Paper ID SP1953

Cooperative adaptive traffic control: predictability versus traffic efficiency

Meng Lu, Xiaoyun Zhang, Robbin Blokpoel

[1] Dynniq, Basicweg 16 3821 BR Amersfoort, The Netherlands. meng dot lu at dynniq dot com
[2]

Abstract

Automated traffic signal control systems have been developed for more than six decades. Traffic signal control is essential for road safety, network efficiency, and air quality in urban areas. Convectional traffic control methods are static control, actuated control, semi-fixed time control and adaptive control. Predictability of the control algorithms has increased over time, but is hampered in a traditional non-cooperative environment by disrupting factors, such as prioritised vehicles and Vulnerable Road Users (VRUs). This paper explores cooperative adaptive traffic signal control for VRUs. A green wave simulation study applying Green Light Optimised Speed Advisory (GLOSA) for cyclists at six consecutive intersections on a city corridor is discussed. The results show that the trade-off between predictability and traffic efficiency is well handled. The paper also elaborates cooperative adaptive traffic control for future applications in road transport.

Keywords: signal control, cooperative, traffic management, traffic efficiency

Introduction

In an urban area with mixed traffic, traffic signal control plays an important role in traffic management for road safety, comfort of road users, network efficiency, and fuel efficiency. The latter two directly contribute to air quality improvement and homogenous traffic flow.

Cooperative Intelligent Transport Systems (C-ITS) has been developed more than a decade. C-ITS is based on ICT (Information and Communication Technologies), such as sensor technology, telecommunications, information processing and control technology. Green Light Optimal Speed Advisory (GLOSA) is one of the C-ITS services [C-ITS Platform, 2016]. GLOSA provides vehicle drivers an optimal speed advice when they approach to a controlled (or signalised) intersection. For GLOSA, green wave and signal optimization, a high degree of predictability of the time to green is required. However, predictability is hampered by disrupting factors, such as prioritized public transport, Vulnerable Road Users (VRUs), and of automated vehicles (either single or in a cluster).

In traditional traffic (without cooperative systems), pedestrians and cyclists are disturbing factors for adaptive control when it comes to predictability. This is due to the detection method, which is usually with a push button or a loop close to the stop line. Once detected they are immediately waiting and therefore the control plan has to be short-term adjusted to keep the waiting time low. However, when the predictability of the control is actively improved by new policies, this information can be fed to pedestrians and cyclists as well. Using a sign or an app, the information about the time to the next green phase can be easily communicated to the VRUs. Especially for cyclists this is interesting as they can adjust their speed to arrive at the intersection during green. If the cyclist has to slow down from the desired speed, energy will be saved, which can be used after the intersection to go faster again, compensating for the lost time. The alternative of stopping and accelerating from standstill will be less favourable from an energetic perspective. This effect should more than offset the small increase of delay time due to lost flexibility due to the control algorithm.

It is important to understand the disrupting factors for predictability to increase the predictability of the control algorithms. The main research questions are:

1) How to overcome or mitigate the impact of disrupting factors for predictability?
2) How to quantify the performance of the improvements of the signal control plan?
3) What are the further applications of cooperative adaptive traffic control, what are the challenges, and how to cope with these?

The paper is structured as follows: the next section presents traffic control methods and predictable control and analysis. A case study of green wave by applying GLOSA for cyclists is chosen, and a simulation study at six consecutive intersections on a city corridor is conducted. Furthermore, an extension of cooperative adaptive traffic control for cooperative and automated road transport is discussed. Finally conclusions are drawn.

Analysis of traffic signal control methods

Main traffic control methods are static control, actuated control, semi-fixed time control, and adaptive control (see Table 1). Each method has advantages and disadvantages. [Blokpoel & Lu, 2017]

Table 1 - Traffic signal control methods [Blokpoel & Lu, 2017]

Control method	**Description**
Static control or *Fixed-time control*	The plans are calculated based on average flow and include a margin to cope with cycle-by-cycle demand fluctuations, to prevent queues from forming. This does imply most of the time these margins are unnecessary and just increase the delay time for all other traffic. When average demand fluctuates by time of the day, multiple static programs are often loaded, which are switched based on the time of the day.
Actuated control	Based on sensors detecting whether traffic is present or not. Typically, two functions for detection are used: stop line detection and gap detection. Stop line detection checks if there is any demand at a signal group that would be next to turn green. If there is no traffic in all signal groups of a stage, it will be skipped. Gap detection is used for extension of green light beyond the minimum duration. This means as long as there is traffic passing, the green duration will be extended until the maximum green time has expired. The plan's stability is very low.
Semi-fixed time control	Based on a fixed time-control plan, but the switching moment can occur between a configured minimum and maximum time. Important for the stability is that there is a fixed cycle time. This means the flexibility is not cumulative. It would have to extend to the maximum switching moment to reach the default green time, which shows a weakness of the method in congested situations. The plan stability is also problematic, due to the moment the decision is taken.
Adaptive control	Based on a model of the approaches towards the intersection. Vehicles enter the model when they are detected by the entry detector. In theory, the predictability could be as low as for actuated control. However, with the modelling of the approaching vehicles, the control algorithm already knows beforehand how much a certain phase will be extended beyond the safety minimum. Disrupting factors can be detection errors, signal groups without entry detection and signal priority calls.

An actuated traffic control with GLOSA can be conducted based on a cooperative algorithm that depends on information exchange between the infrastructure (traffic light) and the vehicles at an intersection. Vehicle information includes elements such as identifier, position and speed, whereas infrastructure information inter alia includes switching times. The advantages of this algorithm are that it is able to process V2X information and that it can adapt to all traffic situations. This can overcome the shortcomings of conventional control approaches, i.e. it works well as long as the vehicles arrive in "typical" patterns, but performs poorly in unusual situations, such as induced traffic due to an event [Blokpoel, et al. 2018].

Recently, plan stabilization for adaptive control has been studied, and applied for cyclists. The results show an increased stability of the adaptive control system, which overcomes the drawback of actuated or traditional adaptive control; while ensuring limited to no extra delay for other traffic and a large reduction in average number of stops, which overcomes the drawbacks of classic green wave with fixed-time control and traditional adaptive control [Lu, Blokpoel & Joueiai, 2018].

Cooperative adaptive traffic control can increase the predictability of the control algorithms. Follow-up previous research on cyclists at one intersection [Lu, Blokpoel & Joueiai, 2018], a corridor in the city centre of Helmond is chosen which has multiple intersections.

A simulation study of green wave by applying GLOSA for cyclists

A simulation study on cyclists is conducted to compare the performance of the current signal control plan with a control plan including GLOSA functionality, targeting the bicycle signal groups. The Helmond network is selected as location for the research (in Figure 1).

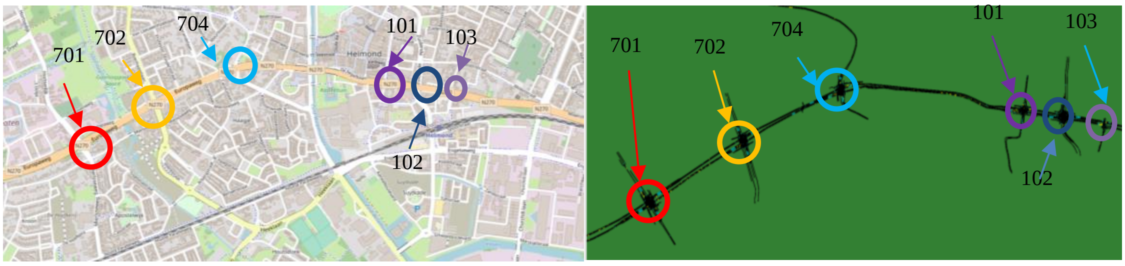

Figure 1 - Six consecutive intersections of the case study in Helmond (left) and the corresponded simulation network in SUMO (right)

The points of interest on this real-world network layout are six consecutive intersections that contain bicycle lanes (only the east-west/west-east directions are considered here). The Helmond-based simulation network is modelled and calibrated in SUMO with focus on the traffic-control-related scenarios, primarily bicycle traffic controls. Supported by predictable adaptive control, a new approach for bicycle detections is applied to the case study. Current detection types at these intersections are either no detection or actuated, by a push-button at the stop line. Providing speed advice using a push button is nearly impossible, because the arrival of the cyclist cannot be predicted and the traffic light controller will try to give green as soon as possible after the button is pressed. In this solution upstream detection will be used to predict arrivals and plan the green phase in advance. In the real world this detection could be implemented either with infrastructure sensors or with an app.

Details of the schematics of six consecutive intersections road layout and six scenarios with adapted control plan has been studied [Zhang, 2018]. The adapted control plan consists of three elements:

1) adding detection upstream in order to predict the arrival of cyclists;
2) constraints in the control plan that conflict with predictability have been removed; and
3) the possibility to attach a weight to predictability has been added.

It should be noted that the main directions of the vehicles are in the same stage. For each scenario, sub-scenarios with different parameter sets are configured and respective simulations are performed with 10 runs per sub-scenario and a 2-hour simulation per run during the evening peak. Cyclists are assumed to estimate their required speed themselves based on the TTG (Time To Green) countdown. In this simulation it is assumed that cyclists learn quickly, when passing the system every day, and that a speed advice calculated and applied to the cyclists in this simulation, is fully complied to by the cyclists.

Speed advice is applied from 200 meters before each stop line, in the speed range of 6-20 km/h. Slower or faster speeds are not considered realistic.

During the simulation, delay time and the amount of stops are tracked for every traffic participant. The evaluation parameters are mainly similar to the ones used in previous research on signal plan stabilization [Blokpoel & Lu, 2017]:

Impact is identified as a Measure of Effectiveness (MOE) that indicates the performance of an adaptive control algorithm. It is defined by formula (1):

$$Impact = \frac{\sum_{i=0}^{i=I} delay_i + 8\, stops_i}{I} \tag{1}$$

The Perceived Change (PC) represents the percentage change between two consecutive predictions relative to the remaining TTG. The calculation of this stability measure is described in formula (2).

$$PC = \left. \sum_{t=1}^{T} \frac{\alpha\, TTG_{t-1} - TTG_t}{min(TTG_{t-1}, TTG_t)} 100\% \middle/ \sum_{t=1}^{T} \alpha \right. \tag{2}$$

$$\alpha = \begin{cases} 0, TTG > 60 \\ 1, TTG \leq 60 \end{cases}$$

Figure of merit (FOM) is a quantity used to characterize the performance of a device, system or method, relative to alternatives. Two types of FOM can be distinguished: un-unified and unified. FOM_un-unified is for evaluating the performance of each simulation scenario, as shown in formula (3). In a nutshell, the lower the FOM_un-unified is, the better the result of the scenario is.

$$FOM = Impact^2 \times MRE \times PC \tag{3}$$

FOM_un-unified takes into account the balance between traffic efficiency (indicated with impact) and stability (indicated with MRE and PC). Square value of impact is to balance the appearance of MOEs in formula (4). To conduct data analysis more conveniently and to have overview of comparing to baseline scenario, this arbitrary formula of FOM_un-unified is transformed to FOM_unified in formula (4).

$$FOM_{uni} = Impact_{uni}^2 \times MRE_{uni} \times PC_{uni} \tag{4}$$

Simulation results and discussions

The results showed a clear success for the green wave by applying GLOSA. In the baseline, cyclists could pass the green light without stopping in only 44% of the cases. The effect on green wave success was already optimal when the stabilization weight (SBW) was configured to SBW=60 for all intersections. This resulted in a 64% green-wave success rate. At the same time, the effect on traffic efficiency was limited with an increase of the impact by 4.9% from an average impact of 26.6s to 27.9s. The MRE dropped from 35% to 12% and PC from 7.6% to 4.1%. With higher values of SBW and setting the extension level (EL)to EL=1, this could further decrease to an MRE of 9.1% and PC of 2.7% (SBW=480, EL=1). However, this was at the cost of traffic efficiency, with an increased impact of 32.6s.

On order to look in some more detail, the figures of merit, *Impact*, *MRE* and *PC*, are extrapolated, and the results are analysed for traffic efficiency and GLOSA functionality. Comparing to the baseline scenario 0 (flat line with FOM value of 1), Figure 2 shows that for all other scenarios (with adaptive GLOSA), the synthesized performance figure FOM_unified decreases with increasing weight in the cost function to configure for predictability. When increasing the weight from 0 to 720, the figure of merit for scenarios 1-5 tends to converge at a low value of around 0.16, which showed a 84% decrease comparing to the baseline, and a decrease of around 60% compared to SBW=0. The case of SBW=0 already has the adjusted configuration where cyclists are detected upstream and certain control constraints are removed. Unexpectedly, there is one exception: scenario 1 (only intersection 701 with GLOSA) already shows good results with SBW=0; increasing the weight to 60 induced a worsened result from 0.10 to 0.17. Intersection 701 is the entry intersection of the network with a high traffic demand. While other intersections receive the vehicles in platoons from upstream, this intersection has vehicles arriving from the west through a Poisson arrival process. Increasing SBW was therefore less effective.

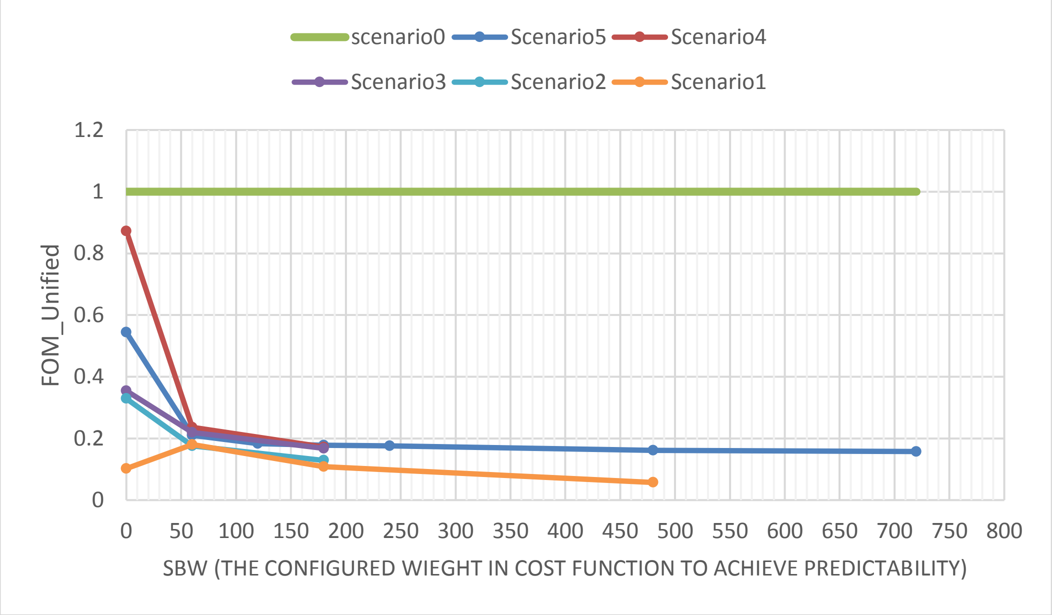

Figure 2 - Relation of FOM_unified to different weight in scenarios 0 to 5

These results show a high potential with green wave success increasing from 44% in the baseline up to 72% when the GLOSA function is used. At the same time impact on other traffic is kept minimal with an increase of only 4.9%.

It is important to consider that the behaviour of cyclists was modelled in these simulations. While real cyclists are probably better at interpreting the countdown and aiming for the green, the tolerance to fluctuations of the behaviour model is higher than in reality. Therefore, the success rate is expected to be better in reality with the lower MRE and PC values that could be achieved by attaching more importance to predictability. The results also showed that the approach is more effective for consecutive intersections, and less effective for very closely spaced intersections.

The trade-off between predictability and traffic efficiency was captured in a figure of merit measure. Increasing weight in the adaptive control algorithm and imposing a rigid plan of no extension in the next stage, shows that green wave for cycling is feasible with adaptive real-time model predictive traffic signal control, without deteriorating the performance of other conflicting traffic too much. Nonetheless, the configuration of constraints and the upstream detection of cyclists are essential for this application, especially for large-scale deployment, which needs careful calibration on the scenario 0 before configuring the importance of predictability in the algorithm.

Applications of cooperative adaptive traffic control

Intelligent Transport Systems (ITS) are a domain of substantial development since more than thirty years. More than twelve years ago, the development of cooperative systems started. Short-range communication would provide connectivity between neighbouring vehicles to exchange information, both of their own position and velocity, and of information observed by vehicle sensors, e.g. concerning obstacles on the road or road surface conditions. The idea was that this would enable a whole range of new safety and driver comfort applications. Also other road users, especially VRUs such as pedestrians and cyclists, could participate in such connectivity, now that smartphones have become widespread. The perspective of C-ITS [C-ITS Platform, 2016] is that ICT infrastructure-based cooperative, connected and automated driving is an option for enhancing traffic safety, traffic efficiency and energy efficiency, and for reducing fuel consumption. Potential C-ITS services are presented in Table 2.

Table 2 - C-ITS services [C-ITS Platform]

List of Day 1 services	**List of Day 1'5 services**
Hazardous location notifications: Slow or stationary vehicle(s) & Traffic ahead warning Road works warning Weather conditions Emergency brake light Emergency vehicle approaching Other hazardous notifications Signage applications: In-vehicle signage In-vehicle speed limits Signal violation / Intersection Safety Traffic signal priority request by designated vehicles Green Light Optimal Speed Advisory (GLOSA) Probe vehicle data Shockwave damping	Information on fuelling & charging stations for alternative fuel vehicles Vulnerable Road user protection On street parking management & information Off street parking information Park & Ride information Connected & Cooperative navigation into and out of the city (1st and last mile, parking, route advice, coordinated traffic lights) Traffic information & Smart routing

Research results on plan stabilisation for adaptive control, cooperative adaptive traffic control for cyclists at one intersection, and cooperative adaptive control at multiple intersections, conducted by under EU-funded Horizon2020 projects MAVEN and XCyle, hold the promise to enhance traffic control and traffic management systems (see also, e.g. [Blokpoel & Lu, 2017], [Lu, Blokpoel & Joueiai, 2018], [Zhang & Blokpoel, 2018]). The results of this paper will further enable applications of infrastructure-based C-ITS services at a network level for improving traffic efficiency (therefore, air quality), road safety, driver comfort, and energy and fuel efficiency. Cooperative adaptive traffic signal control plays an essential role for cooperative and automated road transport. The implementation of automated vehicles, especially at high automation level (see e.g. SAE J3016) in an urban area with mixed traffic, requires support from a cooperative infrastructure, at least from the perspective of system redundancy and effectiveness.

Conclusion and further research

The paper introduced cooperative adaptive traffic signal control for VRUs. A simulation study of green wave by applying GLOSA for cyclists at six consecutive intersections on a city corridor is conducted. The results show that the trade-off between predictability and traffic efficiency is well handled. Plan stabilization for adaptive control and increased predictability of the control algorithms have established milestones for traffic signal control. The results of the paper will enable further enhanced applications of cooperative adaptive traffic control for future applications in road transport. Future research on this topic can be carried out to study if more flexibility of adaptive control can be kept regarding the trade-off between flexibility and predictability.

Acknowledgments

The paper presents some results of the EU-funded project MAVEN (Managing Automated Vehicles Enhances Network). MAVEN has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 690727. The authors especially thank the MAVEN consortium partners for their kind support.

References

1. Blokpoel, R. et al. (2018). MAVEN (Managing Automated Vehicles Enhances Network) Deliverable D4.4 Cooperative adaptive traffic light with automated vehicles, MAVEN Consortium, Brussels.
2. Blokpoel, R., Lu, M. (2018). Cooperative systems for future automated road transport and traffic management in urban areas. In Proceedings: The 7th Transport Research Arena (TRA), 16-19 April 2018, Vienna.
3. Blokpoel, R., Lu, M. (2017). Signal plan stabilization to enable eco-driving. In Proceedings: The 20th IEEE International Conference on Intelligent Transportation Systems (ITSC), 16-19 October 2017, Yokohama. IEEE Xplore 978-1-5386-1526-3/17 pp.133-138.
4. C-ITS Platform (2016). Platform for the Deployment of Cooperative Intelligent Transport Systems in the EU (E03188) C-ITS Platform Final Report, DG MOVE - DG Mobility and Transport, January, Brussels.
5. Li, P., Mirchandani, P., Zhou, X. (2015). Solving simultaneous route guidance and traffic signal optimization problem using space-phase-time hypernetwork. *Transportation Research Part B: Methodological*, Vol. 81, pp.103-130.
6. Lu, M., Blokpoel, R., Joueiai, M. (2018). Enhancement of safety and comfort of cyclists at intersections. IET Intelligent Transport Systems. Vol. 12, Issue 6, pp.527-532. DOI: 10.1049/iet-its.2017.0250
7. Lu, M., Blokpoel, R. (2017). A sophisticated intelligent urban road-transport network and cooperative systems infrastructure for highly automated vehicles. Paper ID EU-TP0769. In Proceedings: The 24th World Congress on Intelligent Transport Systems, 29 October – 2 November 2017, Montréal.
8. MAVEN Consortium (2002). MAVEN (Managing Automated Vehicles Enhances Network) Description of Action, MAVEN Consortium, Brussels. (restricted)
   MAVEN web site: www.maven-its.eu
9. N.N.: Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems, SAE Standard J3016, USA, 2018.
10. Zhang, X., Blokpoel, R. (2018). A scale-up network level study of green wave with speed advice for cycling. In Proceedings: 25th ITS World Congress, Copenhagen, Denmark, 17–21 September 2018. Paper ID EU-TP1125.
11. Zhao, D., Dai, Y., Zhang, Z. (2012). Computational intelligence in urban traffic signal control: A survey. IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews, Vol 42, Issue 4, pp.485-494.
12. Zlocki, A., Fahrenkrog, F., Lu, M. (2016). History and deployment of ITS technologies, and an outline of the book chapters. In: Lu (Ed.) Evaluation of Intelligent Transport Systems: Methods and Results. Publisher: IET (Institution of Engineering and Technology).