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Integrated signal control and route guidance based on back-pressure principles

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Abstract

Traffic signal control and route guidance are the oldest and most applied dynamic traffic management measures. Most of the time they operate in a local mode, although there is trend toward network-wide traffic management. For traffic signal control already several network systems existed, but so far the integration with route guidance is lacking. In this paper we describe a new strategy to integrate traffic signal control and route guidance, based on the principles of back-pressure control. The algorithms developed are tested in a theoretical network and it was shown that traffic signal control based on back-pressure control performs well. Using back-pressure for route guidance required some assumptions which are open for debate. The results show that the average density is not such a good measure for route pressure and that travel time as a pressure variable performs better. A combination of factors of pressure based on density and travel time seems to be the best choice. Using back-pressure for both signal control and route guidance gave promising results, although the differences with optimized local control were small. Future research is recommended on the fine-tuning of the back-pressure traffic signal model, and on further integration and coordination of the control strategies. On the part of route guidance, finding representative route pressure values and making the model applicable of larger networks requires more research.

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Keywords: traffic signal control; route guidance; traffic modelling; back-pressure

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1. Introduction

Traffic conditions, such as congestion resulting into travel time delays, can be improved by balancing traffic demand and network capacity. Dynamic Traffic Management (DTM) systems are developed to improve spatial and temporal utilisation of infrastructures and vehicle fleets by means of dynamic signals. By timely response to changing traffic conditions, DTM goals, in terms of effective, safe and reliable use of the infrastructure, can be met. A number of trends can be distinguished which influence the development of DTM (Hoogendoorn et al., 2012), but two trends

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are relevant for the research in this paper: a shift from local control towards network-wide control and a shift from collective traffic information towards individual advice.

Local traffic control (for example signalized intersections or ramp metering) usually consists of standalone systems. Each system optimises its actions, based on local measurements, to improve the local situation. If these local systems are integrated, larger areas can be managed as a whole. An example is a system that combines neighbouring signalised intersections into one system that coordinates the traffic lights and let platoons of vehicles flow without delay. Various types of traffic control and DTM services could be conducted to work as one system. Network-wide traffic management involves integrating the data collection and measures of a larger network area. A trade-off between the interests of multiple road authorities can be necessary, such as the performance of urban versus highway network. The Praktijkproef Amsterdam (Dutch for Field Operational Test Integrated Network Management Amsterdam) aims at gaining practical experience with applying integrated network management in a large-scale regional (urban and motorway) network (Hoogendoorn et al., 2014).

Besides using roadside systems to manage traffic flows, there are measures that can be directed at the individual road user. Individual advice can be transmitted via in-car technology, such as navigational devices or radio (RDS). This advice can consist of directions for a route to follow, or warnings in case of congestion, weather or dangerous situations. Innovations in vehicle and communications technology makes vehicles increasingly 'smart' and connected, which creates the possibility of interactions between vehicles, road side systems, and road authorities. In-car technology could be beneficial for various applications within DTM, such as individual route guidance, effective car-following, lane-changing, or dynamic speed limits. Moreover, dynamic vehicle data could be added to conventional data collection (such as loop detectors) for better estimation of the traffic state. The Dutch Ministry of Infrastructure and the Environment is keen on further development of services required to provide road traffic and travel information. It initiated a 10-year programme that aims to provide better service to travellers and reaching policy objectives for accessibility, quality of life and safety (Connekt, 2013).

However, until now in-car systems are typically used to improve the route choice of the individual road user (user benefit), whereas DTM aims at improving the network performance as a whole (societal benefit). These different interests are potentially in conflict. New systems should provide a trade-off between user and system utility, user acceptance and social improvements. This paper aims at integrating route guidance with signal control to balance the interests of the road users and road managers. It will focus on the development of a route guidance algorithm, integrated with an algorithm for signalised intersections, both based on the principles of back-pressure control. This control concept stems from communication networks and has the properties of reactive and feedback control, and can be implemented as a distributed or decentralized system. It is a simple and flexible approach, making it potentially appropriate for real-time traffic control.

In the remainder of the paper we first discuss some literature on the topic of integrating route guidance and signal control and on back-pressure. After that we describe the algorithms developed and we will test them in a simulation environment. Finally, the results will be discussed and some conclusions drawn.

2. Literature review

2.1. Route guidance

Route guidance can be considered as a way to influence or override the route choice behaviour. The goal of route guidance can be to minimise the total travel time for the network as a whole, a system optimum situation, or a user optimum where no road user can change its own route to a faster route. A route guidance system can be of use in everyday traffic conditions, but especially when the traffic conditions are irregular, or in case of an incident. Then, people can benefit from the information provided by the route guidance system (Papageorgiou et al., 2003).

There are three ways to receive route information. The first is pre-trip information, for example by means of radio, tv or internet. Traffic updates or route planners can provide the first routing advice (or another advice, e.g. to go by public transport). Secondly there is roadside collective route information displayed by variable message signs at strategic points in the network. The third type is what is considered in this paper, en-route route guidance, which can be provided by in-car navigation systems or other nomadic devices (Papageorgiou et al., 2003).

Apart from the goal of a route guidance system, there are also strategy types that can be distinguished. An iterative strategy performs a repeated process of simulations, to reach the optimal setting at convergence (either system or user optimum). This approach can be put into the group model predictive control. It is hard to put into practice for real-time operations, it requires many computations. The other type is the group of one-shot strategies. This group holds reactive control approaches or (less common) predictive approaches (where a model is used to predict a near future state to react on)(Papageorgiou et al., 2003).

The simplest decision rule is the choice for the shortest path (Ben-Akiva and Bierlaire, 1999). In most cases a enabling spread of used routes is a better approach, which can be achieved by stochastic models based on the random utility model. The multinomial logit model can be used to model route choice when route alternatives are independent. If there is overlap, a path size logit model should better be used. This method takes into account that a route is less distinct if its links are used in other routes as well. The C-logit model (Cascetta et al., 1996) does a similar thing by using a commonality factor.

2.2. *Traffic signal control*

In this paper we cannot go into detail about the developments within traffic signal control strategies. There is a distinction between local and network control strategies and in this paper we focus on the latter. For off-line specification of fixed-time control plans for networks TRANSYT (Robertson, 1969) is an example of a tool, which is well-known and widespread. Real time and adaptive examples of network strategies are SCATS (Lowrie, 1982) and SCOOT (Hunt et al., 1981), developed and tested in the 70's and 80's of the previous century. Other comparable, but less used, systems are OPAC (Gartner, 1983), the French system PRODYN (Henry and Farges, 1989), the Italian UTOPIA, which is tested and used in some cities in Europe and is described in Di Taranto and Mauro (1989), and RHODES, an American development by Head et al. (1992). SCOOT and SCATS are used around the world, but the other systems are only implemented in some cities, mostly for testing. An extended overview of local and network control strategies is given by Van Katwijk (2008). In his thesis he also develops a new adaptive control strategy based on a multi-agent approach.

2.3. *Back-pressure control*

The concept of back-pressure (also known as max pressure, max weight, maximum throughput, maximum differential backlog) routing was introduced by Tassiulas and Ephremides (1992) and their 'maximum throughput policy'. They consider multi-hop radio networks, where customers are routed from origin to destination. At any node in the network, represented as a directed graph, customers may enter. The customers are sent to their destination via multiple nodes that are interlinked by service providers. As these servers (or links) are interdependent and can't all be activated simultaneously, it's only possible to activate particular combinations of servers: activation sets. Here, the control problem is to schedule the activation sets in a way that throughput is optimized. Additionally, the network state should be stabilized.

Back-pressure control typically consists of set of controllers, each belonging to a node in the network. In case of road traffic, each intersection could be controlled by a back-pressure controller. Each controller optimizes its service to waiting queues, according to a back-pressure algorithm. This illustrates the decentralized nature of the approach. Typical for the back-pressure algorithm is that it is based on the difference in traffic load between roads leading into and roads leading out of the intersection. Contrary, other distributed traffic signal control algorithms, such as the P_0 policy of Smith (1980) and Smith (2015), only consider the expected traffic load on roads leading into the intersection.

The literature on back-pressure claims that this control method maximizes the throughput of each node and the network as a whole, while maximally stabilizing the network, keeping the queues bounded. Because the chosen approach is reactive, it won't use prediction and therefore can't look into the future to prevent problems. Nevertheless, the fact that network stability is a prominent feature of back-pressure control, one can expect the approach to be proactive, because of its distributive approach of keeping the network stable.

Although back-pressure control has been applied to traffic signal control (see e.g. Varaiya (2009), Wongpiromsarn et al. (2012) and Varaiya (2013)), it has hardly been used for route guidance of road traffic. It is worth to do research on this application. Normally route guidance is based on travel times, the back-pressure principle would use the traffic loads on routes, and would improve network throughput and stability. Furthermore, the opportunity for a distributed approach is attractive. Lastly, the original back-pressure algorithm for communication networks naturally combines control of switches and routing, which might be possible, to some extent, for DTM as well.

3. Modelling of traffic signal control

3.1. Basic traffic signal control

Traffic signal control plans are typically based on two steps. First, all traffic streams are defined and conflict groups are determined, which traffic streams can't be given green at the same time. Then, phases are formulated. A phase consists of a group of traffic streams that can have green together. By ordering the phases inside a traffic control cycle, all traffic streams can be served. The time share for each phase depends on the related traffic load. This representation of signal control is very simple and limited, as there are more advanced ways to define signal control plans. In this thesis the choice is made to have simple signal control plans with strictly defined traffic phases. Another simplification is to neglect clearance times in between phases. The set of phases is $\mathcal{P}$ is formulated as $\mathcal{P} = \{p_1, \ldots, p_n\}$.

Before the concept of back-pressure control is applied to traffic signal control, two other approaches are briefly discussed: fixed-time and vehicle actuated traffic signal control. Fixed-time traffic signal control is the most conventional way of controlling traffic on intersections. In this case the signal plan has a fixed cycle time with an specified order of phases, each having a fixed amount of green time. The (off-line) optimization of this type of signal plan is usually based on an average traffic demand. Vehicle actuated (VA) control is a type of signal control where phase times depend on the presence of vehicle on detectors or on the actual traffic demand measured at intersection approaches (e.g. with induction loops). Usually each phase has a minimum green time that gets extended to further release the queues. In the simulation experiments VA control will be compared to back-pressure control. A simple way to model VA control is the proportional policy (Le et al., 2013). Each phase has a summed weight W_p to account for the traffic demand on each approach. This traffic demand usually is the number of queueing vehicles, but in this thesis the relative vehicle density is used. The share of green time ξ for phase p and time step t is assigned proportionally:

$$\xi_p(t) = \frac{W_p(t)}{\sum_{i\in\mathcal{P}} W_i(t)} \tag{1}$$

3.2. Signal control with back-pressure

Back-pressure (BP) control is developed based on the findings in the literature. The procedure of assigning phase times according to BP control can be summarized as follows:

1. Each traffic stream has a back-pressure value BP that is based on the difference in pressure P between the incoming link a and the outgoing one(s), b.

$$BP_{ab}(t) = P_a(t) - \sum_b r_b P_b(t) \tag{2}$$

   The pressure of an outgoing link has a weight according to the turning ratio r of that link, which demands that turning probabilities need to be determined first.
2. Determine the accumulated back-pressure values γ for each phase p. This is done by multiplying the BP values of step 1 by the available service rate (saturation flow) μ for each phase p.

$$\gamma_p(t) = \sum_{a,b} \mu_{ab,p} BP_{ab}(t). \tag{3}$$

3. Allocate the right amount of time to the phase(s) to be activated. There are two main approaches here:
   (a) Use a fixed cycle time and divide it among the phases according to a function f of their accumulated pressures γ (similar to the proportional assignment described for VA control).

$$\Xi_p(t) = \frac{f\left(\gamma_p(t)\right)}{\sum_{i\in\mathcal{P}} f\left(\gamma_i(t)\right)} \tag{4}$$

(b) Use time slots and assign the current slot to the phase with the highest pressure (p^*), and repeat the BP procedure every time slot. If two phases result in an equal pressure, the policy should make a random choice.

$$p^*(t) = \arg\max\{\gamma_p(t) | p \in \mathcal{P}\}. \tag{5}$$

In case of all negative pressures at the intersection, theoretically all signals can be put to red. This depends on choices for the control method, and will be elaborated on in the next subsections.

3.3. Definition of pressure

The pressure on a link is a measure for its degree of occupation. For an outgoing link, a low pressure implies that there is much space left for vehicles to enter, with high pressure it is considered full. For the incoming link low pressure means that the amount of vehicles willing to access the intersection is low, and the other way around. By subtracting the outgoing pressure from the incoming pressure (Eq. 2) the value for back-pressure is calculated.

Pressures can be expressed as absolute numbers, such as the number of queueing vehicles. A first choice would to use the occupation of a link relative to its length. Relating the occupation to the length is generally not enough, as a link with many lanes can store more vehicle per km than a link with one lane. A second choice is made, to normalize the pressure per link. Thus the pressure is defined as a function of its total storage capacity. To normalize the pressure function, and using density as the measure of occupation, the pressure on a link on time t can be simply defined by dividing density over the jam density. Finally, to add more weight on situations where the density k is near the jam density k_{jam}, we use the square of this value:

$$P = \left(\frac{k}{k_{jam}}\right)^2. \tag{6}$$

3.4. Fixed cyle time BP algorithm

A traffic signal control approach with fixed cycle times is based on a predetermined order of phases that each have a share in the total cycle time. As back-pressure works best with frequent updates, The control period is chosen to be equal to the cycle time. In equation (4) the function $f(\gamma_p(t))$ is put as a general representation. One approach is to use the exponential (logit) function (Le et al., 2013):

$$f(\gamma_p(t)) = e^{\theta\gamma_p(t)} \tag{7}$$

$$P_p(t) = \frac{e^{\theta\gamma_p(t)}}{\sum_{i\in\mathcal{P}} e^{\theta\gamma_p(t)}} \tag{8}$$

The exponential function is common to use in choice problems. In this application it is an advantage that the BP-value for each phase can be positive or negative, the outcome is always a positive share (other than the proportional function of equation (1). The function can be tweaked by adjusting the parameter θ, which can also be a disadvantage of this method, because the the right value has to be determined.

3.5. Time slotted BP algorithm

An approach quite different from using fixed cycles is traffic signal control using time slots. The term ‘time slot’ is used here, as a reference to the back-pressure methods for communication networks in literature. This approach splits time into fixed steps, such as 10 seconds. Each time step represents a slot that can be assigned to one activated phase. This phase has the highest back-pressure value, as defined by equation (5).

A possible drawback, especially from the road user point of view, is that traffic streams with a low BP value will wait ‘forever’ if they are dominated by others. And on the other hand, a domination traffic stream should give way to others once in a while. To facilitate these requirements a *maximum waiting time* and a *maximum green time* are introduced. For example, whatever the conditions, after 90 seconds of facing red light, an phase should receive green. And after 45 seconds of green, this phase is excluded from receiving green in the next control step.

4. Modelling of route guidance

4.1. Using BP for route guidance

Route guidance is about making travellers take those routes that lead to the best performance for the road network as a whole. One way to improve the performance is to make better use of the available road capacity, diverting traffic from busy roads or parts of the network to parts of the network with more 'space' available. Back-pressure fits this idea, since the principle favours low pressured links above high pressured links. In the back-pressure applications in the field of communication technology route guidance is an implicit characteristic, but other than most examples from this field, for route guidance of traffic it is important to take into account not only the next first links, but the possible routes as a whole. One task will be to attach to routes representative pressure values. Like for traffic signal control in equation (3), the 'weight' A (or attractiveness) for a route r could be defined by:

$$A_r(t) = \mu_r BP_{\text{route},r}(t). \tag{9}$$

$BP_{\text{route},r}$ represents the back-pressure value of the route, and μ_r the service rate of the route. The service rate of a route is hard to define. For an intersection it is the saturation flow from one link to the next. For routes, it can be for example the capacity of the first link of the route. However, multiple routes are assigned at the same time, all taking a share of the capacity. Therefore, taking the capacity as a 'service rate' is probably not correct, but it is a first guess and an assumption that might work. Another attempt would be to use the smallest capacities of all links of the route, but that is not investigated in this paper.

4.2. Route guidance BP algorithm

The general algorithm for route guidance with back-pressure can be summarized as follows: for every link l with multiple next links (other needn't be considered):

- Determine the set of destinations that can be reached through this link, D_l:
- For every $d \in D_l$:
    - For every partial route $r_{l,d}$ starting from l to destination d:
        - Determine the service rate $\mu_{r_{l,d}}$, as the capacity of the first link.
        - Determine the 'utility' $U_{r_{l,d}}$ (including the use of pressures).
    - Determine the proportions for each partial route.
    - Determine the new split vector, based on the route proportions.

A general function for the utility of a route, that incorporates the factors taken into account, can be written as:

$$\text{BP}_r = \alpha_1 P_{\text{route},r} + \alpha_2 P_{\text{firstlink},r} + \alpha_3 P_{\text{user},r} \tag{10}$$

Here, BP_r stands for the utility of the route, $P_{\text{route},r}$ is a measure for the pressure of a route, and $P_{\text{firstlink},r}$ a measure for the pressure of only the first link of the route. The factor $P_{\text{user},r}$ is used to take user preference into account (in our case travel time). The α parameters can be tweaked to the degree a factor should contribute to the utility. Link pressures are based on the relative density and route pressures are based on the weighted average link pressures of that route, but we also test variants in which pressure is based on the route travel time (the third term) or a combination. Details on the third term can be found in Van Kampen (2015).

4.3. Route proportions

The final part of the BP algorithm for route guidance consists of the determination of the route proportions. For this paper the path size logit model is used (Ramming, 2002). The path size logit function does consider route overlap and uses a path size (PS) factor for each route to account for the overlap. A route that is almost similar to another route has a low path size factor, and will have a lower choice probability than if each route would have been treated independently.

There are several versions of the PS factor for route r, here the version of Frejinger (2008) is used:

$$\mathrm{PS}_r = \sum_{a \in \Gamma_r} \frac{l_a}{L_r} \frac{1}{\sum_{s \in \mathcal{R}_{l,d}} \delta_{as}} \tag{11}$$

where Γ_r is the set of links for route r, l_a the length of link a and L_r the length of route r. The value δ_{as} is the number of times link a occurs in a choice set of routes $\mathcal{R}_{l,d}$ which contains partial routes starting from the current link l with the same destination d. The PS value is static, so it needs to be calculated only once, after the routes have been defined.

The probability P to choose route r now becomes:

$$P_r = \frac{\mathrm{PS}_r e^{\theta U_r}}{\sum_{i \in \mathcal{R}_{l,d}} \mathrm{PS}_i e^{\theta U_i}} \quad \forall r \in \mathcal{R}_{l,d} \tag{12}$$

For the utility U_r we normally would take the service rate into account with

$$U_r = \mu_r \mathrm{BP}_r \tag{13}$$

but we leave the determination of μ_r for routes for further research and use a value of 1 for this research.

5. Case study

5.1. Simulation framework

To test the algorithms developed the DSMART (Dynamic Simple Macroscopic Assignment of Road Traffic) model was used (Zuurbier, 2005, 2010). This model is based on the cell transmission representation of the well-known LWR model and therefore it can simulate traffic dynamics and congestion quite well, and in a traceable way. Other features are that traffic in the model is specified per destination, as is route choice (instead of having split fractions on the aggregate traffic). Route guidance is built-in and traffic can be rerouted at every link.

The standard route choice process is used to simulate the natural route choice behaviour of traffic. In DSMART the standard procedure is to update route choice settings (turn ratios) every period of typically 15 minutes. The route choice is based on (instantaneous) travel time values, of which road users are assumed to be well-informed. The standard route choice model is a probit choice model. This means that random 'noise' is added to the link travel times as a measure of perceived travel time. Using randomized sets of travel times and a shortest path algorithm, the number of times a route is perceived as the shortest determines its share of route choice.

The model is fast and efficient and can be applied to larger networks, but a main disadvantage of DSMART is that it doesn't include traffic signal control facilities. Therefore it was extended with this functionality. Traffic signal control objects directly influence the traffic flow at intersections and route guidance is enforced by manipulating turn ratios at intersections and diverges. Periodically, the functions that represent the traffic controllers update their strategy. This is done both for traffic signal control as well as for route guidance. For a detailed description of the model and how the algorithms were implemented the reader is referred to Van Kampen (2015).

5.2. Network and scenarios

To investigate the combined effect of route guidance and signal control the network in Fig. 1 is used. The standard length of links is 1 km, and each has one lane, except the links from the origins (node 1 and 2) and to the destinations (node 3 and 4). The traffic demand (Fig. 2) is equal for all 4 OD relations. Traffic signal control is installed on nodes 8, 9, 11–15, and 17.

The network and demand profile were used to evaluate an number of combinations of types of signal control and route guidance as described in previous paragraphs. In the case study four traffic signal control variants were tested:

- local fixed-time control (Fixed);
- local vehicle actuated control (VA);

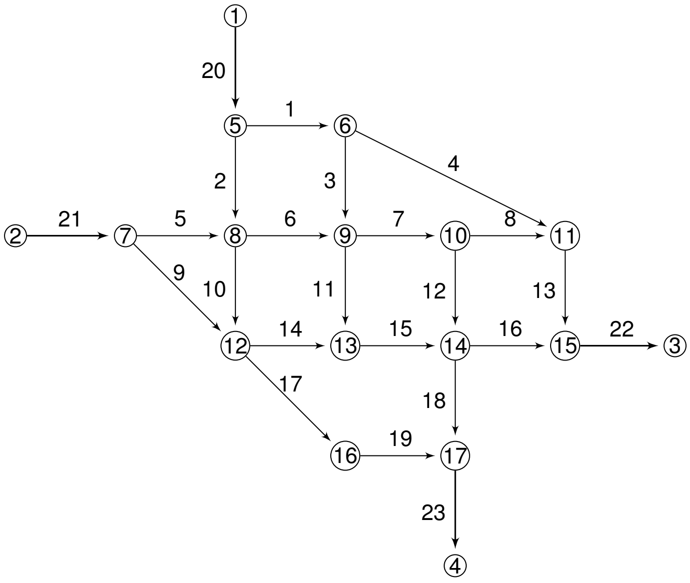

Fig. 1. Case network

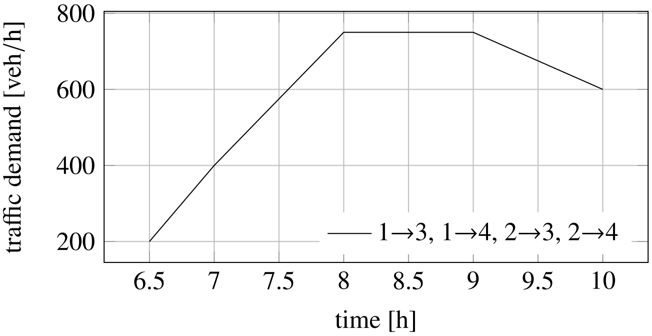

Fig. 2. OD demand

- back-pressure with fixed cycle time (BPcycle);
- back-pressure with time slots (BPslot).

For route guidance, six variants were used:

- reference variant (Std): standard route choice (probit route choice);
- back-pressure based on the first link (BP-1st);
- back-pressure based on path size logit (BP-PSL);
- back-pressure based on a combination of the first link and PSL (BP-1stP);
- back-pressure based on a combination of the first link and PSL, and route travel time (BP-1stP*)
- back-pressure based only on route travel time (BP-TT).

Each combination of these 2 sets of variants are evaluated by simulation. The update frequency for route guidance is once per minute. The simulation step is 5 seconds, which allows the signal control phases a ‘precision’ of 5 seconds.

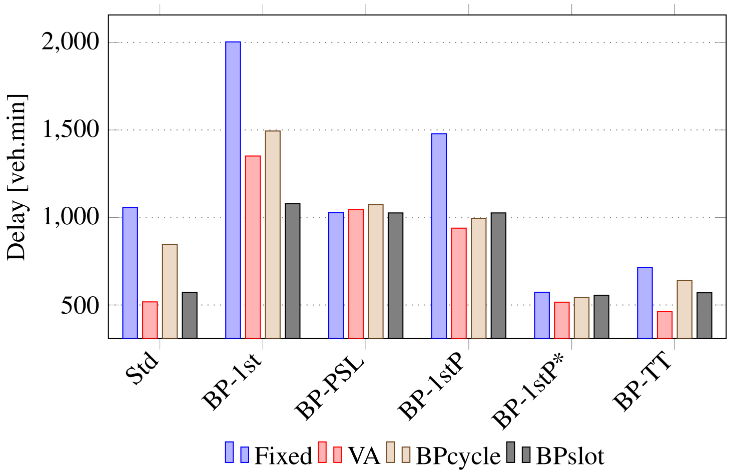

Fig. 3. Total delay per combination of variants

The time slot (BPslot) is 10 seconds. The simulation runs for a period between 7 and 10 o'clock, with a half hour warming-up time in advance.

5.3. *Results*

The combinations of control and route guidance variants were simulated and evaluated looking at total delay in the network. The results are give in Fig. 3. It can be seen that fixed-time signal control performs worst. This was expected, but it should be noted that the control settings hadn't been optimized (or coordinated). Other settings could have given somewhat better results. In this network, vehicle actuated control seems to work best. The reason behind this is not clear, a possible explanation is that in this case pressures downstream of intersections are relatively equal and therefore don't play a big role. However BPslot performs almost as good as VA control. There is a possible explanation for not performing better. If two intersection approaches (or phases) have nearly the same pressure, but one continues to dominate the other direction, then the queue on the other direction that doesn't get served might back-propagate through the network. BPcycle performs slightly worse, but that was expected, because the control strategy is updated less frequently.

Regarding variants of route guidance, most back-pressure variants don't perform that well. This probably has to do with the pressure function (average relative density on the route) not being optimal. And also with the fact that just looking 1 link ahead is not best route guidance strategy. It is clear that BP-1st is a 'myopic' approach of route guidance. Link 15 is the first link to get congested. However traffic from origin node 2 to destination 3 is still sent through this path. Only when congestion spills back to link 14 and 9, more traffic is guided along links 5, 6 and 7.

The variants with travel time in the pressure function perform better than those using density. The back-pressure combination (BP-1stP*) performs best and is stable among its signal control variants. Probably taking a combined strategy (of densities and travel times) leads to good overall results. Of course this is no full proof, since only one network has been tested, at one traffic demand profile.

6. Conclusions and further work

From this research it can be concluded that it is indeed possible to create a methodology, based on back-pressure control, that integrates traffic signal control and route guidance. Traffic signal control based on back-pressure control performs well in the simulations, especially the variant with time slots. Throughput is high and queues remain within reasonable boundaries. Using back-pressure for route guidance requires some (artificial) design choices. The challenge is to define a representative function of route pressure or utility, and to combine this with a service rate value, in order to obtain a high throughput and stability with minimum delays. Several variants for this have been presented. The average density turned out not to be a good measure for route pressure, travel time performed better. Probably, it is best to combine factors of pressure based on density and travel time, in order to use the shortest routes in case of low traffic, and shift to the routes with more capacity if needed.

Future research should focus on the fine-tuning of the back-pressure traffic signal model, and on further integration and coordination of the control strategies. On the part of route guidance, finding representative route pressure values and making the model applicable of larger networks require more research. The control approaches should further be simulated and tested with a microscopic simulation model, on more networks and scenarios. Necessary developments for a practical use include the availability of in-car systems and traffic state estimation.

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