Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-32 (2016) 089–094

Cooperative Mainstream Traffic Flow Control on Freeways *

Eduardo R. Müller * Rodrigo C. Carlson * Werner Kraus Jr. *

* *Post-graduate Program in Automation and Systems Engineering, Federal University of Santa Catarina, Florianópolis-SC, 88040-900 Brazil (e-mail: edurauh@gmail.com; rodrigo.carlson@ufsc.br; werner.kraus@ufsc.br).*

Abstract: Mainstream Traffic Flow Control (MTFC) is a freeway traffic control method which aims to maximize throughput by regulating the mainstream flow upstream from a bottleneck. Using Variable Speed Limits (VSL) as actuators for MTFC, we study the effects of different penetration rates of automated vehicles on MTFC-VSL. Automated vehicles can be designed to be much more strict in complying with VSL, which leads to a better MTFC performance than with ordinary VSL. Simulation results show that higher penetration rates translate into better performance with a significant effect up to 30% penetration rate, and very little gains beyond that; and that mixing forms of applying VSL may be detrimental to traffic.

Keywords: Cooperative systems, freeway control, mainstream traffic flow control, variable speed limits, feedback control.

1. INTRODUCTION

The need for novel traffic management strategies in the late 1990s to tackle increasing congestion on freeways pushed the investigations on variable speed limits (VSLs) (Khondaker and Kattan, 2015a). Previous VSL traffic management strategies were mainly safety-oriented, or were designed without the proper knowledge on how traffic is affected by VSLs or with unclear objectives (Papageorgiou et al., 2008). Thus, these strategies had little or no effect on traffic efficiency, calling for new efficiency-oriented developments.

The VSL strategies proposed since then were developed covering a range of different control approaches and traffic application settings, see, e.g., Alessandri et al. (1998); Hegyi et al. (2005); Popov et al. (2008); Hegyi and Hoogendoorn (2010); Carlson et al. (2010, 2011, 2013); Zegeye et al. (2012); Iordanidou et al. (2014); Müller et al. (2015). Noteworthy are the SPECIALIST strategy (Hegyi and Hoogendoorn, 2010), which was tried successfully in the field, and Mainstream Traffic Flow Control (MTFC) via VSL (Carlson et al., 2010, 2011, 2013) as approached by Müller et al. (2015) that, when compared in microsimulation to three other reactive VSL strategies, had the best performance with respect to traffic efficiency (Grumert et al., 2016). In parallel, the lack of knowledge on the VSLs' effect on traffic triggered studies with field data, see, e.g., Papageorgiou et al. (2008); Heydecker and Addison (2011); Duret et al. (2012); Kianfar et al. (2015), to cite just a few, that substantiated some of these developments. Most studies investigated the homogenization effect of VSLs and/or its capability to serve as a metering device, the latter being the subject of controversies (Soriguera et al., 2015).

One relevant aspect for the success of VSL control strategies is driver compliance to the posted VSLs (Harms and Brookhuis, 2016). Compliance rates may be extremely low in case of familiar routes (Harms and Brookhuis, 2016) and in roads in general, except for road sections with radar enforcement (Soriguera et al., 2015; Riggins et al., 2016). Hegyi et al. (2005), for example, proposed a model predictive control approach in which the traffic model incorporates a noncompliance factor. However, the factor is fixed and may diverge from the noncompliance rates on the road depending on the traffic conditions or traffic composition. In the case of feedback-based MTFC via VSL (Carlson et al., 2011, 2013; Iordanidou et al., 2014; Müller et al., 2015) low compliance may be compensated by the feedback controller that may further reduce the posted speed limit until the desired average speed is achieved. Still, a lower bound for the speed limit exists and may be eventually reached if the compliance rate is too low, i.e., the controller may saturate.

The advances in vehicle automation and communication systems (VACS) are paving a new way for traffic management systems (Roncoli et al., 2015). In the particular case o VSL-based systems, new speed limits could be transmitted directly to the vehicle, speeding traffic response to the commanded VSL. Moreover, the speed limits could be even imposed, circumventing the problem of compliance to the posted VSLs. As a matter of fact, many VSL strategies benefiting from VACS or cooperative systems or vehicle-infrastructure integration have been proposed, see, e.g., Hegyi et al. (2013) (based on the SPECIALIST strategy); Kattan et al. (2015); Khondaker and Kattan (2015b); Roncoli et al. (2015, 2016); Davis (2016); Grumert et al. (2015). However, none was based on the MTFC approach, although Müller et al. (2015) investigated what could be

* The authors were funded by CNPq-Brasil.

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.12.195

considered an in-car speed advice system-based MTFC with full penetration.

This paper is a follow-up of the work by Müller et al. (2015). In this paper, we further investigate MTFC in a microscopic traffic simulator, now with the presence of automated vehicles and vehicle-infrastructure integration. The speed limits are provided by a feedback control law and are imposed to the automated vehicles following the MTFC concept. Several penetration rates of equipped vehicles are considered combined or not with traditional VSL signs. Results indicate that the MTFC concept is suitable in this context and that efficiency improvements may be obtained even for a relatively low penetration rate.

In the next section we review the basics of mainstream traffic flow control and the details of our approach. In Section 3 we present how the simulations are conducted. The simulation results are presented in Section 4. Finally, Section 5 concludes the paper.

2. MAINSTREAM TRAFFIC FLOW CONTROL

2.1 The MTFC concept

Mainstream Traffic Flow Control (MTFC) (Carlson et al., 2010) is a traffic management approach for freeways which aims to maximize freeway throughput. The mainstream traffic flow is reduced upstream from a bottleneck where a controlled congestion is induced in order to avoid (or mitigate) congestion and the related capacity drop at the bottleneck location, a phenomenon by which the freeway operates below capacity after onset of congestion.

VSL may be used as an actuator to implement MTFC because lower speed limits induce lower capacity flows (Papageorgiou et al., 2008). The area subject to VSL is the *application area*. Since vehicles may leave this area with low speeds, the *application area* must be sufficiently upstream of the bottleneck to allow for vehicles to reach a suitable speed at the bottleneck so as to avoid the capacity drop. We denote the section between the *application area* and the bottleneck as the *acceleration area*.

2.2 Feedback MTFC

We can implement MTFC with a feedback control law that regulates occupancy at the bottleneck by controlling the speed limit upstream of the bottleneck (which affects mainstream flow). We define $0 < b \leq 1$ as the ratio of the current speed limit and the nominal (maximum) speed limit of the freeway. Let $o(k)$ be the occupancy measured by a suitable detector at the bottleneck at time instant k. We denote the occupancy reference as $\hat{o}$, and the occupancy error as $e_{\mathrm{o}}(k) = \hat{o} - o(k)$. We can calculate a VSL rate b at time instant k with an integral regulator given by:

$$b(k) = b(k-1) + K_{\mathrm{I}} \cdot e_{\mathrm{o}}(k) \qquad (1)$$

with K_{I} a gain. The set-point $\hat{o}$ is typically chosen around the critical occupancy, a value to which corresponds the freeway capacity flow.

The speed limit/flow relation is highly non-linear, rendering the linear regulator (1) inadequate. Therefore, we can use gain scheduling for choosing K_{I} according to the system operating point. For more details on the modeling process and control structure, see Müller et al. (2015).

2.3 Ways of applying VSL

An important aspect affecting the system dynamics is the form of applying VSL (Müller et al., 2015):

- In Point level VSL (P-VSL), vehicles adjust their speed when passing by the VSL sign and maintain this speed until a new sign indicates a different speed limit further downstream. Hence, with P-VSL a change in the speed limit affects only vehicles arriving at the application area with no effect on vehicles already inside it.
- In Section level VSL (S-VSL), the VSL is applied to a whole freeway section; i.e., all vehicles within the application area immediately adjust their speeds to the new speed limit. This could be implemented with vehicle-infrastructure integration, allowing vehicles to receive the speed limit and display it to the driver or even adjust the speed without the need for human interference.

Generally speaking, traffic under S-VSL responds faster to speed limit changes than when under P-VSL. In addition, P-VSL can create undesirable transitory effects, such as a temporary “void” of vehicles. For more details, see Müller et al. (2015).

Besides P-VSL and S-VSL, we now consider the case of Cooperative VSL (C-VSL) [1]. With C-VSL we assume the control system is capable of transmitting speed limits directly to the vehicles on the road via vehicle-infrastructure integration. The vehicles are assumed automated.

The proposition of C-VSL raises a series of questions related to the presence of both automated and conventional vehicles on the same road. More specifically, we are interested in studying how different penetration rates of automated vehicles in traffic can affect MTFC, i.e.:

- How different penetration rates of automated vehicles affect MTFC performance when we use C-VSL as an actuator for MTFC?
- Considering a scenario in which only a portion of vehicles are automated, if the automated vehicles follow C-VSL and the non automated vehicles follow P-VSL (as this is the most common form of applying VSL), how is MTFC performance affected?

3. SIMULATION SETUP

A simple hypothetical freeway stretch was used to evaluate the effects that different proportions of vehicles following VSL have on traffic. Simulations were conducted using the Aimsun microscopic traffic simulator (Transport Simulation Systems, 2015) and it’s API to implement VSL.

3.1 Freeway layout and traffic demand

Figure 1 illustrates the layout of the simulated freeway stretch, which is the same as the one used in Müller et al.

[1] Not to be confused with C-VSL in (Grumert et al., 2015) which proposes a similar idea but a different approach.