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Intersection Control and MFD Shape: Vehicle-Actuated versus Back-Pressure Control

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Abstract: Various studies have demonstrated that the state and dynamics of an urban network can be described by Macroscopic Fundamental Diagrams (MFD) and that MFDs can be used for perimeter flow control. Perimeter flow control aims at a higher throughput in an urban network by controlling the flow at the boundaries of sub-networks.

For perimeter flow control it is desirable that the MFD has a favourable and consistent shape, independent of fluctuations in traffic demand and of intersection signal variations. From literature it is known that a consistent shape is related to the homogeneity of vehicle accumulation in the sub-network. However, also the signal controller type may influence homogeneity and the MFD shape.

In this paper we investigate the relationship between the type of intersection control and the shape and scatter of the MFD, and the homogeneity of the subnetwork, for Vehicle-Actuated (VA) and Back-Pressure (BP) control. The comparison of the two control methods is performed by means of microsimulation.

The results show that for both control methods the free-flow branch of the MFD has a low scatter with an average relative deviation around 2%. The congested branch shows a much larger deviation, 15% for the Vehicle-Actuated control, 16% for the Back-Pressure control. Furthermore, there is a distinct difference in the shape of the MFDs: for VA control the production increases faster as function of the accumulation than for BP control, but the network breakdown starts at a lower accumulation. So, based on the simulation results, VA control is better in undersaturated situations, and BP is better at higher accumulation levels.

Keywords: Urban Traffic Control, Macroscopic Fundamental Diagram, Vehicle-Actuated Control, Back-Pressure Control, Microsimulation

1. INTRODUCTION

The traffic state and the dynamics of an urban network can be described by a Macroscopic Fundamental Diagram (MFD), as has been demonstrated in many studies, see e.g. Daganzo (2007), Geroliminis and Daganzo (2008). The MFD describes the space-mean flow (internal production or the outflow) in a network as function of the network vehicle density (accumulation of the traffic). In general, the MFD has is bell-shaped: in free-flow (undersaturated) conditions the production increases as the accumulation increases, as a results of an increase in traffic demand. This production increase continues up to a certain point (the critical accumulation), after which it stagnates due to saturation of the network. If the accumulation increases further, the production starts to decrease, this is the congested (oversaturated) branch of the MFD. At a certain point the network is no longer able to accumulate more traffic and the network density remains constant. The main reason for the decreasing production for increasing accumulation is the blocking back of the queues in the network (possibly leading to a gridlock in more severer cases).

The predictable shape of the MFD makes it a suitable concept for network control, where the network is divided into sub-networks, and the flow between the sub-networks is controlled. The MFD is used to describe or predict the resulting or expected flows in the subneworks. This type of control is called perimeter flow control (Aboudolas and Geroliminis (2013); Geroliminis et al. (2013)). Given this context, we investigate in this paper the relation between the intersection signal control type and the shape and scatter of the MFD.

Often the MFDs found in literature are determined by actual traffic data obtained from existing urban networks and therefore based on one specific type of control. It is an open question how the shape and scatter of the MFD depends on the type of control used. Buisson and Ladier (2009) have demonstrated that the homogeneity of the traffic measures have a large impact on the shape of the MFD. As one type of control might be better in distributing the traffic over the network by generating less scatter in the MFD. In Zhang et al. (2013) it has been demonstrated that also for simulation networks, using SCATS and self-organising control, well-defined MFDs exist. They concluded that the traffic signal system plays

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a crucial role in the network performance, with a higher network capacity and higher flows for the self-organising control. Ramezani et al. (2015) and Zhang et al. (2013) also demonstrated that homogeneity of the traffic distribution has impact on the shape of the MFD. From literature, it is also known that hysteresis loops can occur in the MFD as a consequence of inhomogeneities. For these reasons, it is worthwhile to investigate how a controller influences the shape and scatter of the MFD.

In this paper two types of signal control are investigated and compared: Vehicle-Actuated (VA) control and Back-Pressure (BP). Vehicle-Actuated signal control Viti and van Zuylen (2010) is a control method frequently applied in practice. Its main feature is that based on the presence of absence of vehicles on certain approaches, it can skip or extend green phases. This leads to a flexible, and in many cases efficient signal control. Back-Pressure (BP) control (Wongpiromsarn et al. (2012); Varaiya (2013)) is a (currently) theoretical approach, which has no pre-defined signal control cycle, but it prioritizes the (combination of) movements where the upstream queue is long and the downstream queue is short. This type of control is particularly interesting, because it's control concept may lead to a more homogeneous distribution of queues, and because there exists a theoretical proof of optimality under certain conditions Wongpiromsarn et al. (2012).

In this paper, MFDs of both VA and BP control are analysed and compared by means of microsimulation. The objective is to evaluate the two control methods for their potential suitability for combination with an MFD-based perimeter controller. To this end, not only the heigh (production) of the MFD will be considered, but also it's scatter and possible hysteresis. The organisation of the paper is as follows. In Section 2 the two controllers are shortly described, in Section 3 the performance indicators are defined, and in Section 4 the case study is described. In Section 5 the results obtained from the simulations are discussed, and in Section 6 the conclusions are given.

2. INTERSECTION CONTROLLERS

2.1 Vehicle-Actuated control

Vehicle-Actuated (VA) control uses control schemes with a structure that combines non-conflicting streams (movements over the intersection) in successive stages. A complete cycle combines two or more stages. The structure is fixed, meaning that in every cycle the same stages are passed. The control is actuated by the vehicles observed by detectors. The green time of a stream that has traffic in an "active" stage (i.e. the combination of streams that can be granted green) is started and continued for a minimum green time, or until the queue is dissolved, or a prescribed maximum green time is reached. A stream in an active stage is skipped if no vehicles are detected at the start of the stage. The transition between the stages is flexible: if a stream in the active stage stops, streams in the next stage that had conflict with this stream can start provided they have no conflict with the remaining active streams of that stage.

2.2 Back-Pressure control

The Back-Pressure (BP) controller is based on the algorithm described by Wongpiromsarn et al. (2012). For this controller the queue length is measured for every stream, and the 'pressure', i.e., difference between upstream and downstream queue is determined. Every control time interval the pressure of all combinations (phase combination) is calculated. The pressure for phase combination p is defined as:

$$S_p(t) = \sum_{L_a, L_b \in p} (Q_a(t) - Q_b(t))\xi(p, L_a, L_b, z(t)) \ . \tag{1}$$

$Q_a(t)$ and $Q_b(t)$ are the queue lengths, at the current intersection and the downstream intersection respectively, and $\xi(p, L_a, L_b, z(t))$ is the saturation flow of the stream from link L_a to link L_b, which may depend on the properties of links L_a and L_b, the given phase combination p, or some time-dependent conditions $z(t)$. The phase combination of streams with the largest pressure is made active in the next time step. Since the pressure of phase combinations vary from interval to interval, there is no fixed structure as in the case of VA control.

If a stream is present in this phase combination and in the next phase combination, its green is continued: if the stream is not present in the next stage, its green is ended.

Note that, for the sake of simplicity, we will investigate the orignal BP algorithm, while various variasions of the original BP method exist. For example, an adaptation in the BP method is made by Zaidi et al. (2015), where adaptive routing is introduced to the BP algorithm.

2.3 Qualitative differences

Due to the qualitative differences of the two control methods, different MFD shapes can be expected, which may have consequences for the application of these control methods in the context of perimeter control.

First, VA control extends green until the queue is resolved or the maximum green time has been reached. This will often release the current queue, but may cause a queue buildup at conflicting streams that have red. Opposed to this, BP control may end a green phase even if there is still a queue present, if there is another queue (or more precisely, phase combination) that has a higher pressure. It can be expected that this leads to higher queue length fluctuations possibly leading to blocking back or a gridloc, in case of VA control compared to BP control. On the other hand, BP control will lead to more homogeneously distrubuted queue lengths.

Second, VA control does not take into account the downstream queue (or space) when deciding about green times. This may lead to an extended green (due to an unresolved upstream queue), while there is no space anymore in the downstream link. This obviously leads to blocking back.

Third, in the case of BP control, if two conflicting phase combinations have a (nearly) equal pressure, then the algorithm will keep switching between the two, alternatingly reducing the pressure. This frequent switching may be inefficent if a (delay) cost is associated with it. Note that in the optimality proof of BP, switching cost is not taken into account.