Inflow-Regulating Traffic Light Control to Avoid Queue-Spillovers in Urban Road Networks

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Abstract

The capacity of a road network is predetermined by the green times at its intersections. As these are typically designed for expected traffic demands, spontaneous demand peaks or lane blockings will likely lead to congestion spreading over larger parts of the network, possibly ending up in a gridlock situation. We show that critical queue spillbacks can be avoided by an inflow-regulating traffic light control that does not serve more vehicles than subsequent roads can accommodate. In this way, vehicular queues only build up within designated areas of the roads segments, whereas upstream intersections remain fully accessible for non-affected flow directions. The accelerated propagation of segmented queues allows drivers to notice obstructions along their chosen route early enough to consider alternative routes or alternative modes of transport. In consequence, congested parts of the network are relieved from some traffic, whereas remaining capacities on surrounding roads are utilized. In a simulation study, the inflow-regulation principle noticeably prevented the emergence of a gridlock situation in two incident scenarios.

Keywords: vehicular traffic - road network - traffic light control - incident management - gridlock

1 Introduction

The signal timing of traffic lights is typically designed to provide the intersections of a road network with a throughput significantly higher than the average expected demand. A comprehensive overview of traffic light control strategies is given, for example, in Refs. [**Porche1997**; **Hounsell2001**; **Papageorgiou2003**]. Green times classically follow a cyclic scheme, with which a coordination of arterial roads is intended [**Gartner1975**]. In order to cope with variable traffic flows, some strategies, such as SCOOT [**Bretherton2004**], dynamically adapt the control parameters. SCATS [**Sims1979**], for example, recombines the pairs of intersections in coordination depending on actual demands. More recent developments apply more advanced optimization techniques such as rolling-horizon methods [**Porche1996**], genetic algorithms [**Braun2008a**], and model predictive control [**Lin2012**]. Nevertheless, the optimal control of traffic networks remains an unsolved problem of high computational complexity [**Papadimitriou1999**]. Current research activities approach this complexity by designing rules that let desired dynamical properties such as synchronization or coordination emerge in a self-organized way. Relevant candidates are the "organic traffic light control" [**Prothmann2009**], the "self-organizing traffic lights" [**Gershenson2012**], the "schedule-driven control" [**Xie2012**], or the "self-control" [**Lammer2008**]. A review on multi-agent approaches to traffic signal control is provided in [**Chen2010**].

The adaptation of intersection capacities towards variable traffic demands becomes problematic, however, in cases where the demand exceeds the maximum available intersection capacities or where queues start to spill back from one intersection to another. As soon as the growth of queues from cycle to cycle is inevitable, it becomes crucial to utilize remaining capacities in the most efficient way. An option would be to allocate maximum green times to those roads with the highest number of lanes at the cost of the other roads [**Gazis2002**]. More generally, it is important to maximize the potential outflow from a critical region while restricting its inflow [**Daganzo2007**]. Daganzo further distinguishes between "jam" and "gridlock" states. A gridlock state characterizes the precarious situation where an accumulation of vehicles in the network implies a blockade of potential outflow capacity, i.e. where the vehicles hinder themselves from leaving the network. Such gridlocks occur when vehicle queues spill back from one intersection to the next and eventually obstruct other flows. This might, in consequence, trigger a cascade. Therefore, efficient traffic light control requires an efficient prevention of queue spillovers.

This paper transfers Daganzo's principle of restricting the inflow into congested regions to a local traffic light control strategy, which reduces the amount of green times for those traffic flows that lead into congested road segments. Sec. 2 presents the basic idea and postulates particular features. Sec. 3 develops an analytical formulation of how traffic lights can avoid queue spillbacks by regulating its green times. Sec. 4 depicts the simulation study and its results. The key findings are concluded in Sec. 5.

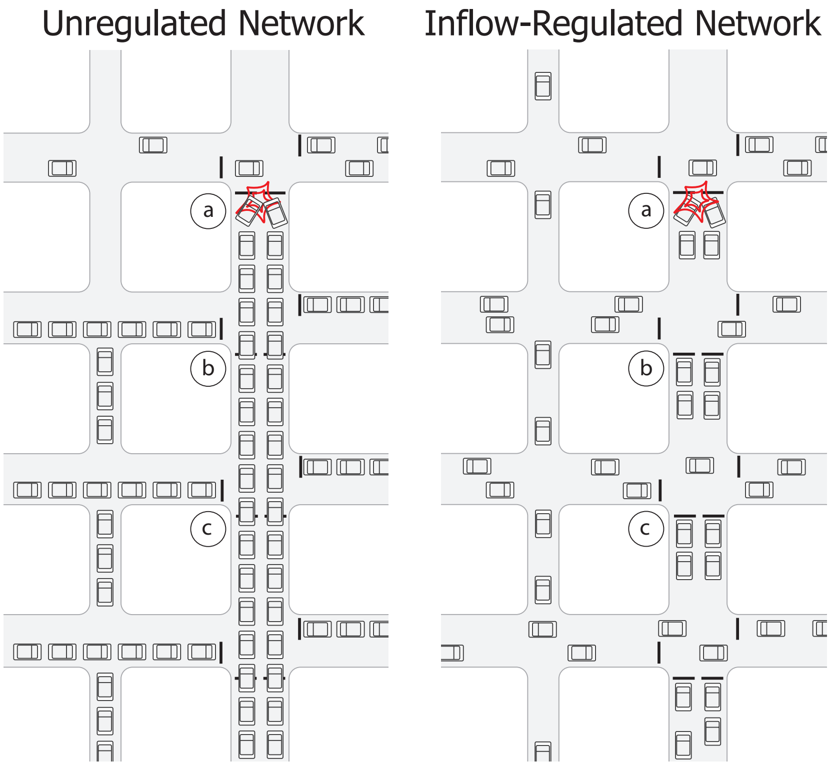

Figure 1: In a simple road network, where the main road is blocked due to an accident, the traffic situation evolves differently dependent on whether the intersections are inflow-regulated or not. Left: In the unregulated case, queues spill back and let larger parts of the network collapse. Right: (a) The purely local inflow-regulation hinders traffic from entering road segment before its queue exceeds a maximum length. Fewer cars encounter a standstill and the accident area remains accessible for rescue vehicles. (b) Intersections are not blocked and remain passable for unaffected flows. (c) The accelerated propagation of segmented queues lets drivers perceive the obstruction far ahead from the accident allowing them to decide for alternative routes.

2 Inflow-Regulation Principle

Inflow-regulation keeps the length of vehicle queues within certain bounds. As this local principle prevents intersections from gridlocks, it has several interesting implications on traffic flow at network scale. Some distinct features are illustrated in Fig. 1 and explained in the following.

2.1 Delimiting the Queue Length on a Road Segment

On a single road segment, congestion grows as soon as its inflow demand exceeds its outflow capacity. Extending the outflow capacity is often not possible, in particular if the downstream intersection is over-saturated or if a lane is blocked. Instead, the upstream intersection can instantaneously limit the inflow into the congested road segment as soon as its queue tends to exceed a certain length. This can be accomplished by skipping or shortening associated green times. This imposes some requirements on the traffic light that controls the inflow into the regarded road segment. It must in particular be able to estimate the remaining queuing capacity of the road segment and how it evolves dependent on measured inflow and outflow rates. The analysis in Sec. 3 develops a formula with which conventional traffic light controls could be extended.

2.2 Keeping Intersections Passable for Unaffected Flows

As inflow-regulating traffic lights avoid the spillback of vehicle queues, the intersection remains passable for all flow directions that lead not into congested road segments. The intersection remains accessible for other modes of transport as well as for emergency vehicles. Notice also, that drivers that intended to enter the congested road segment now face long red times. Since available turning directions are signalized with regular or even extended green times, however, drivers are able to consider alternative routes and use them.

2.3 Segmented Queue Growth Inhibits Global Gridlock Effects

Applying the inflow-regulation principle to multiple intersections in a network has several implications on how traffic and congestion evolves as a result of an incident. Most importantly, vehicular queues do not grow in a continuous manner. Instead, as they are restricted to build up within road segments only, queues grow segmentally. Since they spare out some space, segmented queues propagate faster towards the origins of traffic. While this means that drivers are held back earlier than in unregulated networks on the one hand, they are also able to notice obstructions further ahead on the other hand. Consequently, if some drivers decide to choose alternative routes or alternative modes of transport, traffic is redistributed such that remaining road capacities are utilized. Each vehicle that leaves a congested part of the network allows another vehicle to enter it a certain time later. One might observe that vehicle gaps start to propagate backwards from the exits to the entrances as analytically explained in [**Helbing2006c**]. Congested parts of the network are relieved from traffic while unaffected flows can leave the network unrestrictedly. Since the emergence of gridlock situations is largely inhibited in regulated networks, the outflow capacity is only limited by the incident itself.

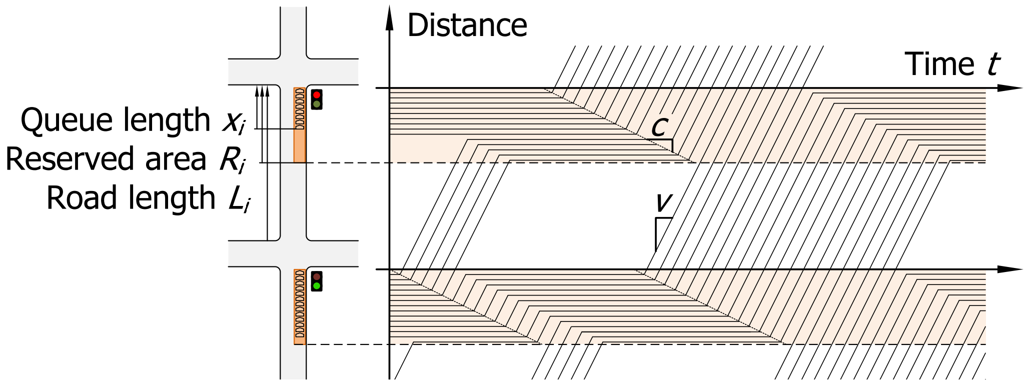

Figure 2: Left: The traffic lights along a road regulate the inflow into subsequent road segments such that vehicles only stop in reserved areas (shaded). Right: Associated vehicle trajectories indicate that maximum queue lengths are never exceeded. Vehicles are being served with a green light in a way, that they join subsequent queues at exactly those time points, at which they can fill in gaps departing vehicles created before.

3 Traffic Light Control

The intersections of a road network are operated with traffic light controllers that, for example, optimize traffic flow with respect to minimum delays or vehicle stops. In order to incorporate the proposed inflow-regulation, the control algorithms are to extend by an additional rule saying *"Do not let more than $d_s(h)$ vehicles depart from traffic stream s within the next h seconds."* The following analysis develops a formula for $d_s(h)$.

3.1 Queue Model

Consider a single-lane road segment i as depicted in Fig. 2. It has a length of L_i meters, on which only the most downstream R_i meters are allowed for queues to build up. If vehicles require an effective space of l meters each in a queue, the number of queued vehicles is limited to R_i/l. In free traffic, vehicles travel at the maximum allowed velocity of v meters per second with which they would need L_i/v seconds to pass through.

The cumulated count of vehicles arriving and departing from road segment i at time t is denoted by $A_i(t)$ and $D_i(t)$, respectively. These numbers can be constructed, for example, from pulse counts of induction loops that are positioned at the upper and lower end of the road segment. Note, that there are two calibration conditions, $A_i(t - L_i/v) - D_i(t) = 0$ in case of free traffic, and $A_i(t) - D_i(t) = 0$ in case of an empty road, that allow to correct detection errors. Also note, that, if the in- and outflow of a homogeneous road section is given, the temporal evolution of the queue length $x_i(t)$ can be analytically estimated with section-based methods, which assume flow continuity and a piecewise linear flow-density-relation [**Daganzo1994**; **Helbing2003a**; **Treiber2013**]. The following analysis is based on an estimate of the current queue length $x_i(t)$ and then balances the number of vehicles joining the queue against the number of vehicle-gaps that become available at the end of the queue after vehicles departed.

3.2 Anticipation of Queuing Capacity

At time t a queue of length $x_i \leq R_i$ has built up. The remaining $R_i - x_i$ meters of queuing space has a capacity for $(R_i - x_i)/l$ additional vehicles. Since this space is being partially filled with vehicles that arrived within the past $(L_i - x_i)/v$ seconds, there remains space for

$$\frac{R_i - x_i}{l} - \left[A_i(t) - A_i\left(t - \frac{L_i - x_i}{v}\right)\right] \tag{1}$$

additional vehicles to arrive.

Departures from the queue create gaps that allow subsequent vehicles to move up. Gaps propagate through the queue in opposite driving direction at a characteristic negative velocity $c \approx -5$ m/s. This means, the gap a vehicle created due to its departure at time $t + x_i/c$ compensates for another vehicle joining the queue at time t. The sum of gaps currently present within the queue, i.e. those that departing vehicles created within the past $-x_i/c$ seconds, can be filled with

$$D_i(t) - D_i\left(t + \frac{x_i}{c}\right) \tag{2}$$

vehicles reaching position x_i up to time t. If a vehicle arrives at road segment i at some future time point $t+h$, it will find a gap in the queue to fill in, if another vehicle has departed before time point $t + h + (L_i - x_i)/v + x_i/c$. Moreover, the sum of all vehicles that departed before that time point will allow another

$$D_i\left(t + h + \frac{L_i - x_i}{v} + \frac{x_i}{c}\right) - D_i(t) \tag{3}$$

vehicles to enter the road segment up to time point $t + h$.

In order to answer the question, how many more vehicles

$$a_i(h) := A_i(t + h) - A_i(t) \tag{4}$$

are allowed to arrive at road segment i within time horizon h, the sum of Eqs. (1) to (3) has to be computed. As a result, the queue will not exceed a maximum length of R_i meters, as long as there will not arrive more than

$$a_i(h) = \frac{R_i - x_i}{l} + A_i\left(t - \frac{L_i - x_i}{v}\right) - A_i(t) + D_i\left(t + h + \frac{L_i - x_i}{v} + \frac{x_i}{c}\right) - D_i\left(t + \frac{x_i}{c}\right) \tag{5}$$

vehicles at road section i within the next h seconds.

3.3 Green Time Adjustment

At the intersection upstream of the investigated road segment i, there are several incoming traffic streams s. Ideally, each stream would lead to exactly one outgoing road segment i, which is the case for separate turning lanes. In more general cases with mixed lanes, however, there will only a certain fraction α_{si} of the vehicles of traffic stream s turn into road segment i. Obviously, $\sum_i \alpha_{si} = 1$ is valid for all streams s. Since the number of vehicles that arrive at i is restricted by Eq. (5), the maximum number of vehicles allowed to depart from stream s within horizon h follows to be:

$$d_s(h) = \min_i \frac{a_i(h)}{\alpha_{si}} \tag{6}$$

In order to ensure that the queues on neither of its outgoing roads i exceed a certain critical length R_i, the corresponding traffic light control must not allocate more green time to its incoming traffic streams s within time horizon h than $d_s(h)$ vehicles require to depart.

3.4 Discussion

In the more general case of multi-lane traffic, the effective length l of a vehicle in a queue has to be divided by the number of lanes. Note also that the turning fractions α_{si} will vary in time as soon as drivers consider alternative turning directions. Even if Eq. (6) only serves as a rough estimate, using it with historical turning fractions obtained from non-perturbed traffic situations is still safe with respect to a reliable inflow-regulation. As drivers tend to avoid congestion, historical α_{si} values overestimate the actual turning rate into congested road segments i, which results in rather under-critical green times for the corresponding streams s. Another practical issue is that safety directives may impose maximum red times. In these cases, at least a short green light must be given after a certain while. Furthermore, the time shift $h + (L_i - x_i)/v + x_i/c$ in Eq. (5) might become positive, which implies a reference to future departures at the subsequent intersection. If the signal timing of that intersection is not known in advance, a safe measure could be to assume that future departures will not take place, i.e. to assume $D_i(t') = D_i(t)$ for future time points $t' > t$. The available queuing capacity will thereby be underestimated. In a scenario, however, with $L_i = 500$ m, $v = 15$ m/s, $c = -5$ m/s, and $x_i = 200$ m, the respective time shift will not become positive for horizons $h \leq 20$ s.

A particularly well suited control strategy to be combined with the proposed inflow-regulation is the "Self-Control" as introduced in [**Lammer2008**]. It is not restricted to cycle times or to a fixed order of phases. It does instead calculate a priority index for each traffic stream based on the short-term anticipation of the number of cars expected to arrive in the queue within the next few seconds, and gives green to those non-conflicting streams for which the priority index is highest. In case of variable inflows, this naturally results in irregular switching sequences, in which some streams might be served more often than others. An implementation of the inflow-regulation principle would require to calculate the

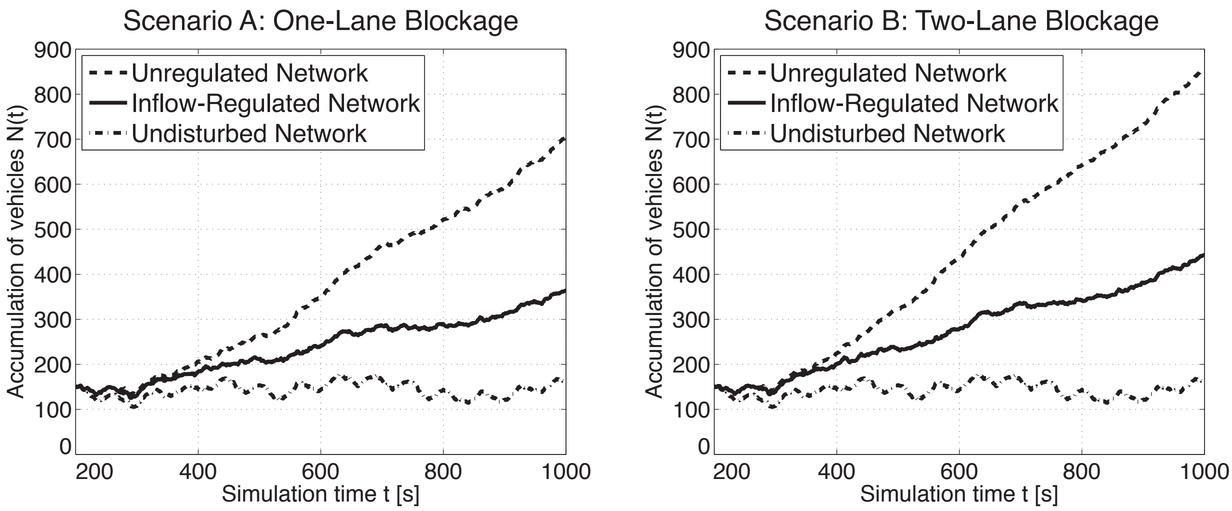

Figure 3: For both scenarios A (left) and B (right), the accumulation of vehicles is significantly lower in the inflow-regulated network (solid) as compared to the unregulated network (dashed). This is due to the fact that inflow-regulated intersections avoid the spillover of queues and, thereby, remain fully passable for all non-affected flows. In both scenarios, the outflow capacity of the regulated network is only limited by the incident itself.

priority indices over no more than $d_s(h)$ vehicles according to Eq. (6). If a particular stream leads into a queued road, the corresponding priority index will drop, and green times are automatically allocated to other streams.

4 Simulation Results

The proposed inflow-regulation principle was validated by using the example network depicted in Fig. 1. The simulation runs were accomplished with the commercial traffic flow simulation tool PTV Vissim[1]. The road segments between two intersections have a length of 70 m. Roads on which traffic enters the network, however, were chosen long enough to accommodate all queues that result from the regarded incidents. The inflow traffic volume was set to 1200 veh/h on the main road and to 300 veh/h on the others. Turnings were generally not permitted. The intersections were operated with fixed-time controllers and a common cycle time of 60 s. Green times were set to 40 s for the main road direction and to 20 s for the other flow directions. The offsets were chosen to let a green wave propagate along the main road. The inflow-regulating principle was implemented such that a scheduled green time is given only if the vehicle queue on downstream road segments does not exceed a maximum length of 35 m. Saved green times were not redistributed to other flow directions.

Two incident scenarios, A and B, are considered. Both reflect an accident near the most downstream stop line of the main road. In scenario A, drivers can bypass the accident via one lane at walking speed. In scenario B, the accident blocks both lanes of the road. Both incidents are active for a duration of 800 s.

[1] Version 5.40

For a quantitative comparison of the regulated and unregulated network, Fig. 3 shows how the accumulation of vehicles N evolves in each case. As the regarded incidents cause a queue to grow along the main road in any case, the difference is on how much non-affected flows were involved. The unregulated network resulted in a distinct gridlock situation, in which eventually no vehicle was able to leave the network anymore. Contrarily, the inflow-regulation principle prevented the main road queues from spilling back to upstream intersections such that the flows from the other roads were not obstructed by the incident. In consequence, the number of vehicles in the network could be reduced by 48.4 %. Results are summarized in Table 1.

Table 1: Accumulation of vehicles N at the end of each simulation run ($t = 1000\,\mathrm{s}$).

	Scenario A	Scenario B
Unregulated Network	703	857
Inflow-Regulated Network	363	442
Relative savings	48.4 %	48.4 %

5 Conclusion

The proposed inflow-regulation principle prevents vehicle queues from spilling back to the most upstream intersection. Traffic lights regulate the inflow into congested road segments by shorter green times to make sure its queue does not exceed a certain predefined length. This purely local principle has several implications. First of all, the corresponding intersections remain fully accessible for traffic with different destinations and, additionally, for traffic that bypasses congestion. Hence, precarious gridlock effects are largely inhibited and the impact of the incidents is limited to a much lesser extent. Taking all effects together, the inflow-regulation principle manages incidents in a much faster and more efficient way.

Only being allowed to build up on road segments, queues grow segmentally. This implies that information of obstructions along a certain route propagates faster through the network. This gives drivers a chance to consider and choose alternative routes soon enough. However, drivers may experience that the traffic lights along a chosen route are red for an exceptionally long time. Neither the reason of this obstruction is obvious, nor will the drivers by themselves be able to estimate expected travel times along alternative routes, nor will they know what routes are accessible at all. Consequently, each individual driver will face a complex decision process in which he must heuristically decide to either stay on the original route for a certain while, or to move on to one of the potentially available turning directions. Online navigation systems [**Cohn2009a**] might support this decision process.

The simulation study has resulted in a significant reduction of the accumulation of vehicles in the inflow-regulated network. Vehicles of other flow directions were not hindered from crossing the intersections and, thus, from leaving the network. The regulated network, therefore, was relieved from some traffic and could also avoid the emergence of a gridlock situation. In the simulation study, drivers were not allowed to turn. It remains a future task to develop an according route choice model of individual drivers. It is to expect that the redistribution of traffic among available bypass roads will further decrease the accumulated number of vehicles in the network.

We further propose to extend the inflow-regulation principle by additionally reallocating the green times of possibly present turning directions. While the green times for flows into congested roads are shortened or skipped, the green times for available turning directions could be likewise expanded. This provides capacity to those drivers that decide for an alternative route. Both, the inflow-regulation principle and the instantaneous reallocation of green times, give rise to a purely autonomous capacity regulating control concept in partially obstructed networks. If it was possible to redistribute all affected traffic flows along the remaining network capacities, the network would have "healed" itself. Several, more theoretical, questions remain to be addressed in further studies. These questions include how non-equilibrium traffic states in networks with capacity regulating traffic lights can be modeled, and what preconditions a network must have in terms of road capacity, traffic load, or routing alternatives, in order to satisfy given traffic demands also in case of incidents.

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