Delay-Time Actuated Traffic Signal Control for an Isolated Intersection

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DELAY-TIME ACTUATED TRAFFIC SIGNAL CONTROL FOR AN ISOLATED INTERSECTION

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Abstract

This paper describes a new approach to control traffic signals at isolated intersections by capturing vehicles' delay times and utilize them to adjust the green times. Similar to a traditional vehicle actuated control a queue clearing policy is applied: Within the bounds of a minimum and a maximum green time, a running green phase is terminated as soon as the accumulated delay on an approach is dissolved. The strength of this new approach is that it can be used for new data-sources like probe vehicles, video cameras, or vehicle infrastructure integration (VII). To assess the quality of the new method, a simulation study is performed which demonstrates that it outperforms the traditional approaches, with the additional benefit of robustness against a particular kind of measurement error.

1 Introduction

The quality of traffic within urban road networks depends strongly on the traffic signal control settings. For this purpose fixed time or conventional vehicle actuated approaches are often used, benefiting in different application areas: Fixed time controls are reliable and cost-efficient but they have no information about current traffic conditions. Predefined green times are applied, which are adapted towards an average number of arriving vehicles within a cycle. If there is a stochastic variation of this mean value, fixed time controls have no possibility to react. In this case of fast changing demand patterns conventional vehicle actuated controls perform better. They are equipped with fixed-location sensors (e.g. loop detectors) on the approaches to measure the current traffic flow. Based on this information green times can be modified. Nevertheless, this additional sensor equipment expenses the control and increases the error rate. Each arriving lane needs to be prepared with at least one sensor and each of them must work in the right order to prevent errors. Besides these differences, a similarity of all presently used controllers becomes obviously: They differ in their setup, but their major objective is to minimize delay times for motorists by allocating green times in a preferably efficient way. However, instead of processing motorists' delay times directly to adjust these green times, only delay time correlated values like the occupancy, the volume, or the time headways are used.

The usage of these proxies instead of the real deal times is of course due to limitations in detection technology. Meanwhile a lot of new traffic data sources have become state of the art. This makes it possible to measure vehicles' delay times directly and estimation becomes unnecessary. However, so far no control logic is able handle these data directly, therefore this work describe a new signal control logic which was developed to process on-line measured delay times directly. So far, this is restricted to the control of an isolated intersection.

2 Delay-based Signal Control

2.1 Basic Approach

The underlying idea for the new controlling scheme is to apply a queue clearing policy. That means a green phase is extended until all queued vehicles from a previous red phase are cleared. Presently applied headway based controllers already use it: During a running green phase, headways of arriving vehicles are continuously measured. Considering a minimum and a maximum green time, these headways are utilized by a control logic to decide to prolong or terminate the running green phase. Termination condition is the crossing of a predefined critical headway. This always occurs when the queue on an approach is completely dissolved and previous constantly small headways become randomly distributed.

This queue clearing policy can also be applied when using vehicles' delay times instead of their headways. While dissolving a queue, not only the headways increase but also the accumulated delay times of arriving vehicles at the queue's back decrease. The first vehicle crossing the intersection with no deceleration must have a delay time close to zero. This correlation can now be utilized in a control logic [1], similar to the headway based control: Bounded by a minimum and a maximum green time (*g_min*, *g_max*), a running green phase is terminated as soon as the first vehicle with a delay *d* smaller than a critical delay time *d_min* (about zero) passes the stop line. This principle is depicted in Fig. 1.

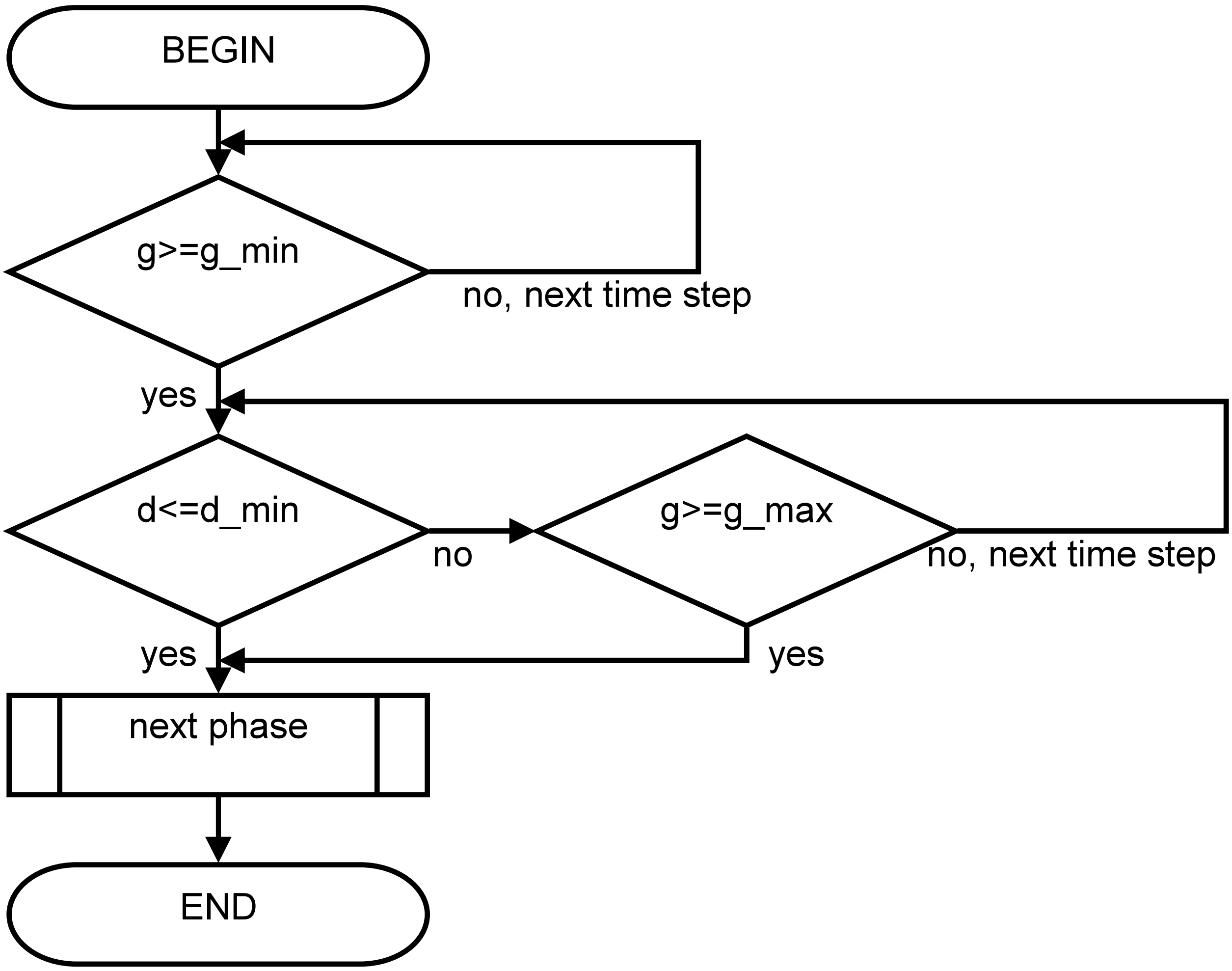

FIGURE 1 Flowchart of the delay-based signal control. The scheme is passed through while a green phase on an approach is running.

2.2 *Data Capturing*

The delays needed for this type of control can come from different sources such as video processing, probe vehicle data, or vehicle infrastructure integration. Given the current speed $v_i(t)$ of a vehicle, and a small time increment Δt (such as the inverse frame-rate of a video camera or the time between subsequent GPS readings), a delay d_i always occurs when $v_i(t)$ has been below a maximum achievable speed v_{max}:

$$d_i = \Delta t \left(1 - \frac{v_i(t)}{v_{\max}} \right) \qquad (1)$$

Here, v_{max} is a maximum speed close to the speed limit. It is simple to determine v_{max} in a simulation, in reality it is necessary to calibrate this number. The delay d for the whole approach is the summation of the single delay times d_i of all the n vehicles on that approach:

$$d = \sum_{i=1}^{n} d_i \tag{2}$$

Depending on these equations several traffic data sources can be applied to gather delay times, which certainly have different intervals Δt to capture recent vehicle speeds $v_i(t)$. One option are probe vehicles equipped with GPS devices [2], collecting their own trajectories. Delay times can either be calculated onboard or centralized in the traffic signals controller. Anyway, data must be submitted to the signals controller using e.g. a vehicle-infrastructure-integration. Another possibility to measure delay times is the capturing of MAC addresses [2]. These are unique and are assigned to electronic wireless devices like laptops, cell phones and MP3 players. When carrying such devices in a vehicle and the communication interfaces are in an active mode, MAC addresses can be logged and time-stamped at two fixed positions along an approach. Afterwards by matching these MAC addresses, an average speed can be calculated, leading to delay times. The same principle can be applied when doing automatic license plate recognition (ALPR) [4]. The usage of video cameras is a further alternative to gather delay times. A fixed area on an approach is observed and by tracking positions of vehicles in an image sequence, the required speed information becomes available.

2.3 Components of the new controller

Sources of delay times are numerous but they differ in the penetration rate of actually captured vehicles. While e.g. the usage of the automatic license plate recognition (ALPR) delivers a high degree of all the delay times required, the GPS based probe method can only capture a fraction of it. This is caused by their currently still low penetration rate. To handle low penetration rates in an appropriate way and to make the delay-based control still work, the whole control consists of three components [5]. The first module is the decision making logic described in section 2.1: As soon as the accumulated delay times on an approach have dropped close to zero, a running green phase is terminated. A second module copes with the case when delay times are still available but are too scarce to use the decision making logic. Here, the minimum green time needed to clear the approach is estimated as described below. For time intervals where no measured delay times are available, a memory is used as third module. Previously stored green times are applied to run a fixed time control.

The estimation in the second module is dissolved by approximating the tailback at the end of a red phase. Based on it a minimum required green time is calculated to clear that queue. Several approaches are known to estimate tailbacks at intersections e.g. [6], [7]. The most suitable solution for the control issue under consideration has been presented by Priemer [8] for the example of the processing of GPS position data of probe vehicles: The length l of an entire queue at the end of a red phase consists of two parts l_1 and l_2

$$l = l_1 + l_2 \tag{3}$$

where l_1 is determined by the distance between the known stopping position of the last probe vehicle in that queue and the fixed position of the stop line. l_2 is the unknown part behind this last queued probe vehicle and needs to be approximated. For this purpose Little's law [9] is applied

$$l_a = \lambda \Delta t_{red} \, . \tag{4}$$

Under the assumption of a stable system, the average length l_a of the queue is the product of the average expansion rate λ over the known duration of the red phase Δt_{red}. Supposing λ to be equal for l_1 and l_2 during a red phase, the expansion rate λ_2 of the queue is

$$\lambda = \lambda_1 = \lambda_2 = \frac{x_{stop\_veh}}{\Delta t_{stop\_veh-begin\_red}}. \tag{5}$$

Here, x_{stop_veh} is the stopping position of the last probe vehicle in the queue (= l_1) and the time period $\Delta t_{stop\_veh-begin\_red}$ elapsed between the start of the red phase and the arrival of the probe vehicle at the queue's back. Using Little's law, λ_2 and the time period $\Delta t_{end\_red-stop\_veh}$ elapsed between the arrival of the probe vehicle at the queue's back and the end of the red phase, l_2 can be calculated

$$l_2 = \lambda_2 \Delta t_{end\_red-stop\_veh}. \tag{6}$$

By summing l_1 and l_2 at the end of a red phase the queue length l is

$$l = l_1 + l_2 = x_{stop\_veh} + \lambda_2 \Delta t_{end\_red-stop\_veh}. \tag{7}$$

Finally, a linear outflow of the queued vehicles is assumed during a green phase. Then the minimum green time g to clear that queue is the product of queued vehicles n with a vehicle length l_f and their critical headways τ_c

$$g = n\tau_c = \frac{l}{l_f}\tau_c. \tag{8}$$

The strength of this approach is that it is not important to know the penetration rate or many equipped vehicles are actually on an approach: If the position of at least one vehicle on an approach is measureable, green times for a following phase are estimated during a red phase. If no equipped vehicle was available, the stored green times are used. Starting the following green phase with one of these fixed values, the control automatically switches in the delay-based mode as soon as the first vehicles with accumulated delay times arrive. If none arrives, it sticks with the predefined green time.

3 Simulation Study

3.1 Study Area

To benchmark the delay-based signal control simulations are performed. The microscopic simulation tool SUMO (Simulation of Urban MObility) [10] of the German Aerospace Center is used for it. An isolated intersection consisting of four links is modelled, depicted in Fig. 2.

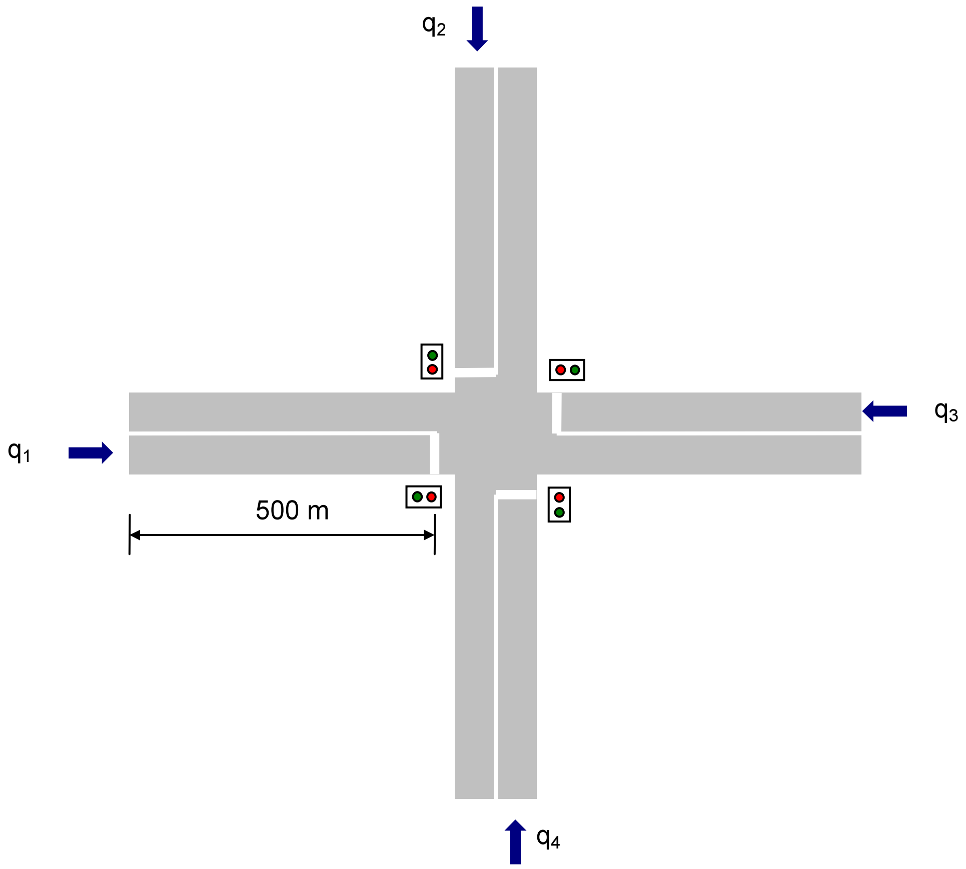

FIGURE 2 Intersection scenario used for microscopic simulation.

The four links are fed with vehicles drawn from a Poisson distribution of inflow strength q_i (i = 1...4) which enter the simulation with a speed of 50 km/h (13.88 m/s). Turning and overtaking are not allowed. Furthermore, opposite flows are grouped in the same phase and are assumed to be equal. The required delay times to control the signals are constantly measured on each approach in the simulation's time step size of 1 s. One simulation run lasts 20000 s. The inflow and the ratio of ascertainable delay times are stepwise increased with each run. The performance indicator is the vehicles' average delay times.

To compare the delay-based signal control to other well-established control schemes, an optimized fixed time control and a conventional vehicle actuated control are simulated as well. For the fixed time control the minimum delay cycle length C_0 is calculated by using Webster's equation [11]

$$C_0 = \frac{1{,}5L + 5}{1 - Y_i}. \tag{8}$$

Here, L is the sum of lost times per cycle and Y_i is the sum of the degree of saturation for all critical phases. Based on the ratio of inflows the available green times are allocated. For each combination of input flows in the following simulations the optimum fixed time control is computed and used to compare the other approaches with. The vehicle actuated control measures headways 30 m ahead the stop line and adjusts green times [12] to the current traffic flow. A running green phase is extended as long as the gathered headways are below the critical headway $\tau_c = 3$ s (the unit extension).

3.2 Results

Figure 3 shows how this delay-based control works. It is displayed how the number of delayed vehicles (Figure 3a) and the total delay time (Figure 3b) change with time. In the example below, "delayed" is true if a vehicle has a speed below the preferred speed of 13.88 m/s (50 km/h, 31 mph). In the simulation set-up used to obtain these figures, the controller had access to the delay times of all the approaching vehicles. It can be observed very nicely, how the control switches to the next phase if the delay has dropped to zero.

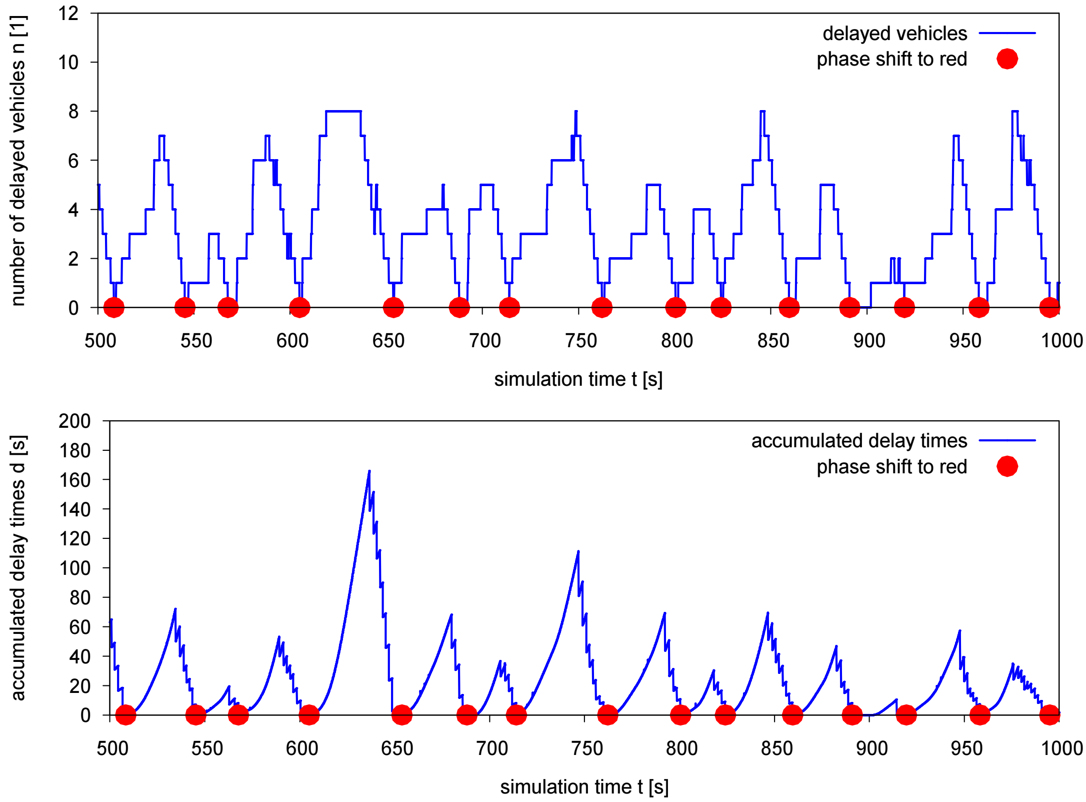

FIGURE 3 The number of delayed vehicles (top, (a)), and the accumulated delay times (bottom, (b)) on an approach with the moments of phase shift to red. Input volume was fixed to 0.18 veh/s (648 veh/h), in this case the delay times of all the vehicles were used by the signals controller.

The following Figures 4 and 5 are the main results of this work. More simulations, whose results are not shown here, have demonstrated that the symmetric case $q_1 = q_2 = q_3 = q_4 = q$ captures the main results of this study. Figure 4 describes the average delay time as function of demand and penetration rate, while Figure 5 gives a more detailed look on the delay times as function of the penetration rate for a fixed demand. This is done for all three control strategies, each delay time in the two plots is the average out of 10 different simulation runs (different initial seeds) and over all the vehicles passing the study area in the simulation (the first 5000 simulation runs are ignored in the statistics).

The delay-based control works as well as the two traditional controls for small penetration rates below (roughly) 10%. It outperforms the traditional strategies for penetration rates above 10%. Note, that this demonstrates in addition an amazing robustness of this control: even if the detector is missing half of the vehicles, the control logic still delivers an astonishingly strong performance. Albeit we do not know about such investigations, it is unlikely that this is possible with a traditional actuated control.

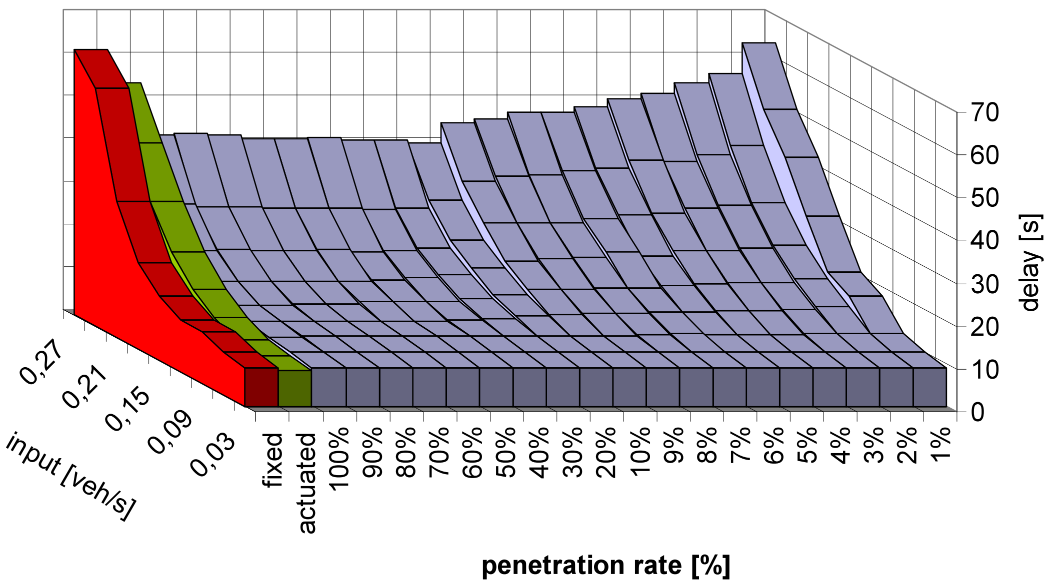

FIGURE 4 Average delay times of the headway actuated control (red), the fixed time control (green) and the delay-based control (grey) as function of ratio of captured delay times and traffic flow.

The following Fig. 5 shows these results into more detail, here for an input volume of q=0.24 veh/s (864 veh/h).

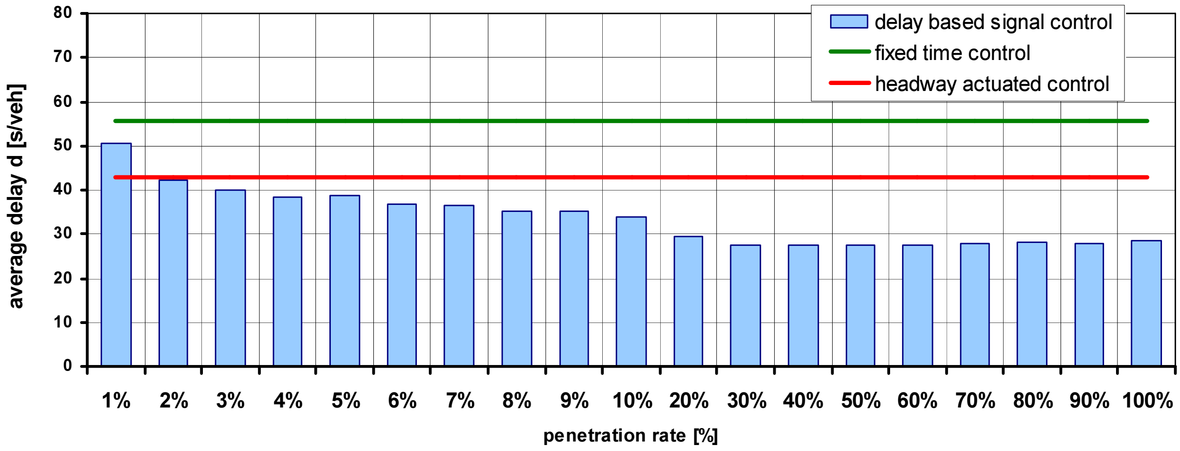

FIGURE 5 Average delay times of the delay-based control as function of ratio of captured delay times for a fixed traffic flow 0.24 veh/s (864 veh/h).

Finally, the charts in Fig. 6 demonstrate once more, where the strengths of this new delay-based control scheme are. By plotting the average gain of the delay-based control for the fixed-cycle control (Fig. 6a) and the headway actuated control (Fig. 6b) it could be seen, that gains up to 50% are possible when the input volume comes close to the saturation volumes of the intersection. So, the delay-based control is a good approach for large and medium demands, and expected penetration rates above 10%.

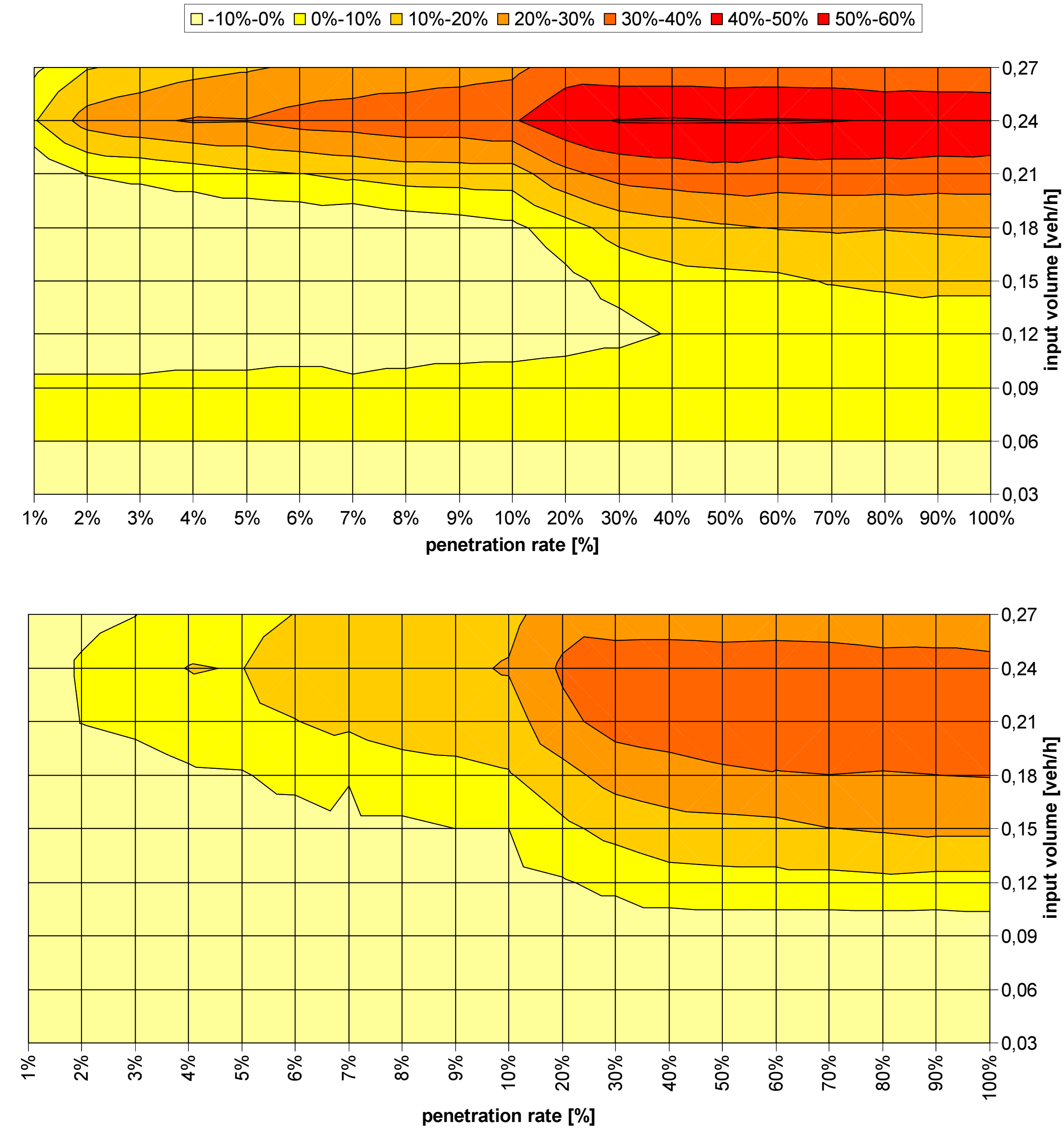

FIGURE 6 Gain in delay time compared to an optimized fixed cycle control based on Webster's equation (top, (a)) and a headway-actuated control (bottom, (b)).

4 Conclusions

The results presented here show that a delay-based control as described in this paper outperforms more traditional control schemes given a penetration rate above 10%. Especially Fig. 5 shows furthermore, that for penetration rates beyond 30% no further gains were possible, at least with the approach as described here. This convincing performance has an interesting additional effect: it means that this control is a really robust one, since it works well already with 10% equipped vehicles.

Delay-based control is a very promising approach, since it utilizes the many new data-sources available like video processing, probe vehicle data, vehicle-infrastructure integration, or Bluetooth-based approaches which usually deliver travel and delay-times, but often no traffic volumes.

This work here describes only the first steps into the new world of what can be done to work with these new data-sources. Clearly, the results obtained have been reached with a highly abstract simulation set-up, which was designed to demonstrate the main effect. It would be interesting to look into more realistic examples, which is one of the next steps to be taken, and to try to realize this set-up in the field.

Further avenues for research are the question how these results can be extended from a single isolated intersection to the level of whole networks, or how especially the VII can be used to set-up green control strategies, which e.g. consider the vehicle type (extending the green phase to let a truck pass if not too many vehicles are affected) and the like.

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