The Effect of Signal Settings on the Macroscopic Fundamental Diagram and its Applicability in Traffic Signal Driven Perimeter Control Strategies

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***Abstract*— It has been proposed that a macroscopic fundamental diagram (MFD) can be used as input for perimeter control strategies. We consider a network consisting of a perimeter with traffic lights and a subnetwork without traffic lights. The MFDs for the two parts, i.e. the controlled subnetwork and its perimeter, are determined by means of microsimulation.**

We found that different signal settings change the shape of the MFD for both parts considerably. Also the ratio between the performance of the subnetwork and the corresponding perimeter is often fairly constant regardless of the signal timings. Thus, metering traffic heading towards the subnetwork is not always a good control strategy, as the performance of the subnetwork is eventually affected in the same way as the performance of the perimeter. Furthermore it has been found that the shape of the MFD of the perimeter, including the critical network density, strongly depends on the signal timings. It is therefore concluded that the MFD is difficult to use for control strategies aiming to adapt signal timings, because the changed signal timings themselves will result in a different value for the critical network density.

I. INTRODUCTION

Urban traffic congestion is one of the major sources of delay in vehicular traffic. Modern IT techniques allow for large quantities of data to be collected, and for coordination of traffic control measures. However, computation time and stochasticity of the traffic models form a problem in control optimization schemes for larger areas and longer time horizons. As such, different tools are needed to control large networks in an effective way, without the need for highly complex algorithms. One of the more promising tools is the macroscopic fundamental diagram (MFD), relating the average flow (or production) and average density (or accumulation) of a network to each other[1], [2]. The resulting shape is mostly concave, implying that network output is maximized when a fixed number of vehicles can be maintained in the network.

One of the methods proposed to maintain a steady amount of vehicles in a network is perimeter control [2]. Within this control strategy, traffic signals on the boundary of a network (or part thereof) are used to keep the amount of vehicles in that network constant, by either reducing or improving the flow from the perimeter to the subnetwork, or vice versa. Although current work shows promising results, the way in which traffic on a controlled perimeter interacts with the underlying subnetwork and how this affects the shape of the MFD remains unclear.

The interaction between the controlling and the controlled part of the network can become an important factor when developing and executing network control strategies. This because a strong relation between the two should theoretically exist, as changing the signal timings could lead to spill-back in either the controlling or the controlled part of the network, eventually blocking upstream intersections, hampering flow or even the control strategy itself. This implies that a relation between the two network parts exists and that an optimal signal plan can be found, for which the total network output is maximized. However, it has not been investigated what type of control strategy generates the best results. In [3] and [4] it is assumed that in applying a perimeter control strategy (or gating), the amount of traffic in the subnetwork should be kept at an optimum and that inflow to the subnetwork should be regulated on the perimeter. Looking at real-life (heterogeneous) networks, jams are most commonly found on arterial roads and not within the subnetworks. This then implies that controlling the amount of traffic within the arterial, by limiting the inflow from the subnetworks should lead to better results than vice versa.

Research has shown that the way in which a network is controlled affects the shape of the MFD. However, the exact manner in which the MFD changes, has not been investigated in-depth. A more thorough understanding of this relation is important, as it can have an impact on the way a network can be controlled. Therefore, in this paper we will investigate how a change of timing of the traffic lights at the perimeter influences the MFD. Two types of perimeter control will be studied: (1) decreasing the inflow into the subnetwork and (2) increasing the outflow out of the subnetwork. Both control strategies theoretically should lower the accumulation in the subnetwork and might improve production. We will focus on the effects that changes in signal timing have on the traffic operations in both the subnetwork and perimeter itself.

The goal of this paper is to provide more insight in the way the shape of the MFD is affected when signal timings are changed and what the effect of different control strategies is. To this end, a short review of the work done with respect to the MFD is treated in section II. Subsequently, the methodology and set-up of the experiment will be discussed in section III, followed by an overview of the results from the experiment in section IV, which are then discussed in

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section V. This paper will close with a conclusion in section VI.

II. LITERATURE REVIEW

The first time a macroscopic relationship between average flow and density has been proposed, was in 1969 [5]. In the past century, a number of researchers have tried to improve on the proposed theory using simulation[1], [6] or real data[7], [8]. This subject has been reintroduced in [2], where it was used as a part of an urban traffic dynamics model. A theoretical relationship between the accumulation and the exit flow (number of vehicles leaving the network) was formed, called the exit function. Geroliminis and Daganzo[9] showed, using data for the city of Yokohama, that this exit function, relating average density and flow indeed seems to exist on a network level and was named the macroscopic fundamental diagram. Further proof of the existence of the MFD was given using real data for Toulouse [10] and model results for Amsterdam respectively[11].

The effect of signal settings on the shape of the MFD was first shown in [12], in which variational theory is used to mathematically predict its shape. This work was extended by incorporating different signal cycles[13] , offsets and street lengths and determined their effect on the MFD. It was found that an optimal range for different combinations of signal timing and offsets exists and that "bad" offsets can have a serious impact on the production of a network. Using a Cellular Automaton Model, the same results were found [14]. Helbing [15] presents an utilization-based formulation, creating a relation between the average network density and signal settings, showing that the shape of the MFD relies on the way in which signals are configured. Zhang et al. [16] made a comparison between the MFDs of an arterial road network, governed by different types of adaptive signal systems. Simulations using different signal systems, resulted in differently shaped MFDs, again showing that the shape of the MFD is affected by the chosen control method.

Application of the MFD in perimeter control, as suggested by [2] was first investigated in [3], which applied the theory to the downtown city center of San Francisco using a model. This whole network was modeled as a single reservoir in which the demand, generated at the boundary, was restricted in such a way that the accumulation within the network was maintained as close to the optimal value as possible. In Geroliminis et al. [17] the MFD is used in a two-region system, governed by a perimeter control strategy. Results of a case-study showed that using an estimated MFD and MPC, improvements of 20 percent over a greedy control strategy (using local optimization) could be obtained. [4] uses the MFD as input for a feedback gating algorithm, in which traffic signals are used to keep the amount of traffic in a part of the network at such a level, that output can be maximized. Reductions in delay in the order of 35 percent were achieved.

In summary, we find that literature either describes how the MFD changes within a network if traffic light settings are changed, or focusses on how the average flow (production, see equation 1 changes if traffic is metered at the perimeter.

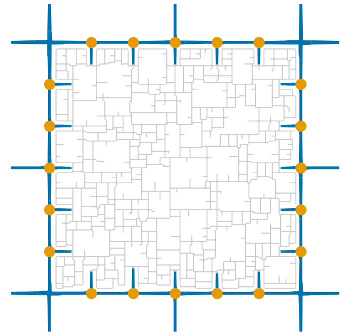

Fig. 1. Network used in simulation

This paper combines both research ideas and investigates how perimeter control, applied via traffic light settings at the arterial around the subnetwork, influences the MFD of the subnetwork.

III. METHODOLOGY

This section describes the methodology. The first part (section III-A shows how the basic situation is set-up. Section III-B then discusses the way we will test the effect of different traffic light settings.

A. Simulation set-up

1) Simulation environment: In order to gain more insight in the effect of signal timings on the shape of the MFD, a controlled environment is needed, in which all data can be measured. Hence, we use a microscopic dynamic simulation model. We choose VISSIM in particular, as it has a detailed node model, making it possible to study the traffic process at intersections and the effect of different signal timings on the shape of the MFD in-depth. Apart from that, signal timings can be set for each intersection individually, creating heterogeneous (and thus more realistic) conditions.

2) Network and OD matrix: As input for the simulation, a fictional network is used, measuring 3x3 kilometers and consisting of two parts, the subnetwork and arterials. For the sake of simplicity, we reduce the network to a single perimeter (the surrounding arterial) and a single subnetwork (the inner part), see figure 1. The perimeter consist of an arterial road with traffic lights. A fixed signal scheme is calculated for each intersection individually, using the method developed by Muller [18]. In the subnetwork, roads have one lane per direction and there are no traffic lights.

The OD-matrix is generated randomly and the number of lanes for links on the perimeter and signal schemes are dynamically matched to the corresponding flows, creating a network capable to accommodate the assigned traffic. The layout of the subnetwork is randomly generated.

3) Reference MFD: In order to obtain a reference MFD, simulations are carried out using different traffic loads and patterns. For each link in the network, speed, flow and density are obtained at a 5-minute interval. Traffic is loaded into the network over a period of 2 hours. The simulation is stopped if the network is empty or in gridlock (90 percent of vehicles in the network has not changed link over the last interval). In case the network ended empty, the number of trips in the network is increased. When ended in gridlock, the number of vehicles is decreased. This process is repeated iteratively, until a full MFD ranging from free flow to complete gridlock, is created.

The resulting data are presented in the MFD, in which the network production is related to the average network density. Production and average network density at a given time T are the weighed sum of the flow q and density k of all links i in network Z, with length l and are calculated as

$$P_T = \frac{\sum_{i \in Z} q_{i,T} l_i}{\sum_{i \epsilon Z} l_i} \tag{1}$$

and

$$K_T = \frac{\sum_{i \in Z} k_{i,T} l_i}{\sum_{i \epsilon Z} l_i} \tag{2}$$

ddj: uiteindelijk wordt in dit artikel niets gedaan met snel en langzaam laden van verkeer. Is het dan wel verstandig om dit hier aan te halen? – VLK: opgelost, zo, toch?

B. *Experimental set-up*

We test two control strategies, one which limits the inflow from the perimeter to the subnetwork, and one which limits the outflow from the subnetwork into the perimeter. The complete experimental set-up is presented graphically in Figure 2.

1) Inflow control: We investigate the effect of the amount of the traffic entering from the perimeter to the subnetwork (i.e., the inflow into the subnetwork) has on the shape of the MFD. To this end, we vary the traffic lights controlling the flow from the perimeter to the subnetwork from 100 to 500 veh/h/intersection in steps of 100 veh/h.

For each of these inflow rates, the signal schemes for all intersections in the network are recalculated using these given flows. To this end, the method[18] is reapplied, but the flows into the subnetwork are fixed. If the algorithm cannot find a proper scheme could within the given maximum cycle time, the input into the algorithm is changed. In fact, the flows from the uncontrolled turns are lowered which until a feasible signal scheme is obtained. Note that as such, the input for the traffic light scheme is different from the flows in reality.

2) Outflow control: We also investigate the effect of controlling the flow from the subnetwork into the perimeter. As with inflow control, we use metering rates of 100 to 500 veh/h/intersection. The algorithms for setting the signal times are the same as with the inflow control.

3) Performance indicators: For each of the metered flows in each of the control stragegies (inflow and outflow control) the MFD is determined. Especially the maximum production and the critical accumulation are considered to be indicators of the change in traffic operations at the road.

Ultimately, the traffic may end in gridlock, with the vehicles being blocked. Another measure of performance is the total number of arrivals up to the start of the gridlock.

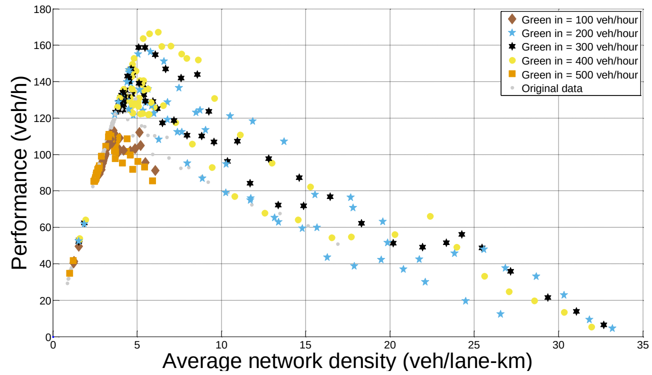

Fig. 3. The MFD of the subnetwork under a metered inflow into the subnetwork

IV. RESULTS

In this section we present the results of the experiments. First, the results of metering the subnetwork inflow are presented, and then, in section IV-B, the results of metering the subnetwork outflow are presented.

A. *Controlling subnetwork inflow*

The results of the simulation, when controlling the traffic flow from the perimeter to the subnetwork, are shown in Figure 3 and Figure 4. The resulting graph clearly shows that the shape of the MFD differs for different signal timings. Whereas the maximum production is only approximately 110 veh/h at a setting of 100 and 500 veh/h, it reaches 160 veh/h when signals are set to 200 - 400 veh/h, with the estimated optimal average network density shifting from approximately 3.5 to 5 veh/lane-km for the subnetwork. For the subnetwork it can also be observed that an improvement in the production is achieved over the original situation, when signals are fixed at a timing of 200 - 400 veh/h. Key characteristics of the MFDs for this experiment and the experiment on controlling outflow are summarized in table I.

When looking at the MFD of the perimeter, it is found that a production of 250 - 300 veh/h can be sustained over a large density-range for multiple signal timings. For high densities, the production is best if the flow towards the subnetwork is limited to 100 veh/h.

Regarding the number of vehicles finishing their trip before the network ended in gridlock, it is found that 30,000 vehicles reach their destination at an inflow restriction of 100 veh/h. At other timings, this was only 15,000 - 20,000. However, the average travel time of these vehicles at 100 veh/h is found to be approximately 60 percent higher than in the other four scenarios.

As is shown in table I, the optimal network density for the subnetwork does not change significantly when signal timings are changed. On the other hand, the critical density for the perimeter is strongly affected by different signal timings. Especially at an inflow restriction of 100 veh/h, the density found differs strongly from the other values.

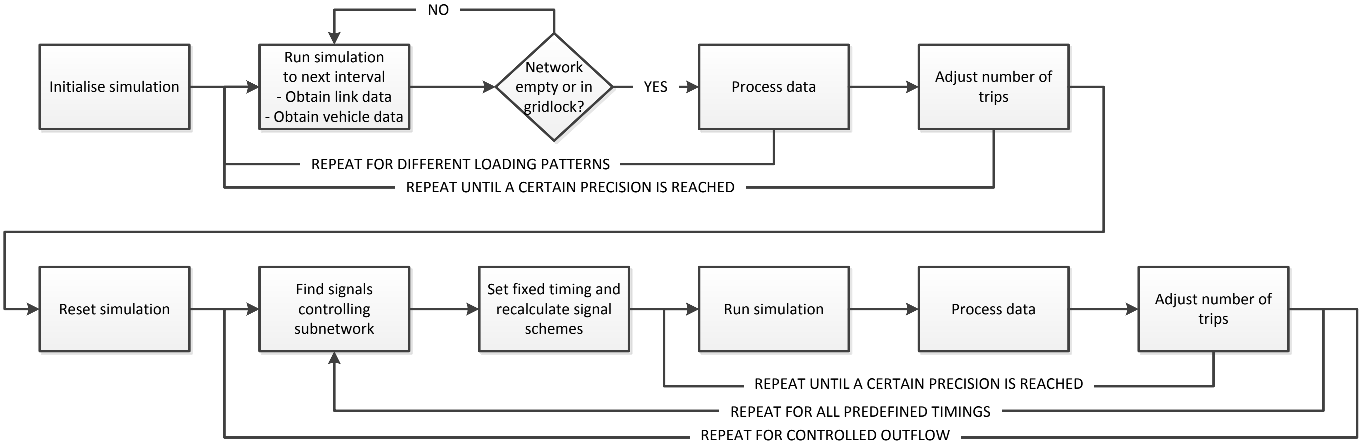

Fig. 2. Simulation algorithm

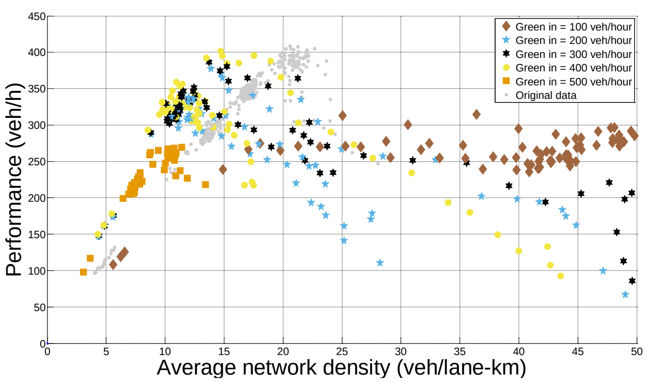

Fig. 4. The MFD of the perimeter under a metered inflow into the subnetwork

TABLE I

CRITICAL NETWORK ACCUMULATION, I.E. ACCUMULATION FOR MAXIMUM PRODUCTION

Control scenario	flow veh/h	Subnetwork A_{crit} (veh/lane-km)	Perimeter A_{crit} (veh/lane-km)
Reference		4.26	21.47
Inflow	100	3.58	36.42
Inflow	200	5.79	13.91
Inflow	300	5.10	13.73
Inflow	400	6.25	14.72
Inflow	500	3.55	10.42
Outflow	100	3.43	8.85
Outflow	200	3.43	8.85
Outflow	300	5.44	13.24
Outflow	400	5.72	14.09
Outflow	500	5.53	16.82

B. *Controlling subnetwork outflow*

The MFDs resulting from controlling the flow from the subnetwork into the perimeter are shown in Figure 5 and Figure 6. Their respective shapes, as well as the maximum achieved production and critical network accumulation, are similar to the MFDs resulting from controlling the inflow. An important difference however are the values for the signal timings, for which the highest production is achieved. In this case, the production is maximized when the controlling signals are set to a flow of 300 - 500 veh/h.

When controlling the outflow, the maximum number of vehicles finishing their trip is 32,000 - 35,000 at 400 and 500 veh/h. At the other three timings, this is approximately 25,000. The average travel time in this case is only 15 percent higher. This is in contrast with the results of the previous section, as in this case the scenarios with the highest production also have the highest output.

Finally, it can be observed that in this case too, the signal timings at which the highest production is achieved, is equal for both the subnetwork and its perimeter, as has also been found when controlling the inflow.

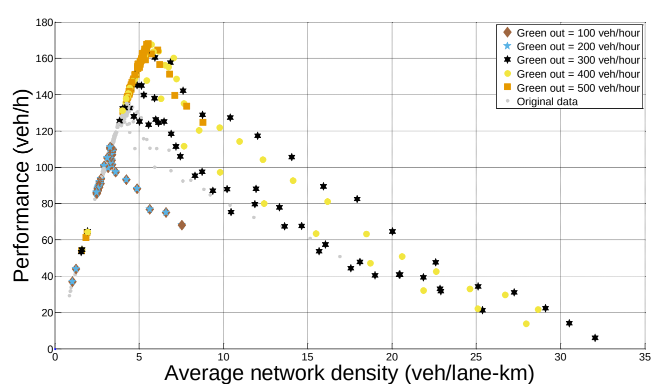

Fig. 5. Controlled outflow: subnetwork

V. DISCUSSION

A. *Improvements in traffic flow*

The results of controlling the traffic flow between the subnetwork and perimeter, by means of changing the signal timings, show that an improvement of the network over a situation in which signals are optimized locally, can be achieved. These results can be attained either by an improved production of the network, or because a certain production can be sustained over a large density range. Nevertheless,

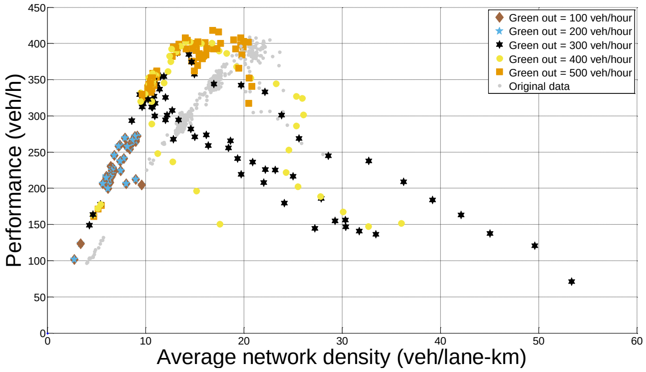

Fig. 6. Controlled outflow: perimeter

the control strategies/signal timings resulting in the highest production do not automatically result in the highest network output. As shown for the case of controlled inflow, signal timings resulting in a low production, actually generated a higher output. The reason for this is, that due to the restricted inflow, the formation of gridlock around a blocks in the subnetwork is severely reduced, due to the lowered amount of vehicles in the subnetwork.

From the resulting MFDs it is also found that the production of the perimeter is far higher than that of the subnetwork, implying that controlling the amount of traffic on the perimeter should result in a higher overall network output, then when the subnetwork is controlled. In both control strategies, the production is maximum if as many vehicles as possible are kept within the perimeter. In the simulation with the controlled outflow the production is maximum if as many vehicles as possible are let into the perimeter. This can be explained by the fact that the perimeter is better capable of processing traffic and thus preventing the formation of gridlock. Also, the reduced amount of traffic in the subnetwork reduces the probability of spill-back resulting in gridlock. From this it is concluded that holding back traffic in the perimeter in favor of the subnetwork, generates the best results, which is in accordance with the control methods proposed in [3] and [4].

B. Relation subnetwork and perimeter production

Following from the last observation, let us reconsider the relation between the subnetwork and the perimeter and in particular the way in which both are affected by different signal timings. To this end, the ratio between the maximum production of the subnetwork and the perimeter is calculated. From this ratio (figure 7) it can be concluded that production of the subnetwork is strongly positively related to the production of the perimeter.

From this it can be derived that an optimum for the signal timings exists, which is most beneficial to both parts of the network. The opposite also seems to hold true: that bad signal timings have a negative impact on the total network due to the formation of spill-back and congestion, resulting in local gridlock, which then rapidly spreads throughout the network.

An explanation for this relation is, that as long as the network is in free-flow, traffic is not affected that much when signal timings are changed and the traffic state in both the subnetwork and the perimeter remains equal for a long period of time. Nevertheless, Figure 7 shows that this relation seems to hold for almost every point found within the MFDs.

Thus, when optimizing the traffic flow by adapting signal timings, not only the controlled network can be optimized, but its controlling part as well. Nevertheless, these findings imply that the effectiveness of perimeter control (or gating) is questionable, as the results suggest that either part of the network cannot be preferred over the other; or at least over a long period of time.

C. Critical accumulation

Another important finding is that the network accumulation at which the production is maximized differs (and with it the shape of the MFD), given different signal timings. The implication of this is, that when the critical network accumulation for the perimeter would be based on the original MFD (uncontrolled situation), a control value of 21.5 veh/lane-km would be chosen (see Table 1). Limiting the accumulation to this accumulation by reducing the flow from the subnetworks does not yield good results because when the flow is reduced the critical accumulation for the perimeter reduces to approximately 9 veh/lane-km, eventually resulting in even more congestion.

From these findings, the conclusion is drawn that perimeter control is probably only effective if either the subnetwork or perimeter has an accumulation far below the optimum, or when it is executed for a short period of time.

VI. CONCLUSIONS

We simulated a network, consisting of a perimeter and a subnetwork, with inflow and outflow control at different levels. For the two types of control tested, no substantial differences in the production of either tactic is found. Nevertheless, it is found that higher productions are achieved when the amount of traffic in the subnetwork is kept low, which can result from either high outflows, or low inflows. The reason for this is, that the uncontrolled part of the network

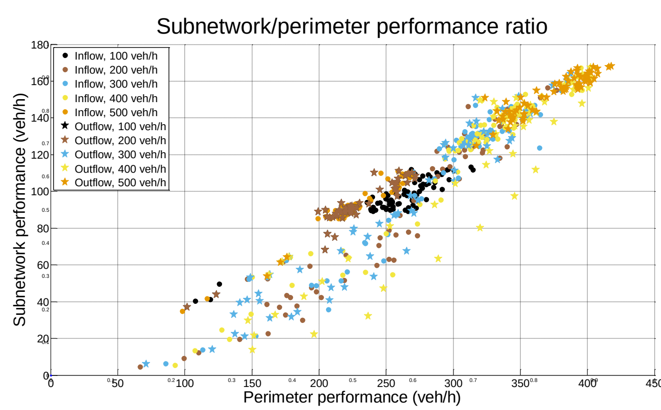

Fig. 7. Subnetwork/perimeter performance ratio

tends to end up in gridlock much easier than controlled parts of the network.

Moreover, it has been found that the production of both the subnetwork and the perimeter change in the same way as a result of changes in signal timing. It has been shown that a strong relation between the two exist, from which it is concluded that one part of the network cannot immediately be preferred over the other when control is exercised, as eventually both parts will end up in the same state. This does however imply that signal schemes do exist that optimize the total network production, which may differ from signal schemes resulting from local optimization.

The results of this paper show that signal timings can have a strong impact on the shape of the MFD, i.e. the maximum production and the critical network density. The MFD of the perimeter in particular is highly sensitive to changes in signal timings. The most important reason for this, is that all of the signals within the network are found on the perimeter. As such, it should not be too surprising, that the MFD of the perimeter is affected the most when signal timings are changed.

Since the critical accumulation also changes as result of the control, it cannot be directly utilized as input for control strategies. In fact, a signal timing change can lead to more congestion. It is not known how much time it takes for this new state to set in. This transitional time can be studied further, since it might be possible to exploit the network in this time.

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