Transportation Research Part C 46 (2014) 209–221

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Integrated feedback ramp metering and mainstream traffic flow control on motorways using variable speed limits

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ARTICLE INFO

Article history:
Received 26 January 2014
Received in revised form 7 April 2014
Accepted 27 May 2014

Keywords:
Traffic management
Integrated motorway traffic flow control
Ramp metering
Mainstream traffic flow control
Variable speed limits
Feedback control
Optimal control

ABSTRACT

Ramp metering (RM) is the most direct and efficient tool for the motorway traffic flow management. However, because of the usually short length of the on-ramps, RM is typically deactivated to avoid interference of the created ramp queue with adjacent street traffic. By the integration of local RM with mainstream traffic flow control (MTFC) enabled via variable speed limits (VSL), control operation upstream of active bottlenecks could be continued even if the on-ramp is full or if the RM lower bound has been reached. Such integration is proposed via the extension of an existing local cascade feedback controller for MTFC-VSL by use of a split-range-like scheme that allows different control periods for RM and MTFC-VSL. The new integrated controller remains simple yet efficient and suitable for field implementation. The controller is evaluated in simulation for a real motorway infrastructure (a ring-road) fed with real (measured) demands and compared to stand-alone RM or MTFC-VSL, both with feedback and optimal control results. The controller's performance is shown to meet the specifications and to approach the optimal control results for the investigated scenario.

1. Introduction

Traffic flow congestion on motorways is a serious and increasing problem of modern societies. Congestion is known to reduce the nominal capacity of the motorway infrastructure (Papageorgiou and Kotsialos, 2002), with serious impact on travel times, traffic safety, fuel consumption and environmental pollution.

Various traffic management measures have been proposed to alleviate traffic congestion but are known to face limitations. Ramp metering (RM), for example, is the most direct and efficient tool for motorway traffic flow control but has a major limitation: the created ramp queues should not spill over to the adjacent infrastructure. Because the ramp storage space may be limited, RM is typically released when the ramp queue has covered the whole on-ramp. Thus, RM may delay the onset of congestion, accelerate its dissolution and reduce its space extent, but it may have to be deactivated for most of the peak period due to full ramps (Papamichail et al., 2010).

To overcome these limitations, the integration of different traffic control measures has been investigated in the past, for example RM integrated with route guidance (Kotsialos et al., 2002; Karimi et al., 2004); or RM integrated with variable speed

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http://dx.doi.org/10.1016/j.trc.2014.05.017

limits (VSL) (Hegyi et al., 2005a,b; Zhang et al., 2006; Chang et al., 2007; Carlson et al., 2010a,b; Lu et al., 2010; Zegeye et al., 2012). Most of these approaches are, however, based on sophisticated methods that may face difficulties in field applications; in some cases even simulation results were not satisfactory. Another approach for integration of RM and VSL called SPECIALIST-RM (Schelling et al., 2011), based on the field-tested VSL strategy SPECIALIST (Hegyi et al., 2008; Hegyi and Hoogendoorn, 2010), deals with the particular case of moving limited-length jams.

Mainstream traffic flow control (MTFC) on motorways by the use of VSL was proposed by Carlson et al. (2010a,b) along with its integration with RM via a sophisticated optimal control approach. These studies have shown that MTFC-VSL can improve motorway performance substantially, particularly when integrated with RM. Because of the limited practicality of the optimal control approach employed, Carlson et al. (2011a) designed, based on the same MTFC concept of Carlson et al. (2010a,b), a simple but efficient feedback controller for MTFC-VSL that is deemed suitable for field implementation, without considering, however, the integration with RM.

In this paper we propose the integration of MTFC-VSL with RM using a feedback control approach. The cascade feedback controller for MTFC-VSL developed by Carlson et al. (2011a) is extended via a split-range-like scheme (Stephanopoulos, 1984) such that MTFC-VSL is only applied when the metered on-ramp storage space is about to be exhausted or if the RM lower bound has been reached. The use of the developed strategy for the case where RM and MTFC-VSL operate with the same control period is relatively straightforward. However, very often the control period for RM is smaller than the control period used for VSL. When distinct control periods are used for RM and MTFC-VSL, additional care should be taken for the integration of these techniques. Therefore, the proposed control strategy also takes into account the possibility of RM and MTFC-VSL operating with distinct control periods. Preliminary results were presented by Carlson et al. (2012a,b, 2013b). Simulation-based investigations for a real motorway network using the second-order macroscopic traffic flow simulator METANET (Messmer and Papageorgiou, 1990) demonstrate the features of the proposed integrated control strategy and compare its efficiency against stand-alone feedback-based RM and feedback-based MTFC-VSL. Simulation results with the optimal control tool AMOC (Kotsialos et al., 2002) are also included.

In the next section, the concepts of motorway traffic management involving RM and MTFC-VSL as well as their integration are briefly reviewed. Section 3 presents a review of the feedback control strategies employed in this paper for RM and MTFC-VSL, and introduces the design of the integrated controller. The feedback controllers are tested and compared in Section 4. Finally, Section 5 concludes the paper.

2. Motorway traffic management

This section outlines two motorway traffic management methods, ramp metering (RM) (see Papageorgiou and Kotsialos (2002) for an overview) and mainstream traffic flow control (MTFC) (Carlson et al., 2010a), as well as their integration. These techniques are employed to improve traffic conditions on motorways, avoiding the capacity drop at bottlenecks and/or the blocking of off-ramps by the congestion, and the resulting reduction in traffic flow throughput (Papageorgiou and Kotsialos, 2002).

2.1. Ramp metering

Ramp metering (RM) (see Papageorgiou and Kotsialos (2002) for an overview), sketched in Fig. 1(a), is useful when the demand d (veh/h) arriving from the on-ramp and the mainstream arriving flow q_{in} (veh/h) upstream of the on-ramp exceed the motorway capacity q_{cap} (veh/h) downstream of the on-ramp, activating the bottleneck. In this case, a capacity drop would occur that could be avoided with RM. Ramp metering consists in metering the inflow of vehicles from the ramp into the

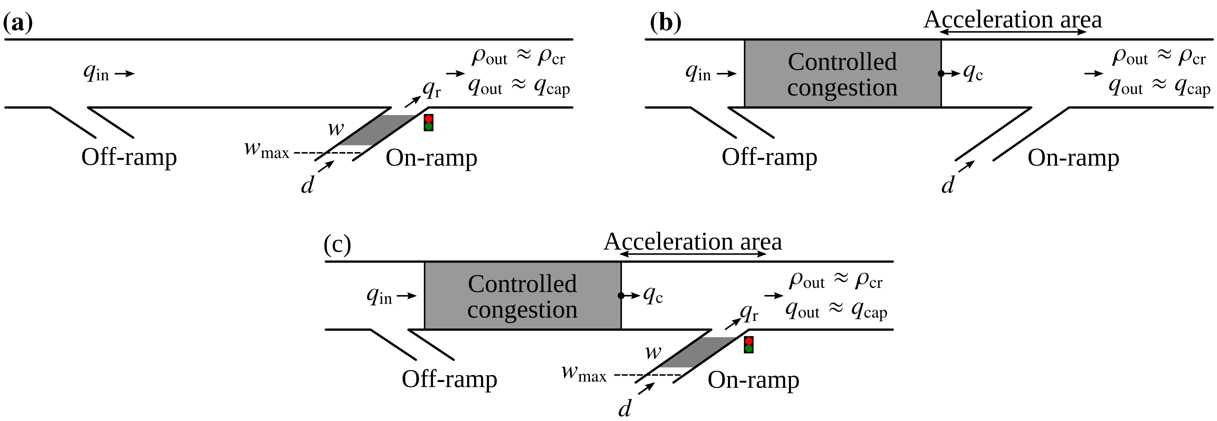

Fig. 1. (a) Ramp metering; (b) mainstream traffic flow control; and (c) integrated ramp metering and mainstream traffic flow control.