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Salomons, A. Maria; Hegyi, Andreas

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

A. Maria Salomons * Andreas Hegyi

* Delft University of Technology, Transport & Planning, P.O. Box 5048, 2600 GA Delft, the Netherlands, (e-mail: a.m.salomons@tudelft.nl)

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.

3. PERFORMANCE INDICATORS

To systematically evaluate the signal controllers in terms of resulting MFDs, various performance indicators are defined. Regarding the shape and scatter of the MFD the following features will be determined:

(1) the overall MFD shape: the production as a function of the accumulation,
(2) the maximum production and the corresponding accumulation (the critical accumulation),
(3) the accumulation at which the network break down occurs (where the production starts to decrease with increasing accumulation),
(4) whether there is a possible hysteresis loop,
(5) the scatter of the free-flow and congested branches of the MFD.

To determine the scatter the average relative deviation (in percentage) is taken:

$$\gamma^{\text{ARD}} = \frac{100}{N} \sum_{n=1}^{N} \frac{\sigma(n)}{\mu(n)} \,. \tag{2}$$

where $\mu(n)$ and $\sigma(n)$ are the mean and standard deviation of the MFD at accumulation n, where N is the number of accumulation points in the branch. The MFD is denoted as $P_{s,d}(n)$: the production P as function of the accumulation n for simulation s, at data point d. At accumulation n there are $m(s)$ observations for simulation s, and there are S simulations, so in total $M(n) = \sum_{s=1}^{S} m(s)$ data points. The average $\mu(n)$ and standard deviation $\sigma(n)$ at accumulation n are then calculated as:

$$\mu(n) = \frac{1}{M(n)} \sum_{s=1}^{S} \sum_{d=1}^{m(s)} P_{s,d}(n) \,, \tag{3}$$

$$\sigma(n) = \sqrt{\frac{1}{M(n)} \sum_{s=1}^{S} \sum_{d=1}^{m(s)} (P_{s,d}(n) - \mu(n))^2} \,. \tag{4}$$

The homogeneity of the network is determined as the spread of the density (similar to the definition in Knoop et al. (2015)). Since the intersections are equidistantly spaced, the spread of the density can be determined from the standard deviation of the queues at the stop line:

$$\gamma_X = \sqrt{\frac{1}{N} \sum_{x \in X} (l_x - \bar{l})^2} \,, \tag{5}$$

where l_x is the queue length in region x (here the region is defined as all links that are part of an intersection) and $\bar{l}$ the average queue length.

4. SIMULATION SET-UP

The two controllers were analyzed by simulation, using the microsimulation tool VISSIM 5.40 with default settings. In this section the details of the simulation set-up are given.

4.1 Network

The network has, for simplicity reasons, a grid-like structure. It consists of sixteen equidistant intersections, with each intersection consisting of four approaches with three controlled streams per approach (see Fig. 1). The intersections are 400 m apart, at 200 m before the intersection the single approach lane splits in three turning lanes for each stream. The number of intersections is chosen based on a trade-off between the expected scatter of the MFDs (fewer intersections will result in more scatter) and the duration of the simulation (more intersections will lead to unacceptable simulation time). Each stream has its own traffic signal.

4.2 Traffic demands

The traffic consists of passenger cars only, which can enter and leave the sub-network at the perimeter only, there are no sources or sinks within the network. The OD-matrices for the traffic input are designed such that the traffic demand per intersection is comparable. As shown in Fig. 2 two traffic demand patterns were chosen such that they result in qualitatively different MFDs. As found from the simulation, the maximum traffic demand that the network could accomodate was 1050 veh/h per network entrance, so the demand patterns were chosen lower than or equal to this flow.

The simulation duration is 9000 s. The simulations are run for the same traffic demand with three different random seeds, to include stochasticity in the simulation.

4.3 Application of the Vehicle-Actuated Controller

The order of the control stages, i.e., the order in which a group of parallel signals receives green, is pre-set according to Fig. 3. For the actuation of the control, two detectors per lane are available, at 2 m and 60 m upstream of the stop line.

The minimum green time is set to 6 s. The maximum green duration is limited such that the cycle time does not exceed the maximum of 120 s. The intergreen time between successive conflicting signals is the yellow time of 3 s.

4.4 Application of the Back-Pressure Controller

The BP control has a control interval of 12 s (the minimum green time of 9 s plus the yellow time of 3 s), and in each control step it is determined whether a new phase should be granted green, or that the current one should be continued. The decision for the new phase is made by determining the pressure for all possible combinations of non-conflicting phases for the simulated intersection lay-out. In this case, a phase combination can consist of two, three or four streams. The pressure is calculated according to Eq. 1, where $\xi(p, L_a, L_b, z(t))$ is set to fixed saturation flow values (1800 veh/h/lane for through going, 1530 veh/h/lane for right turning, and 1715 veh/h/lane for left turing traffic, in accordance with the saturation adjustments given in HCM (2000)). Since every stream is controlled by its own signal, the pressure of all possible phase combinations can be determined unambiguously. Also for this controller the intergreen time only consist of the yellow time.

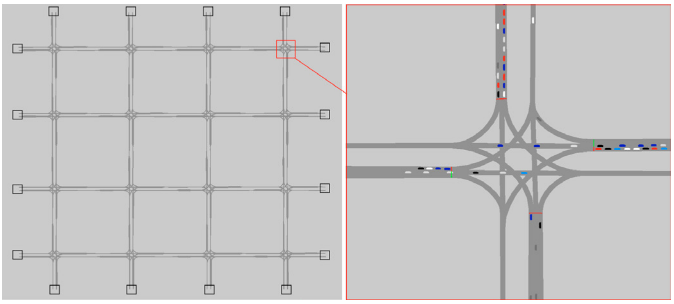


Fig. 1. VISSIM grid network of 16 equidistant intersections with 4 approaches per intersection, and three streams per approach

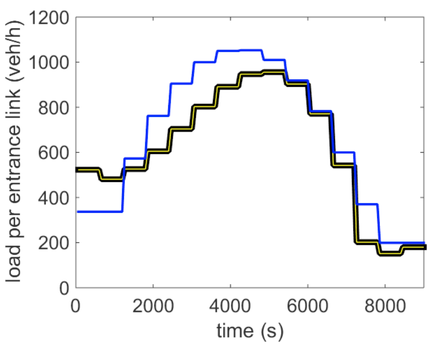


Fig. 2. Two types of traffic demand variation at the entrance links (veh/h/link), yellow/black line: traffic demand 1, thin blue line: traffic demand 2)

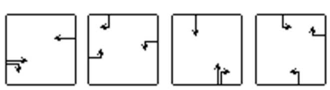


Fig. 3. The successive stages of the VA control

4.5 Measurements in the network

The accumulation and flows are determined by the measurement locations at the entrance and at the exit links, and between intersections just before the lane splits into the auxiliary lanes. The measurements are taken per second, and by VISSIM translated into the number of cars that have passed during this time interval. The flow is aggregated to a level of 1 minute, in addition, the MFD is determined as running mean with a time window of 1 minute.

The queue measurements are used for both the BP algorithm and for homogeneity determination, and are measured for every stream, starting from the stop line, and including in upstream direction only vehicles with speed less than 10 km/h.

5. RESULTS AND DISCUSSION

Based on the MFDs found in the experiments, in Table 1 an overview of the the maximum production, maximum accumulation, and the critical accumulation is given. From this table it can be seen that the maximum production is comparable for the two demands and both controllers. The maximum accumulation is lower if VA control is used, and the critical accumulation is also found to be lower, which suggests that blocking back and gridlock occurs at a lower accumulation for VA than for BP control.

Table 1. MFD values

	demand 1	demand 2
max. Prod. VA (veh/h)	686	702
max. Prod. BP (veh/h)	698	724
critical Acc. VA (veh)	1281	1378
critical Acc. BP (veh)	1679	1905
max. Acc. VA (veh)	1650	2521
max. Acc. BP (veh)	2091	2845

In Fig. 4a the MFDs are depicted when VA control is used with traffic demand 1. When the traffic demand at the network entrance starts to decrease, the production still decreases, until for a certain accumulation the production increases again. This happens at the moment that the congested area can release its traffic after a (near) gridlock. The production increases, but since the entrance traffic demand decreases again, the production stays level, until the curve coincides with the MFD curve at the start.

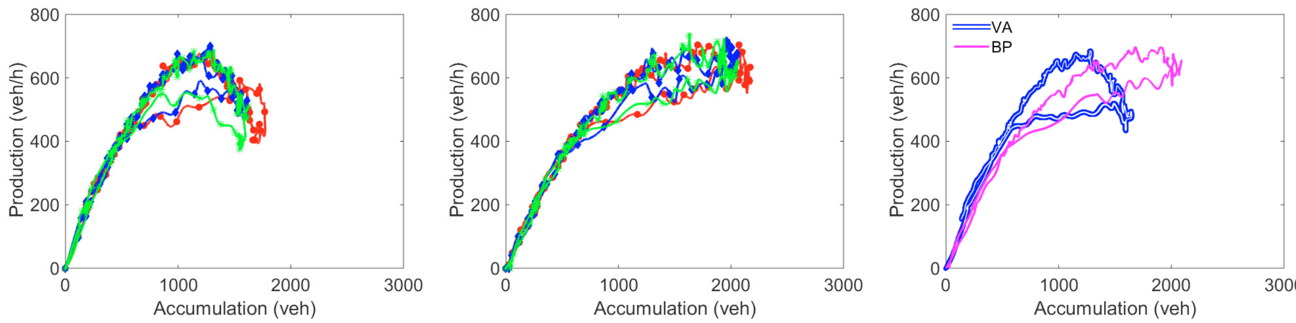
In Fig. 6a one of the simulations is displayed separately, because its hysteresis loop is remarkable, namely anti-clockwise. In the simulations of Zhang et al. (2013) also anti-clockwise hysteresis loops in MFD patterns were found and were explained from non-uniform loading. In the current research this anticlockwise hysteresis loop is not a consequence of non-uniform loading, but of non-uniform distribution of the traffic over the links. In VA control, a long queue can be dissolved quickly if a gridlock dissolves and the green time is extended, resulting in a larger production.

In Fig. 4b the MFD is given when the BP control is used for traffic demand 1. For this traffic demand pattern the production stays near maximum level, until the production reduces due to a reduction of the traffic demand. The congested branch shows a slight hysteresis.

In Fig. 4c the mean MFDs for VA and BP control are compared. It is noticeable that for lower accumulation levels the production is higher for the VA control than for the BP control, but if the accumulation increases the network break down is at a lower accumulation than for BP. This suggests that VA is more efficient for lower accumulation levels (most likely due to less frequent switching), but suffers from blocking back and gridlocks already at lower accumulation levels than BP.

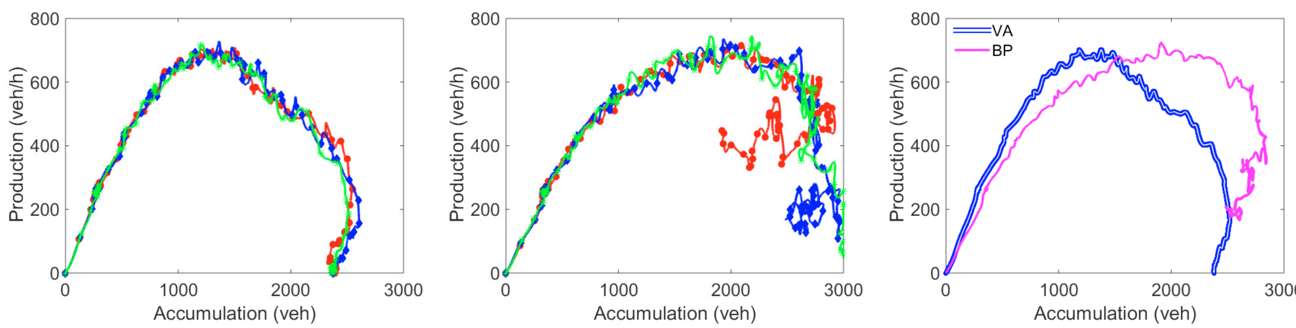
In Fig. 5a the MFD for VA control for traffic demand 2 is given. Also here the production starts to drop already when the traffic demand is not yet reducing. The production decreases until a gridlock occurs that is not resolved. The maximum production occurs roughly at the same accumulation for both demands. In Fig. 5b the MFD for BP control for the same demand is given. In this situation the production of the BP controlled network starts to collapse at a clearly higher accumulation than for VA control. Also in this case the maximum production and the critical accumulations are the same for both demands.

For the free-flow branch the Average Relative Deviation of the MFD curve is about 2% for both VA and BP controllers. The scatter is larger in the congested branch, about 15% for VA and 16% for BP.



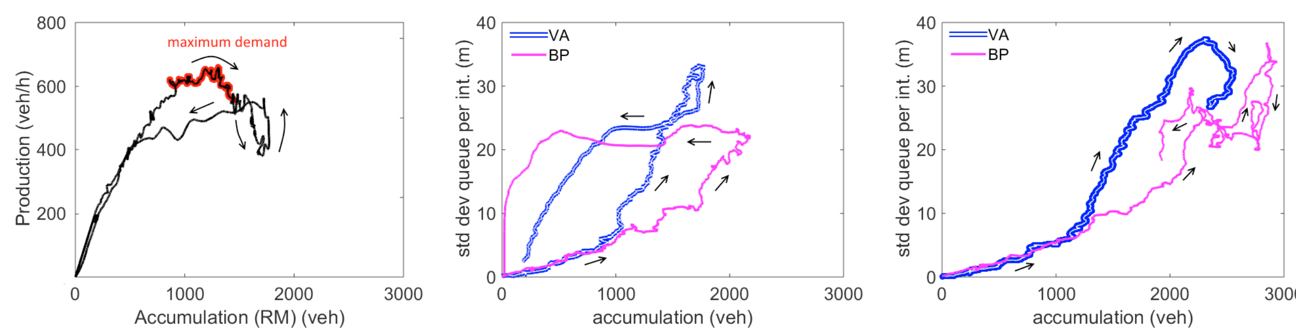
(a) VA control (b) BP control (c) average MFD

Fig. 4. Traffic demand 1, left/middle:MFD for three different seeds, right: average MFD



(a) VA control (b) BP control (c) average MFD

Fig. 5. Traffic demand 2, left/middle:MFD for three different seeds, right: average MFD



(a) MFD VA control (b) deviation queue length, demand 1 (c) deviation queue length, demand 2

Fig. 6. Left: MFD for VA control, arrows indicate the progress over time. Middle and right: Deviation of queue length

MFD compared for VA and BP control If the MFD for the VA control is compared to the MFD for the BP control, it appears that critical accumulation is lower for VA than for BP. On the other hand, in free-flow situation, the production increases quicker with accumulation for VA than for the BP control.

The reduced slope for BP can be explained from the timing of the control: the control interval combined with the minimum green time settings leads to unused green time. Once a phase is started, it will remain green for 9 s, which can be too long in the free-flow situation. Only after the control time is expired, a new set of phase combinations is started. However, if the minimum green time and control interval are made smaller, the number of switches during a cycle, and hence the lost time, will increase. Further research should focus on the control interval and minimum green time used for BP.

Considering VA control, the setting of the maximum green time can play an important factor in the occurrence of gridlock situations. If a queue is long, the green time will be prolonged, whether or not the traffic can proceed, which can result in gridlock on the intersection. Also conflicting directions will be affected, because their queues will increase during their prolonged red time, which can result in blocking back.

BP control can achieve higher production at higher accumulations, which is likely due to the fact that it distributes the traffic more evenly over the network.

Homogeneity of the traffic distribution In Figs. 6b and 6c the deviation of the average queue length is given for demands 1 and 2 respectively. As can be seen, the standard deviation of the queue length for VA control is generally higher than for BP control, which suggests that VA control tends to result in blocking back and gridlocks starting from a lower accumulation. Comparing Fig. 6b with Fig. 4c, and Fig. 6c with Fig. 5c respectively, suggests that the earlier breakdown of the network performance with the VA controllers (at a lower accumulation) is related to the earlier blocking back and gridlocks.

6. CONCLUSION

A comparison was made between intersection control, with either the VA or BP method, analysed in terms of their effect on the MFD. The scatter and maximum production is found to be comparable for both types of control. However, the simulation results also show that VA control is more efficient (in terms of production) for low accumulation levels, when there is no risk of blocking back (due to fluctuating queue lengths). At higher accumulation levels, the production for the BP controller is higher, and the results suggest that this is due to the favourable property of BP that it distributes queues more evenly over the network (and thus prevents blocking back and gridlock). Therefore in a context of perimeter control the preferred control method depends on the accumulation levels, and best performance a favourable combination of the two methods should be sought as a generic solution.

Since various control parameters (such as min/max green times, control time step) in VA and BP may influence the occurrence of blocking back or gridlocks, a wider range of scenarios should be investigated regarding the influence of these parameters on the shape of the MFD. Also a combination of VA and BP can be investigated as proposed by Kouvelas et al. (2014) where after each cyle the green split is determined by the BP method.

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