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Real-time merging traffic control for throughput maximization at motorway work zones

A. Tympakianaki [a,*], A. Spiliopoulou [a], A. Kouvelas [a], I. Papamichail [a], M. Papageorgiou [a], Y. Wang [b]

[a] Dynamic Systems and Simulation Laboratory, Technical University of Crete, 73100 Chania, Greece
[b] Institute of Transportation Engineering, College of Civil Engineering and Architecture, ZheJiang University, Hangzhou 310058, PR China

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ABSTRACT

Work zones on motorways necessitate the drop of one or more lanes which may lead to significant reduction of traffic flow capacity and efficiency, traffic flow disruptions, congestion creation, and increased accident risk. Real-time traffic control by use of green–red traffic signals at the motorway mainstream is proposed in order to achieve safer merging of vehicles entering the work zone and, at the same time, maximize throughput and reduce travel delays. A significant issue that had been neglected in previous research is the investigation of the impact of distance between the merge area and the traffic lights so as to achieve, in combination with the employed real-time traffic control strategy, the most efficient merging of vehicles. The control strategy applied for real-time signal operation is based on an ALINEA-like proportional–integral (PI-type) feedback regulator. In order to achieve maximum performance of the control strategy, some calibration of the regulator's parameters may be necessary. The calibration is first conducted manually, via a typical trial-and-error procedure. In an additional investigation, the recently proposed learning/adaptive fine-tuning (AFT) algorithm is employed in order to automatically fine-tune the regulator parameters. Experiments conducted with a microscopic simulator for a hypothetical work zone infrastructure, demonstrate the potential high benefits of the control scheme.

1. Introduction

Work zone management aims at safe working conditions for work-zone workers, as well as safe and efficient passage of vehicles. An extensive report by the FHWA (2005) provides very useful insights on motivation, traffic management possibilities and impact. This paper addresses the sub-class of major motorway work zones, where one or more lanes need to be closed over a period of several days or months; as a consequence, the traffic flow approaching the work zone needs to merge from a higher number of lanes into a lower number of lanes within a limited space. When the arriving flow reaches or exceeds the reduced downstream capacity, congestion is created, leading to an additional, congestion-induced capacity drop; although the exact reasons for the occurrence of capacity drop have not been fully explored until now, a major

* Corresponding author. Present address: Traffic and Logistics Division, KTH Royal Institute of Technology, Teknikringen 72, 100 44 Stockholm, Sweden. Tel.: +46 8 7908891.

E-mail addresses: athina.tymp@gmail.com (A. Tympakianaki), natasa@dssl.tuc.gr (A. Spiliopoulou), tasos.kouvelas@gmail.com (A. Kouvelas), ipapa@dssl.tuc.gr (I. Papamichail), markos@dssl.tuc.gr (M. Papageorgiou), wangyibing@zju.edu.cn (Y. Wang).

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influencing factor is deemed to be due to the need for vehicles to accelerate from low speeds within the congestion to higher speeds downstream of the congestion head.

For example, referring to a tunnel bottleneck, it was found already 50 years ago that "*congestion inside the tunnel reduces its throughput. ... due to the fact that most cars do not accelerate very efficiently once they have to stop, or even just slow down*" (Gazis and Foote, 1969), see also the discussion in Papageorgiou et al. (2008)). Also, empirical field experiments carried out in Japanese motorways at sag bottlenecks indicate that the capacity drop is mitigated if drivers are alerted to accelerate promptly at the head of the congestion (Murashige, 2011).

In the past, several procedures and strategies have been proposed or used to improve traffic conditions at work zones, including speed limitations, as well as signing, markings and particular geometric design (see e.g. Lin et al., 2004; FHWA, 2005; Wei and Pavithran, 2006). More recently, real-time merging traffic control was proposed (Lentzakis et al., 2008), aiming at throughput maximization and minimization of delays in work zones in a similar way as the mainstream traffic flow control concept by Carlson et al. (2010), albeit by use of traffic lights instead of variable speed limits. As a matter of fact, mainstream traffic flow control was already applied in the late 1950s and 1960s to increase the throughput of the tunnels under the Hudson River, which connect New York City with New Jersey (Gazis and Foote, 1969). More recent work on mainstream traffic flow control is reviewed in Carlson et al. (2011).

This paper continues on the work of Lentzakis et al. (2008) and Papageorgiou et al. (2008) by improving and extending the related investigations, tools and insights in a number of ways which increase the chances of a successful field deployment of the method. To start with, an important issue that had been neglected in previous works is the impact of the positioning of the traffic lights when applying real-time traffic control. The distance between the traffic lights and the merge area is crucial as it affects the vehicles' behavior and particularly the acquired speed when approaching the merge area. It is shown in this paper that the appropriate location of the traffic lights may improve the results of merging traffic control, as the capacity drop can be mitigated or even eliminated in case of proper merging vehicle speeds, and this contributes to a more efficient and safe passage through the merge area. This aspect is farther highlighted by the inclusion of trucks in the simulation-based demonstration. In view of the potentially longer distance of the traffic lights from the merge area, the usage of a PI-type feedback regulator (in replacement of the previously used I-type regulator) is employed in this paper.

Another novel issue addressed, is the calibration of the employed regulator parameters for the applied control strategy by use of a recently proposed (Kosmatopoulos, 2009; Kouvelas, 2011; Kouvelas et al., 2011) automatic fine-tuning procedure (called AFT). Novel aspects in this respect include the usage of both Support Vector Machine (SVM) and polynomial, approximators within AFT, along with the comparison of the corresponding resulting tuning behaviors; as well as the specific fine-tuning results for simple PI-regulators and their set-points, along with the investigation of application conditions that ensure improved performance of the utilized control strategy. This fine-tuning investigation is, at the same time, an additional demonstration of the automatic fine-tuning capabilities of AFT, the relevance of which reaches beyond the present work zone traffic control application.

2. Work zone traffic control

2.1. Merge area

A typical motorway work zone area is sketched in Fig. 1a. The vehicles arriving on M lanes, must change lanes appropriately within the (typically trapezoidal) merge area (or earlier) so as to fit into the μ lanes of the exit (where M is higher than μ). The merging procedure may be quite complex in terms of the required vehicle maneuvers, especially when the traffic density in the merge area is high.

The capacity of work zone areas is usually lower than the mainstream motorway capacity due to the drop of one or more lanes at the work zone entrance. Fig. 1b displays a typical flow-density diagram for the merge area, where the flow q_{out} is the

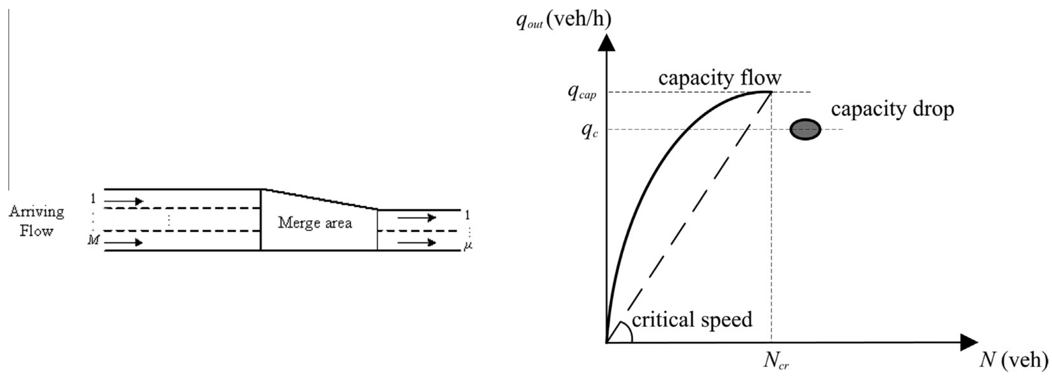

Fig. 1. (a) Typical motorway work zone area and (b) fundamental diagram of a merge area.