Minimization of Vehicle Stops by an Early Termination of Green Times in Traffic-Light Controlled Road Networks

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Abstract

Traffic lights are typically operated with cycle times and green splits being optimized for average expected demands. Unexpected demand fluctuations on shorter time scales require reactive adjustments to the green times. A commonly applied technique is to terminate green times within a scheduled period if the time interval to the next arriving vehicle exceeds a pre-defined value. However, this so-called vehicle interval method does not consider arrivals on subsequent stages.

As a model based alternative the paper proposes to anticipate the number of vehicle stops in the current as well as in the next stage as a function of possible termination time points. A stage transition is initiated when the total number of stops is at a minimum. The window of possible termination time points can be defined for each stage seperately. Additionally, synchronization time points guarantee fixed cycles and offsets for coordinated movements between intersections. Thus, the proposed method is qualified as a component/ module in traffic light networks and compatible/ works with fixed-time as well as traffic adaptive control strategies. Comparative simulations of a coordinated arterial indicate highly significant reductions of both, the number of vehicle stops and delay times.

Keywords: traffic light control, urban traffic, coordination, vehicle stops

1 Introduction

Vehicular traffic has shaped urban mobility throughout the last decades. As the functionality of the underlying infrastructure crucially depends on how road intersections are operated, much effort has been put into the investigation of traffic light control strategies that increase throughput and reduce delays. The first advancements have been made by fixed-time strategies that were optimized offline based on historical traffic data, for example, TRANSYT [Rob69]. In contrast, online control strategies aim to adapt to steadily changing traffic conditions by a permanent feedback of real-time detector data. The probably most famous examples are SCOOT [Hun81] and SCATS [SD80]. A broad overview of these and other approaches is given in the review articles [HM01; Pap03; Pap07].

A particular difficulty in the optimization of signal timings is the anticipation of traffic demands. As both the adaption and re-optimization of control parameters take place on time scales of several 10 minutes even with modern technology, assumptions have to be made. Some optimization methods assume periodic arrival patterns, such as OPAC [Gar83] or MOTION [BK01] whereas others assume uniform or stochastic arrivals, such as TUC [Dia03] or MOVA [VP88] which is based on Miller's algorithm [Mil63]. Although MOVA detects arrivals for the current stage as our proposed method, it further relies on traffic flow assumptions.

In order to react on short-term demand fluctuations, these (network control) strategies generally incorporate traffic-responsive elements. The most commonly used technique is the vehicle interval method. It terminates green times if (besides other conditions) the time gap to the next arriving vehicle is larger than a specified threshold. As large time gaps usually imply that an initial queue has been resolved and the majority of arrivals have been served, an early transition to the next stage will in most cases be more beneficial in terms of total vehicle delays and stops than the continuation of the present one. This heuristics fails, however, in two distinct situations: (a) A significant number of vehicles arrive after the critical gap was exceeded so that all of them have to stop at a red light. (b) A few stray vehicles postpone the transition to the next stage where an earlier green start would have prevented a larger vehicle platoon from being stopped.

By refraining from traffic demand assumptions beyond the detection horizon and with the purpose to overcome the problems of the vehicle interval method, this paper presents an alternative way to identify suitable termination time points. Real-time measurement is used to detect approaching vehicles employing a temporary rolling horizon. Thereof the method anticipates the number of vehicle stops caused by an early termination of the current green times. Then, they are compared against the number of stops that can be avoided by an earlier green start of the next stage. The chosen transition time point is determined by mimimizing the total number of stops under the conditions that (i) the termination time is within a specified time window, (ii) all initial queues have been cleared.

The paper is organized as follows. Chapter 2 introduces the concept of stop anticipation, chapter 3 formulates the control strategy, and chapter 4 quantifies the potential of stop minimization by the simulation of a coordinated arterial. The paper concludes with a discussion of the most relevant results.

2 Methodology

We consider a traffic light controlled intersection with a given cycle-based signal timing. The cycle is divided into stages s, in which all associated signal groups i show green simultaneously and control traffic movements on one or more lanes l. Since the green times of the signal groups often do not start (or end) at the same time point, a stage is defined as the period in which all associated signal groups display green. Consequently, the duration of a stage is generally shorter than the green times of the individual signal groups. Interstage timing periods seperate the stages.

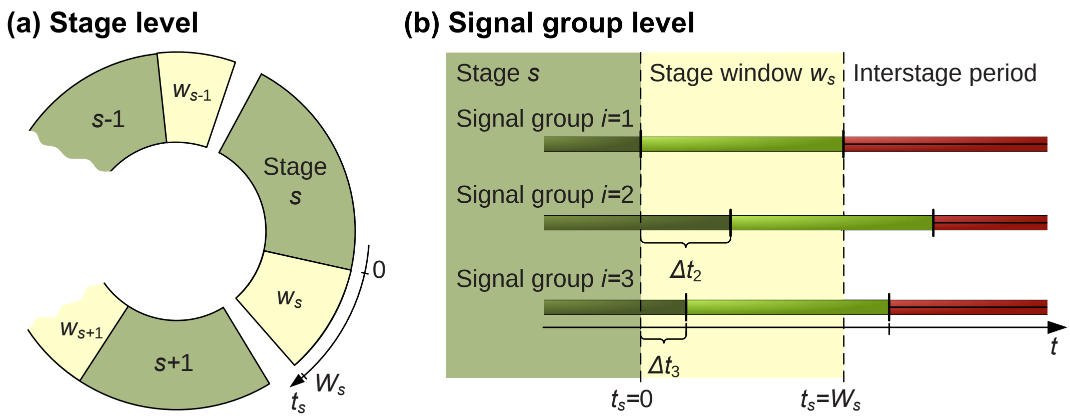

Figure 1: (a) The cycle of a given signal timing plan is divided into stages s (green), and interstage timing periods (blank). Possible stage termination time points t_s are defined by the window w_s (yellow). (b) The individual green end for an associated signal group i is shifted by Δt_i and lies within $[\Delta t_i, W_s + \Delta t_i]$ (light green bar).

2.1 Stage Transitions

Each stage s might be associated with a window w_s of possible termination time points. A window is assumed to cover the last W_s seconds of the correspondig stage period as Fig. 1 indicates. As soon as such a window is reached and all the conditions to be developed below are fulfilled, the controller immediately proceeds with the subsequent interstage timing period and thereby initiates the transition to the next stage. An early termination of the previous stage causes all signal groups of the following stage $s + 1$ to start its green times and its asociated window earlier by the same amount of time. The window end can be forwarded as well, or it remains fixed in the cycle. If we decide for fixed window ends, this means that previously saved green times are applied to extend the window.

In order to compensate for an undesired time drift, and to guarantee fixed cycle and offset times as required for coordination, at least one synchronization time point per cycle has to be included. Whenever the potentially advanced controller's time coincides with such a synchronization time point, it pauses until it is synchronized with the actual time again. Synchronization time points are to be placed within a stage period before the start of a window. Hence, the windows of those stages remain fixed. Typically, all stages that control coordinated traffic flows should be synchronized.

2.2 Termination Time Points

The termination time point of stage s relative to the associated window w_s is denoted by t_s. The value of $t_s = 0$ ($t_s = W_s$) corresponds to the start (end) of an associated window w_s, such that $t_s \in [0, W_s]$, see Fig. 1 (a). Note that, in terms of absolute time, the green times of the associated signal groups $i \in I_s$ do not end simultaneously at the termination of stage s. Since the green ends are constantly shifted by a time interval Δt_i, which is set according to the signal timing plan, some signal groups might end within the subsequent interstage timing period, as shown in Fig. 1 (b). Therefore, it is necessary to consider individual termination time points $t_i = t_s + \Delta t_i$. The same applies to the signal groups $j \in I_{s+1}$ of the next stage $s + 1$. Their individual starts t_j are linked to t_s by $t_j = t_s + \Delta t_j$, where Δt_j are generally scheduled to be larger than Δt_i because of the intergreen times. This notation will be used in the following to anticipate the number of vehicle stops that different termination time points will produce or avoid.

2.3 Arrival Detection

At least one inflow detector at each lane l of signal group i measures the crossing time points of the approaching vehicles sufficiently far ahead. A stop line detector per lane detects vehicles that pass the stop line during the green time. The free-flow travel time from the inflow detector position to the stop line is initially assumed to be invariable and should be larger than the previous interstage timing period plus the time required to clear an initial queue. For example, given the last two to be 5 s and 8 s, the free-flow travel time should be larger than 13 s. At a speed of 50 km/h, it requires an inflow detector distance of more than 180 m from the stop line. If intersections are closely spaced and to satisfy the minimum desired distance, stop line detectors of upstream intersections could be utilized. Possible additional inflow detectors allow to correct the arrival prognosis in case of variable velocities and lane changes.

Under the assumption that detector failures are neglectable, this setup allows an estimation of queue lengths, for example, by applying the section-based-model [Hel03; TK13]. Furthermore, it allows an anticipation of the green time required to clear a queue under the presence of irregular arrivals [LDH07]. From the balance of the inflow and the time-shifted stop line detector counting we can anticipate remaining queues at the end of a green time. If we additionally count the inflow detection impulses for all vehicles that will arrive at the stop line during red and during the estimated queue clearing process we are able to anticipate the initial queue length.

Each detection impulse at an inflow detector indicates that a new vehicle $v \in V_{s,l,i}$ is about to arrive at the associated lane l. Under free traffic conditions, i. e. if the regarded vehicle is neither delayed nor stopped, it will pass the stop line later than the detector impulse occured, namely after the according free-flow travel time. Its earliest possible arrival time point on lane l of signal group i is denoted by $t^{\mathrm{arr}}_{v,l,i}$. In order to account for the number of vehicle stops, we need to evaluate for all approaching vehicles whether the traffic light shows green and whether the queue is cleared at the time when they could arrive at the stop line.

2.4 Vehicle Stops in the Current Stage

We consider a state in which all signal groups i of stage s show green, first, discharging initial queues and then serving arrivals. To detect queue clearing in practice, we suggest to measure if the saturation flow rate of a lane s_l decreases for the current stage. Since the control strategy as developed below will not terminate a stage before all queues have been cleared, it is not neccessary to account for queue-related stops. We will also not account for vehicles that arrive after the window end W_s, as they always have to stop for a red light independent of whether the stage was terminated earlier or not. Therefore, the total number of vehicle stops $A_s(t_s)$ that result from an early termination of the present green times can be written as a function of the termination time point t_s.

$$A_s(t_s) = \sum_{i,l,v} \alpha_{i,l,v}(t_s) \quad \text{with} \quad \alpha_{i,l,v}(t_s) = \begin{cases} 1, & \text{if } (t_s + \Delta t_i < t^{\text{arr}}_{v,l,i} < W_s + \Delta t_i) \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

If vehicles $v \in V_{s,l,i}$ of lane $l \in L_{s,i}$ arrive later than the associated signal group $i \in I_s$ terminated,

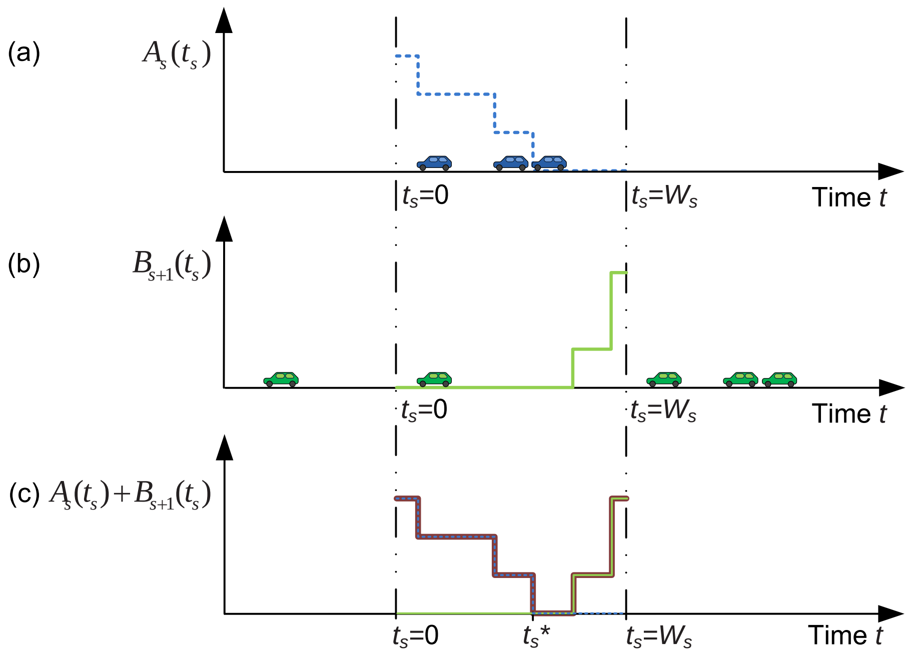

Figure 2: Anticipated number of vehicle stops as a function of the termination time (a) in the current stage, (b) in the next stage, and (c) in total.

they have to stop. Hereby, the indicator function $\alpha_{i,l,v}(t_s)$ is used to select those vehicles. The function $A_s(t_s)$ describes a stepwise decreasing curve that reaches zero at the window end $t_s = W_s$. Any earlier termination time point $t_s < W_s$ might result in a positive number of stops dependent on how many vehicles arrive between t_s and W_s, see Fig. 2 (a).

2.5 Vehicle Stops in the Next Stage

After the current stage s is to terminate at time point t_s, the green times of the signal groups j of the next stage $s+1$ will start accordingly sooner. Consequently, initial queues will be cleared earlier and further arrivals are potentially prevented from being stopped. Since the queued vehicles can only leave one after the other, the earliest time at which vehicle $v_{l,j}$ on lane l can pass the stop line is the time $t_j = t_s + \Delta t_j$ at which signal group j has turned to green, plus the time τ_v that all other vehicles in front of $v_{l,j}$ need to depart. Therefore, all vehicles from a potentially remaining queue after the previous green end and from the ongoing red period are counted starting with the first stopped vehicle $v_{l,j} = 1$. Hereby, τ_v can be estimated as the number of vehicles in front of $v_{l,j}$ divided by the saturation flow rate of the associated lane s_l.

$$\tau_v = \frac{v_{l,j} - 1}{s_l} \tag{2}$$

Accordingly, vehicle $v_{l,j} \in V_{s+1,l,j}$ will have to stop if it arrives before $t_j + \tau_v$, i. e. before all previous vehicles have departed on green. This leads to the following expression for the number of stops $B_{s+1}(t_s)$ that occur on lane $l \in L_{s+1,i}$ of signal groups $j \in I_{s+1}$ in the next stage $s+1$ as a function of the termination time point t_s.

$$B_{s+1}(t_s) = \sum_{j,l,v} \beta_{j,l,v}(t_s) \quad \text{with} \quad \beta_{j,l,v}(t_s) = \begin{cases} 1, & \text{if } (\Delta t_j + \tau_v < t^{\text{arr}}_{v,l,j} < t_s + \Delta t_j + \tau_v) \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

The indicator function $\beta_{j,l,v}(t_s)$ accounts for only those stops that will be avoided if the previous stage terminates at t_s. Since the earliest possible green start of signal group j is $t_j = 0 + \Delta t_j$, the above formula does not capture vehicles with arrival time points earlier than $\Delta t_j + \tau_v$, i. e. it ignores stops that occur in any case (contrary to the estimation of τ_v). Therefore, the function $B_{s+1}(t_s)$ is zero at $t_s = 0$ and increases stepwise from there on.

Note the strong sensitivity of $B_{s+1}(t_s)$ on arriving vehicle platoons. All vehicles whose stop can been avoided by an early termination of the previous stage, i. e. all vehicles with arrival time points $t^{\text{arr}}_{v,l,j} > (\Delta t_j + \tau_v)$, will extend the τ_v-values of their successors. Thereby, these vehicles enlarge the upper bound $t_s + \Delta t_j + \tau_v$ of arrival time points and the scope of vehicles which $\beta_{j,l,v}(t_s)$ accounts for. In consequence, a platoon of n closely following vehicles will cause $B_{s+1}(t_s)$ to jump by the same amount n as soon as the termination time point t_s causes the platoon to stop, see Fig. 2 (b). Another implication of this oberservation is that $B_{s+1}(t_s)$ is not strictly limited. It can, unlike $A_s(t_s)$, be larger than the number of vehicles that arrive within the associated window w_s.

3 Control Strategy

The following control strategy is being applied: Given the window w_s of stage s has started, i. e. $0 \le t_s < W_s$, and all vehicle queues of the associated signal groups have been cleared. Then, the current stage s is terminated, and the transition to the subsequent stage $s+1$ is initiated as soon as the total number of anticipated stops

$$A_s(t) + B_{s+1}(t) \tag{4}$$

over all remaining termination time points $t_s \leq t < W_s$ is at the minimum for the current time point t_s.

In case of multiple minima, i. e. if several different termination time points lead to the same minimum number of stops, the above strategy decides for the first time point. In particular, if the minimum ranges over a continuous time interval due to larger arrival headways, this strategy terminates the current green times right after the last vehicle has passed the stop line and turns on the green lights of the next stage sooner.

4 Simulation Results

The above control strategy, referred to as Stop-Minimization, has been implemented in Java and integrated to the microscopic simulation tool VISSIM using the COM-interface. We simulated an arterial consisting of five intersections, as depicted in Fig. 3. As we had access to all vehicle positions through the COM-interface, specific detector positions have not yet been implemented. Based on a set of signal timing plans that was designed and optimized according to the Traffic Signal Timing Manual [Tra08], we implemented the fixed-time, the vehicle interval, and the proposed Stop-Minimization control at unsaturated conditions.

Table 1: Demand and Flow relations.

Approach	Origin traffic demand	Right turns	Through	Left turns
West (I1, I3, I5)	840 veh/h (I1)	5 %	95 %	–
East (I1, I3, I5)	640 veh/h (I5)	10 %	90 %	–
East/West (I2, I4)		10 %	80 %	10 %
North (I1-I5)	250 veh/h (I4: 200 veh/h)	30 %	50 %	20 %
South (I1-I5)	250 veh/h (I2: 200 veh/h)	40 %	30 %	30 %

We applied the inflow rates and turning relations as given in Tab. 1. The signal timing was designed to propagate a green wave eastwards at a speed of 50 km/h. Based on the most saturated intersection I4, a common cycle length of 90 s, the following green splits, and four stages were chosen: (1) the coordinated bidirectional arterial with through movements and right turns (split: 42 %), (2) main street left turns (12 %), (3) all northern movements (22 %), and (4) all southern movements (23 %). The other intersections give 42 % of the cycle to the coordinated main street as well. For those without main street left turns, the spared green times were proportionally assigned to the north and south approaches. In order to keep the saturation of green time at a level below 75%, the inflow at I2 south and I4 north was reduced (see Tab. 1).

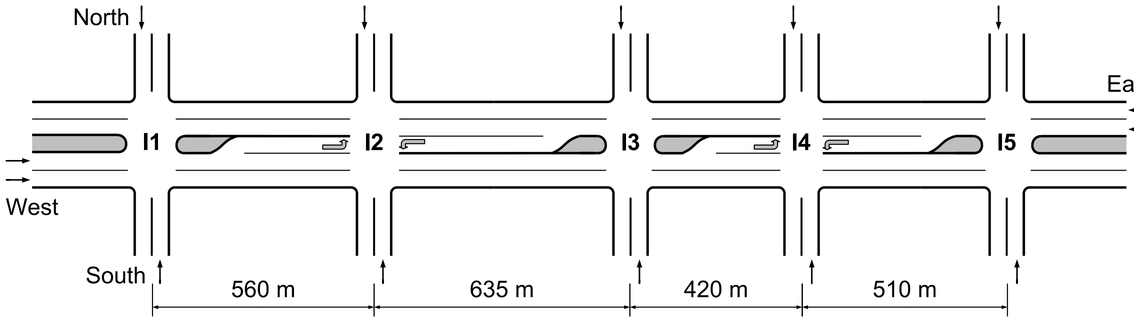

Figure 3: Arterial with five irregularly placed intersections.

For the Stop-Minimization and the vehicle interval control, equivalent windows were allocated within the so specified green times. The window start was defined: (a) for the non-coordinated stages immediately after a minimum green of 5 s, (b) for the coordinated stage after the green time that is necessary to serve the average expected number of vehicles at maximum flow rate. For the vehicle interval control, we chose a critical time gap of 4 s as Akçelik [ABR99] suggests in his study on queue discharge characteristics. For both strategies, saved green times from early terminations were allowed to extend further windows of the next stages up to the coordinated stage, in which a synchronisation time point was assigned to.

Table 2: Average stops and delay times per vehicle based on 40 simulation runs of one hour, each. The relative savings refer to the fixed-time control. Corresponding t-values indicate a high significance ($p < 10^{-9}$).

Strategy	Stops	t-value	Delay	t-value
Fixed-time control	1,410	–	53,43 s	–
Vehicle interval control	1,356 (-3,9 %)	20,275	51,52 s (-3,6 %)	21,32
Stop-Minimization	1,318 (-6,5 %)	36,958	49,71 s (-7,0 %)	39,75

By setting the fixed-time control as the reference, the other two strategies performed significantly better (see Tab. 2). The proposed Stop-Minimization even outperfomed the vehicle interval control. Most termination decisions of the two strategies had the same effect on stop savings as Fig. 4 (b) illustrates. Whereas the vehicle interval method was designed to wait for gaps above 4 s, the Stop-Minimization occasionally accepts smaller gaps in cases where many stops are prevented (see Fig. 4 (a)). Furthermore, the red dots at the lower half of the scatter plot in Fig. 4 (c) indicate that the vehicle interval control fails to save stops by waiting for large enough time gaps.

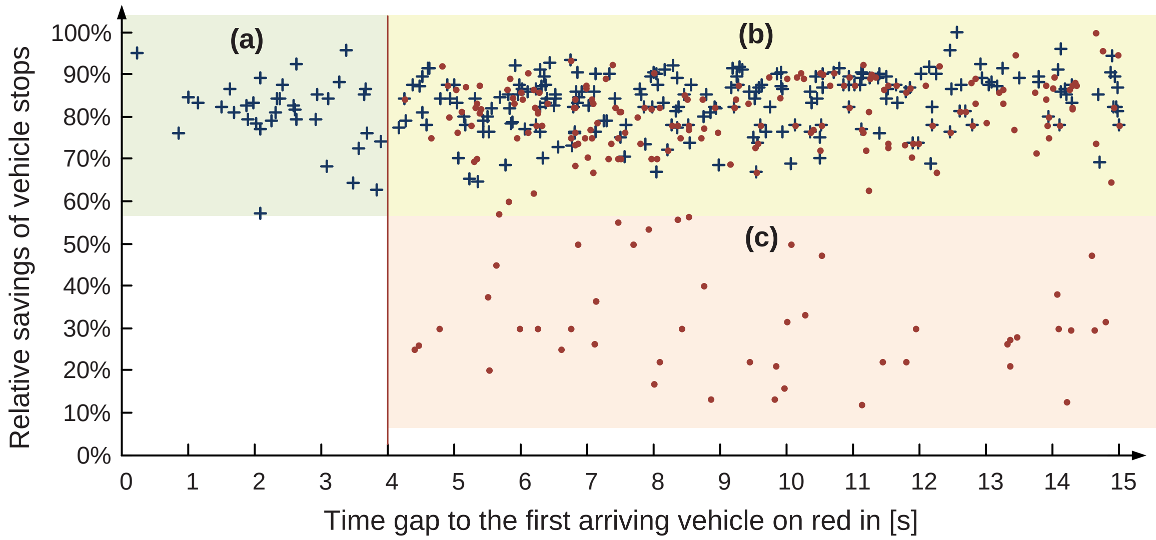

Figure 4: To compare the performance of the Stop-Minimization (crosses) and the vehicle interval control (dots), the control parameters of each were measured at the stage termination point: (1) The relative stop savings within the window for both stages as ratio of undelayed vehicles to total arrivals that could have been stopped and (2) the time gap from the green end to the next arriving vehicle at the stop line.

5 Conclusion

We proposed a method to enhance a coordinated traffic light control by traffic-responsive elements. In order to miminize vehicle stops, a stage is allowed to be terminated between a minimum and a maximum green time. The coordination based on common cycle length and fixed offsets was maintained due to (i) introducing synchronization time points and (ii) applying the concept of windows.

This concept is compatible with any cycle-based control strategy that is arranged in stages. Furthermore, it appears to be a significantly better performing alternative compared to the heuristic vehicle interval control. Since the proposed model-based approach considers all arrivals within the available prognosis horizon, and as it also accounts for arrivals in subsequent stages, it is more anticipative than the vehicle interval control. This might be the reason for the improved adjustment to short-term traffic fluctuations.

The way how the chosen termination time points influence the stages after the next is not explicitly evaluated. If a stage is terminated earlier, it can induce more vehicles waiting at the next start of the same stage, and this may postpone its termination. Furthermore, the effect on the next intersection, for example, by an earlier starting platoon, is disregarded. The results of the simulation indicate that in most cases the controller of that intersection is able to react on the time changed arrivals in the same way. While the Stop-Minimization concept operates on a limited temporal as well as spacial horizon, it seems still able to adapt to global demands. More broadly, research is needed to validate the effects in a more complex and realistic simulation scenario, for example, by implementing a real-world traffic network.

Further investigations have to be made on how to overcome limitations of vehicle detection. So far, a sufficient prognosis horizon has been assumed to detect every vehicle that is affected by an early termination. However, especially long queues in the next stage would require extensive horizons and thus impracticable large detector distances. Short lanes are not yet considered. Besides additional inflow detectors they need a more advanced anticipation of how many vehicles will enter that lane. An additional objective is to enhance the control for oversaturated traffic conditions, for example, by extending the strategy with a capacity maximizing mode. Then, green times could be adjusted within the framework of windows to increase departure flow rates.

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