systems. Parsimonious paradigm refers to modelling approaches which approximate the real world systems with simple mathematical relationships without detailed modelling. In particular, recently we have seen a number of studies exploring the use of the Macroscopic Fundamental Diagram (MFD) to approximate the traffic characteristics on motorways for control design purposes (see Buisson and Ladier, 2009; Ji et al., 2010; Geroliminis and Sun, 2011; Saberi and Mahmassani, 2012; Saberi and Mahmassani, 2013). Nevertheless, it is found to be difficult to derive a well-defined and reproducible MFD function on motorways. Geroliminis and Sun (2011) and later Saberi and Mahmassani (2012) observe a clockwise hysteresis loop appears during the recovery phase in motorway MFDs. It is revealed (Gayah and Daganzo, 2011; Geroliminis and Sun, 2011; Cassidy et al., 2011; Daganzo, 2011) that this is due to the inhomogeneous distribution of traffic on motorway networks. This hysteresis loop nevertheless indicates an inefficient operation because it implies the discharge rate of traffic will be reduced during recovery from congestion (Daganzo, 2011). Daganzo (2011) suggests that a more even distribution of traffic over space can help to reduce the hysteresis loop and hence improve the efficiency of the system operations. The (re-)distribution of traffic can be achieved by various means including the use of variable speed limit (VSL).

Although the MFD approach may not be used readily for managing motorway traffic, the study here aims to develop a set of decentralizsd control schemes by utilising the lessons we learn from previous MFD and centralised optimal control analysis of motorways. In this paper, we start with formulating and solving a centralised global optimal control problem based upon the cell transmission model (CTM). The CTM is chosen here due to its credibility and desirable mathematical properties for modelling and optimizing road traffic. An optimal spatio-temporal distribution of traffic is sought such that the corresponding total travel delay in the system is minimised via ramp metering and mainline speed control. As will be shown, the complexity of this centralised optimal control problem grows exponentially as the decision variables increases over space and time. The second part of the study is to derive a set of decentralised control rules for regulating the ramp inflows and mainline traffic propagation through observing the characteristics of the centralised optimal control solutions. The control strategies are applied to a case on UK M25 motorway and the results show that the proposed decentralised control method can produce a similar performance to the centralised ones with significantly simpler implementations and calculations. This study provides new insights to motorway management.

The paper is organised as follows: Section 2 presents the CTM-based traffic modelling and centralised optimal control formulations. Section 2 concludes with an analysis of the global optimal results and explores how they can be applied to the development of parsimonious decentralised control schemes. Section 3 presents a set of decentralised control rules based upon a parsimonious modelling platform with illustrations through a case study on M25 motorway. Finally, Section 4 provides some concluding remarks.

2. Traffic modelling and centralised optimisation

The centralised optimal control presented here aims to derive a global control scheme that can minimise total motorway system delay via coordinated ramp metering and mainline variable speed limit. The control problem is formulated based upon the cell transmission model (CTM) (Daganzo, 1994). The cell transmission model is a finite difference approximation of the widely accepted kinematic wave model (Lighthill and Whitham, 1955; Richards, 1956). Under CTM, the motorway section is discretized into a collection of cells i in which each cell can be associated with an on-ramp with demand flows $r_i(t)$ or an off-ramp with exit flows $s_i(t)$ over time t. Given the boundary and initial values, CTM estimates the flows and densities in each cell i and time interval t by conservation and propagation laws (Eqs. (1) and (2)).

With the density $\rho_i(t)$ in cell i during time interval $t, \rho_i(t+1)$ is updated by the conversation law as:

$$\rho_i(t+1) = \rho_i(t) + \frac{\Delta t}{\Delta x_i}[f_{i-1}(t) - f_i(t) + r_i(t) - s_i(t)], \ \forall i, t \tag{1}$$

where $f_i(t)$ is the traffic outflow from cell i during time step t, and hence $f_{i-1}(t)$ (outflow from upstream cell $i-1$) will be the inflow to cell i during the same time t; Δt and Δx_i are respectively the lengths of simulation time step and cell i. The value of Δt satisfies $\Delta t \leqslant \min_i \frac{\Delta x_i}{v_i}$, where $\min_i \frac{\Delta x_i}{v_i}$ refers to the smallest ratio of cell length to the assocaited free-flow speed along the section. The above condition is known as the Courant–Friedrichs–Lewy (CFL) condition (Courant et al., 1928) which is used to ensure the numerical stability and non-negativity of traffic quantities by ensuring the traffic not travel further than the length of the cell in one simulation time step. Moreover, the propagation of flow from cell i to its downstream cell $i+1$ in time interval t is modelled as:

$$f_i(t) = \min\{v_i\rho_i(t), Q_i(t), Q_{i+1}(t), w_{i+1}[\bar{\rho}_{i+1} - \rho_{i+1}(t)]\} \tag{2}$$