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A scale-up network level study of green wave with speed advice for cycling

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Abstract

Recent advances in C-ITS have enabled realizing green waves through speed advice instead of offset calibration in fixed time control plans. This is especially interesting for cyclists as they have high variation in desired speed. However, the most common control strategy, vehicle-actuated control, can be problematic because its flexibility hinders a predictable plan required for speed advice. ImFlow is a state-of-the-art adaptive control that enables configuring for predictability and is applied here to achieve green wave for cyclists. The key for a successful green wave for cyclists is to balance between flexibility and predictability, while still achieve minimal disruption for other traffic. The concept has been proven for a single intersection in Groningen. This paper embarks on scaling up the solution on multiple intersections along the N270 in Helmond. Green wave success rate went up from 44% to 72%, while the mean relative prediction error decreased from 35% to 9.1%.

Keywords:
Traffic control, predictability, speed advice

Introduction

For decades, cars have been benefiting from reasonable implementation of traffic signal solutions in areas where “green wave” for vehicles was implemented. Cyclists, a group of vulnerable road users, have not benefitted as much yet. However, to stimulate cycling to achieve a modal shift, they should not need to encounter constantly braking for red phases, but to experience unimpeded, safe and comfortable riding. Knowing this, the XCYCLE project (Advanced measures to reduce cyclists' fatalities and increase comfort in the interaction with motorised vehicles) uses GLOSA (Green Light Optimal Speed Advisory) with adaptive control, to achieve the same benefit towards cyclists as to motorised vehicles. This will reduce the time cyclists have to wait at intersections and thus, reduces the red light violation of cyclists, increases the comfort and thereby encourages the use of this green mode of transport [1]. Respecting design and implementation, a GLOSA for bicycles is successfully applied on a single intersection in Groningen.

Intelligent Transportation Systems (ITS), including the possibility to wireless information exchange among vehicles and between vehicles and infrastructure, offer a broad range of applications [2]. Traffic lights are one of the dominant factors for traffic flow dynamics in urban areas. ITS solutions in these areas should therefore be efficiently sought in cooperation with traffic light controllers [3]. For motorised vehicles, GLOSA is a commonly used application for eco-driving [4]. Such a GLOSA system was shown in [5] and [6] to have a potential CO2 reduction of up to 7.0%.

Over the last 10 years, Dynniq has been involved in development of GLOSA systems. The aforementioned traffic control algorithm ImFlow prevents vehicles from stopping and starting, which saves fuel and pollutant emissions that can cause health problems for people especially in congested urban environments [7]. With sufficient research and practice, it was shown that this GLOSA application is not restricted to vehicles. However, the difference between GLOSA for vehicles and bicycles needs to be addressed and related problems need to be solved.

The basis for effective GLOSA functionality, is the time to green prediction, which is given by the traffic light controller, and this prediction has to be stable. For instance, a driver only needs to receive a GLOSA once, for example, around 250 meters ahead of the stop line, in the form of speed advice (km/h), process and accept this information by adjusting the speed of the vehicle referencing the speed shown on the in-vehicle dash board. Meanwhile, an average cyclist has limited understanding of its own speed. Thus, a cyclist relies on the GLOSA constantly along the route until the stop line. A constantly available, reliable and stable GLOSA with time to green count-down is important to the cyclist to adjust its speed to catch a green wave. ImFlow has the option of configuring the predictability, which is used to enable this GLOSA for cycling.

In practice, it is difficult to present the advice to a cyclist on a dedicated personal display, e.g. smart phone or navigation system. Therefore, a large display at the stop line (shown in Figure 1) is presenting a reliable count-down in seconds to the approaching cyclists. Note that there is a bus symbol on the display in Figure 1. This bus symbol will only light up when a priority to bus on the conflicting direction is just processed and granted. It intends to inform cyclists why the time to green for them has suddenly changed. This is because public transport usually has a higher priority in the policies of a road operator than a cycling green wave. By informing cyclists about this priority, cyclists' trust in the system shall not deteriorate.

As shown in Figure 1, the basic idea is that when a cyclist is at 200 meter from the stop line with 60 seconds to green remaining, it may have to stop if continue to cycle at the speed of 20 km/h (travel time is only 36 seconds at this speed). With a remaining time to green count-down advice (shown in Figure 1), cyclists can slow down to 12km/hour (i.e. ease down on peddling and cruising forward), which will take around 60 seconds to the stop line and therefore, can continue cycling without stopping. This paper intends to expand this practice from a single to multiple coordinated consecutive intersections, with the ultimate goal of predictable adaptive traffic control for cyclists on the network level.

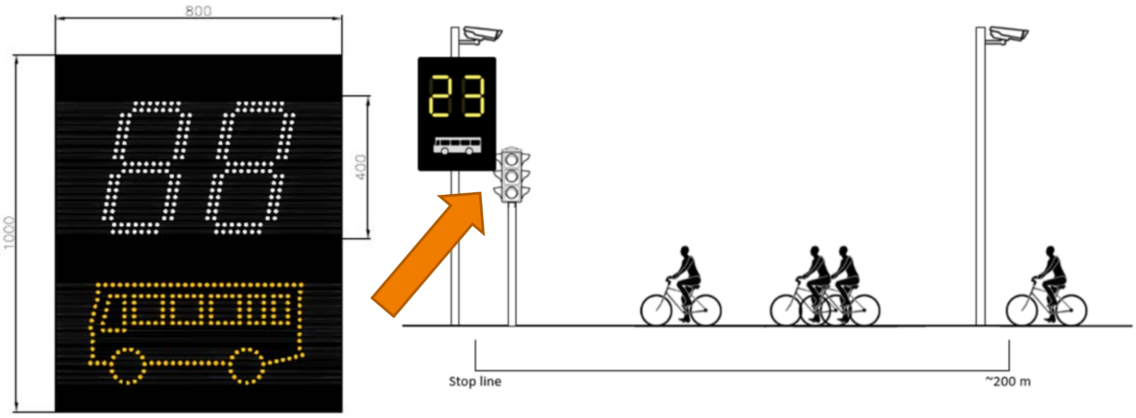


Figure 1 - Speed advice sign and detection system in Groningen intersection

Adaptive GLOSA is feasible through configuring the traffic control algorithm for additional predictability. Fluctuations in the prediction about when the light will turn green directly lead to

fluctuations in the speed advice. In order to control the quality of the time to green prediction, a trade-off between predictability and flexibility has to be made. Less flexibility generally results in a higher average delay, which is also undesirable [8]. Similarly, a stable speed advice is also important when considering green wave for cars. Slow and small changes may be acceptable when at a large distance from the traffic light, but large fluctuations will deteriorate the fuel savings and user trust in the system.
There is limited scientific research in the domain of increasing the predictability of traffic control methods, such as stabilizing GLOSA to enable green wave. Researchers often focused on macro level where the process of speed changes is ignored. Often the control system is not specified. Most previous studies only target the sustainability evaluation of eco-driving through simulation [3]. Even fewer studies are focusing on optimization and predictability of GLOSA for cycling green wave, nor the related adaptive control algorithm. Adding an extra cost function to the adaptive control algorithm ImFlow to control the predictability, shows a reduction of perceived change for GLOSA users from an average 9.0% to 2.3% [8].
Intrigued by the promising results of aforementioned paper and supported by the successful previous test on a single intersection, this paper continues the research on multiple intersections.

Research concept and methodology

A variety of different control systems are used to accomplish smooth and safe traffic. Based on the research of [3], there are several primarily types of traffic light controller, listed in Table 1. An arbitrary comparison with relevance to GLOSA is given here. In Table 1, symbols from “--” to “++” are used as a scale of five, “--” is the worst and “++” is the best, to demonstrate the performance of a traffic control on a respecting criteria. Table 1 shows that adaptive GLOSA can achieve both predictability and flexibility, or the feasibility to provide a trade-off between them.

Table 1 - Traffic control strategies evaluation overview

	Level of complexity	Maintenance cost	Predictability	Flexibility
Static control	++	--	++	--
Actuated control	0	-	--	+
Semi-fixed time control	0	-	+	-
Adaptive control	-	++	0	++
Adaptive GLOSA	-	++	+	+

The theory of various traffic controls and the control algorithm of ImFlow is described in paper [3]. This paper explores the effect of adaptive GLOSA for bicycles using the state-of-the-art application, ImFlow. The principle concept of ImFlow system is the optimiser, which uses the cost formula to optimize traffic signal timing, see the following schematic formula as reference:

$$StateCost = Cost_1 + Cost_2 + Cost_3 \ldots + Cost_n \quad (1)$$

This $StateCost$ is applied to each signal group of each intersection to calculate the intersection cost for the planned signal timing. The optimiser will compare many alternative signal-timing plans and execute the plan with the lowest intersection cost. Specific policies can be configured by the user, respectively from $Cost_1$ to $Cost_n$. The extensibility of this adaptive control algorithm allows for adding new elements to the cost function. In the scope of this paper, it means that adding new elements of cost can overcome excessively frequent changes of signal plan timing and increase the reliability and accuracy of predictions for the green phase. Furthermore, it helps cyclists modifying their speed to meet the green phase of the traffic light. A patent for a new algorithm adding this predictability configuration was applied, targeting on making the control algorithm more suitable for GLOSA at little to no cost for other traffic. Additionally, public transport priority calls can still be configured as more important than predictability [3].

The core of this new methodology (that has been implemented in ImFlow), is to prevent the optimizer from changing the planning frequently or by a large deviation. Therefore, the aim is not to give more priority to bicycles, but rather making the planning more predictable - particularly close to the green phase - so that bicycles receive reliable speed advice in order to pass the green light [3].

The implementation of this cost function (C) is further explained in the following formulae [3]:

$$C = \frac{SBW.d^2}{TTG_{t-1}} \tag{2}$$

$$d = TTG_{t-1} - TTG_t - T \tag{3}$$

SBW: The configured weight for predictability. It allows the traffic engineer to configure the importance of predictability with respect to other control targets.

d: The deviation. It is calculated using the difference between the time to green (*TTG*) of two consecutive time steps. The quadratic characteristic to the deviation means that higher deviations are increasingly worse for the user acceptance of a speed advice.

TTG_{t-1}: The time to green of a time step (*t-1*). The cost C is inversely proportional to TTG_{t-1}. This means that the closer to green, the more impact a change has on the plan. This is a major improvement compared to semi-fixed time strategies, which allow for flexibility around the stage transition and could therefore still change the prediction very close to the actual moment of the transition.

TTG_t: The time to green of a time step (*t*)

T: The time period of a time step (*T*). It is used for the expected decrease (time elapsing) of the *TTG*.

Since this cost function can be activated on a per signal group basis, it is particularly beneficial to the case study in this paper. It is often difficult to realize green waves consecutively for multiple intersections, as distances between intersections vary. With this methodology, a green wave along a string of intersections could be achieved with individual cost functions with optimal *SBW* parameter. Consequently, different speed recommendations (remaining time to green count down) for each intersection will compensate for varying intersection spacing and varying traffic demand on conflicting traffic streams. In this way, the proposed methodology gains both predictability and flexibility.

The implementation of extension level (*EL*) refers to different levels of vehicle actuated (VA) control. *EL* can be set to 0 or 1. When *EL* is set to 0, VA extension is enabled as the baseline scenario setting of the network; When *EL* is set to 1, VA extension is disabled if the next planned stage has a signal group with GLOSA, which will be indicated as a “GLOSA signal group” in the remainder of the paper.

Simulation method

City of Helmond is a small/medium-sized (90.000 inhabitants) city in the south-east of the Netherlands, a region also known as the “brain port” region. This paper chooses Helmond network because of its characteristics of multiple intersections on a corridor in the city centre of Helmond, shown in Figure 2.

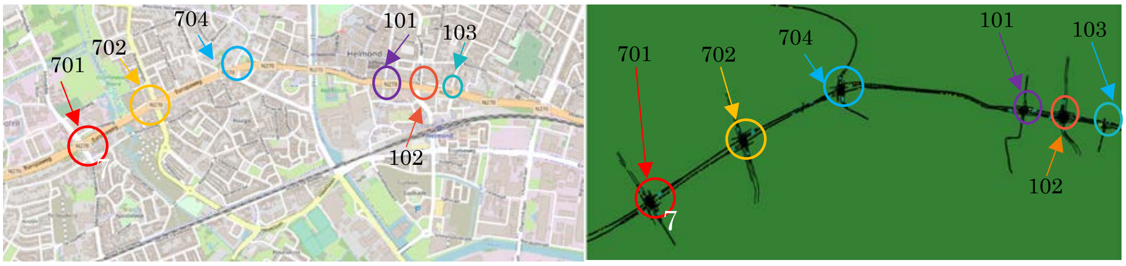
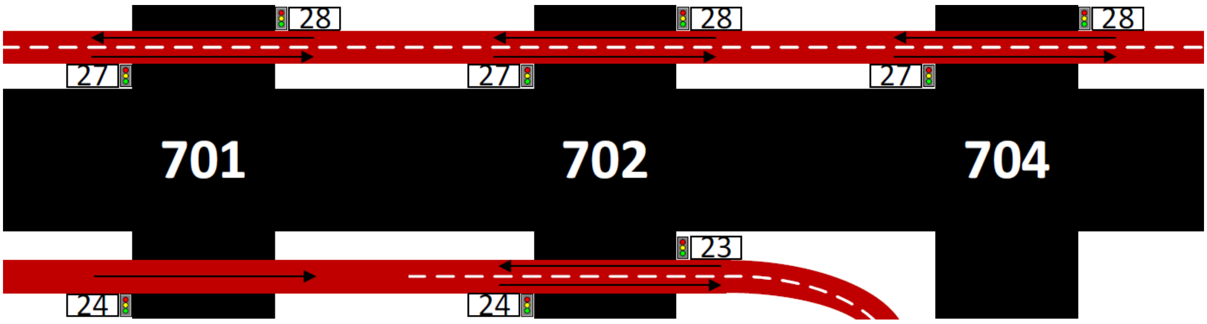


Figure 2 - Six consecutive intersections of the case study in Helmond (left) and the corresponded simulation network in SUMO (right)

- Intersection 701, Hortsedijk/ Europaweg
- Intersection 702, Boerhaavelaan/ Europaweg
- Intersection 704, Prins Hendriklaan/ Kasteel-Traverse
- Intersection 101, Zuid Koninginnewal/ Kasteel-Traverse
- Intersection 102, Zuidende/ Kasteel-Traverse
- Intersection 103, Penningstraat/Smalstraat/ Kasteel-Traverse

In Figure 2, the real world network and corresponding simulation network are depicted. 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 and it focusses on the traffic control related scenarios, primarily bicycle traffic controls. Supported by predictable adaptive control, a new approach of bicycle detections is applied to the case study. Current approach of detection type at these intersections are either no detection or actuated, which is 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.

As shown in Figure 3, these bicycle lanes are composed of dual carriageway (car lanes in the middle) with one-way/two-way bicycle lanes, for example, link 27, 28 and link 24 on intersection 101, or link 27, 28 and link 23, 24 on intersection 702. Additionally, they can be composed of single carriageway with one-way/two-way bicycle lanes, for example, link 27, 28 on intersection 704, or link 24 on intersection 103 (Referred to as Link 103_{24}, see Note 1 below for the detailed numbering convention).



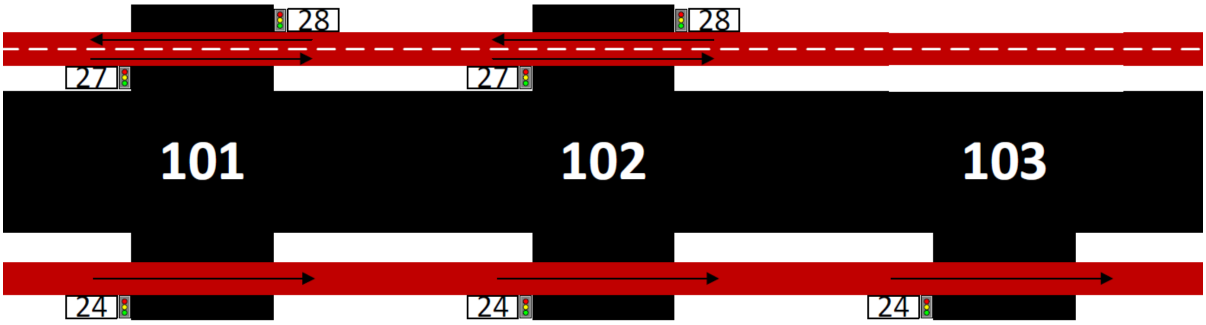


Figure 3 - From west to east, schematics of six consecutive intersections road layout, showing only the bicycle lanes (red) and corresponding signal controls

Note 1: The numbering of signal controls replicates real world signal group situation. Signal group number 24, 23, 27 and 28 are used here. The bicycle link segment at the intersection also follow this numbering convention, i.e. $701_{27,28}$ refers to the two signal head 27 and 28 at intersection 701; Link $701_{27,28}$ refers to the two-way bicycle lane segment at intersection701.

The goal of simulations in this paper is to compare the performance of the current signal control plan with a control plan including GLOSA functionality, targeting the bicycle signal groups. Six scenarios, scenario 0 to 5 are designed in order to compare the effect of baseline (scenario 0), single and multiple intersections with GLOSA, as shown in Table 2.

Table 2 - Simulation scenario designs overview

	Description	Traffic control configuration	GLOSA
Scenario0	Baseline, do nothing	Current control plan	NO
Scenario1	$701_{27,28}$	Adapted control plan	YES
Scenario2	$701_{27,28}$+$702_{27,28,24,23}$+$704_{27,28}$	Adapted control plan	YES
Scenario3	$101_{27,28,24}$	Adapted control plan	YES
Scenario4	$101_{27,28,24}$+$102_{27,28,24}$+103_{24}	Adapted control plan	YES
Scenario5	$701_{27,28}$+$702_{27,28,24,23}$+$704_{27,28+}$ $101_{27,28,24}$+$102_{27,28,24}$+103_{24}	Adapted control plan	YES

The adapted control plan consists of three elements, the first is adding detection upstream in order to predict the arrival of cyclists. Additionally, constraints in the control plan that conflict with predictability have been removed and finally, the possibility to configure a weight for predictability as indicated in formulae 2 and 3 was added. For each scenario, sub-scenarios of different parameter sets (different *SBW* and *EL*) are configured and respective simulations are performed with 10 runs/sub-scenario and 2-hour simulation/run during the evening peak. The speed advice that is given to the cyclists in this simulation is assumed to be fully complied by the cyclists, as an estimate of their behaviour. Speed advice is applied from 200 meters before each stop line and they are subject to a 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. Average impact for each traffic participant (*s*) is defined by the following formula [3] to emphasize the punishment on full stops of bicycles.

$$impact = \frac{\sum_{i=0}^{i=I} delay_i + 8\ stops_i}{I} \tag{4}$$

- *Delay time*: this is a basic measure for evaluating the traffic efficiency. It compares the actual travel time with the free flow travel time. It is important to note that waiting time is different from this as delay is also incurred when a road user slows down without stopping.
- *Number of stops*: they greatly contribute to user discomfort and when used for a specific signal group, stops reflect the green wave success rate. For bicycles, there is a risk of red light violation during a stop and for motorized traffic there is an additional CO_2 emission due to reacceleration.

The formula (4) sums over all traffic participants and calculates the average impact. It can both be applied to the total network or to a single signal group [3]. In this paper, the impact is applied to the total network to see the effect on all traffic participants when GLOSA is considered for vulnerable road users: bicycles. Due to the high value of impact itself, a unified impact (*Impact_unified*), the quotient of sub-scenario impact divided by scenario 0 impact is calculated later in the result section, to obtain a comprehensible results. And the *unified* character of *Impact_unified* indicates each scenario/sub-scenario refers to the baseline.

A mean square error (*MSE*) is calculated as a good indicator for overall reliability of the data. Here, a mean relative error (*MRE*) is used, which divides the error by the remaining *TTG* and expresses this as a percentage, because deviations close to the actual moment of switching needs to be penalized more. A last predictability measure is the Perceived Change (*PC*), which represents the percentage change between two consecutive predictions relative to the remaining *TTG*. The calculation of this measure is described in the formula below [8]:

$$pc = \left. \sum_{t=1}^{T} \frac{\alpha |TTG_{t-1} - TTG_t - T|}{min(TTG_{t-1}, TTG_t)} 100\% \middle/ \sum_{t=1}^{T} \alpha \right. \tag{5}$$

$$\alpha = \begin{cases} 0, TTG > 60 \\ 1, TTG \leq 60 \end{cases} \tag{6}$$

The *PC* measure serves to estimate the users' perception of the system. A low value is preferred for users' perception. Similar to impact, *MRE* and *PC* can both be applied to the total network or to a single signal group. In this paper, due to the complexity of sub-scenarios, applying them to the total network level (all signal groups at intersections) show a quick overview of performance, but it is not fair comparison among different sub-scenarios. Therefore, *MRE_unified* and *PC_unified* are introduced. *MRE_unified* is the quotient of sub-scenario *MRE* on GLOSA signal groups divided by the *MRE* of the baseline scenario on GLOSA signal groups, to make sure to follow the consistency of extracting *MRE* on the same GLOSA signal groups within the scope of each sub-scenario. Results of *PC_unified* is defined the same as *MRE_unified*. Together with *Impact_unified*, a unified figure of merit (low is better in this paper) can be expressed in the formula below:

$$FOM\_unified = Impact\_unified \times MRE\_unified \times PC\_unified \tag{7}$$

Results

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 *SBW*=60 was configured for all intersections. This resulted in 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 *EL*=1, this could decrease further 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. Looking at the subnetworks, the scenario of 701, 702 and 704 was most successful with GLOSA success of 72%. When only 101, 102 and 103 were enabled the success rate was 60%. Enabling isolated intersections was less successful than several intersections in a corridor with 64% success for only 701 enabled.

Looking in more detail, the figures of merit: Impact, MRE and *PC* are extrapolated, and results are analysed for traffic efficiency and GLOSA functionality. Comparing to baseline scenario 0 (flat line with FOM value of 1), Figure 4 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 scenario1-5 tends to converge at a low value around 0.16, which showed a 84% decrease comparing to the baseline and around 60% decrease comparing 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: scenario1 (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.

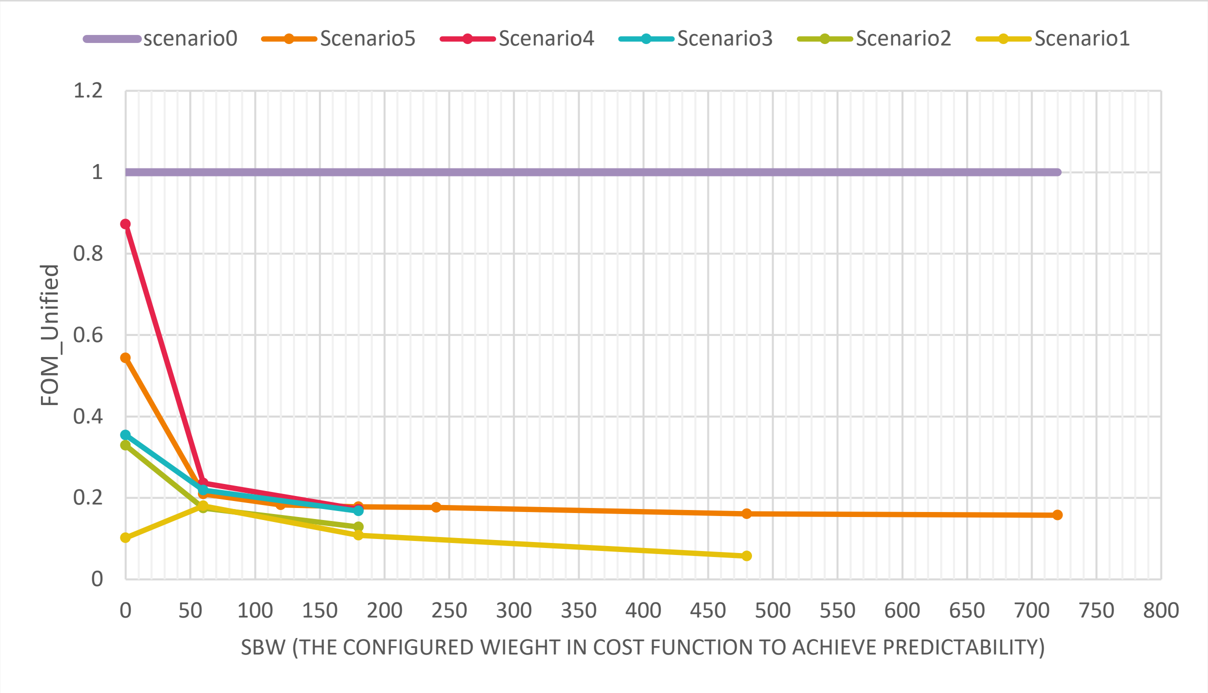
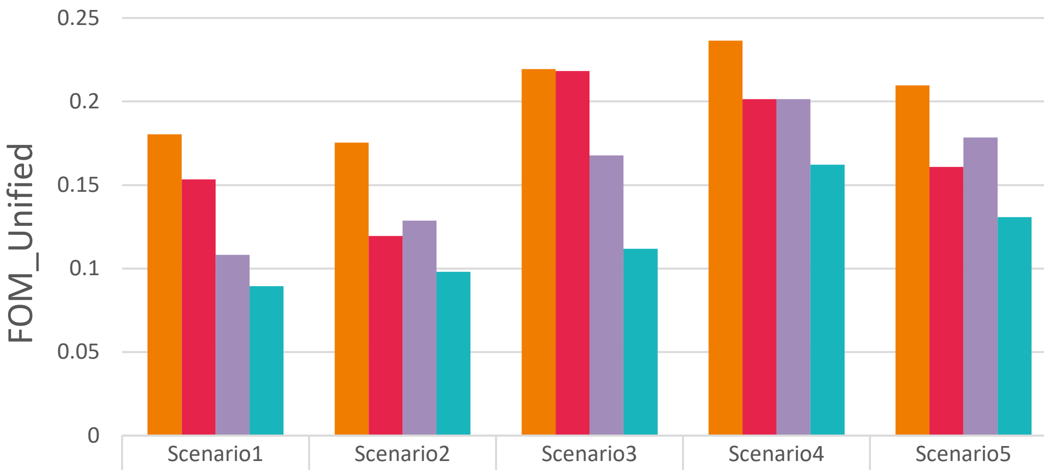


Figure 4 – Relation of FOM_unified to different weight in scenario0-5



	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5
SBW=60, EL=0	0.180316312	0.175446132	0.219372128	0.23644643	0.209742995
SBW=60, EL=1	0.153337473	0.119485371	0.218223139	0.201479579	0.160773701
SBW=180, EL=0	0.108307982	0.128689068	0.167735825	0.201479579	0.178443446
SBW=180, EL=1	0.089466847	0.098152337	0.111918918	0.162213211	0.130886656

Figure 5 – Relation of FOM_unified with different weight in scenario0-5 for *EL*=0 and 1

Furthermore, results of simulations with *EL*=0 and 1 are shown in figure 5. With *EL*=1, which means extension of vehicle actuation for the next stage is disabled to have a more predictable plan, a visible decrease ranging from 10% to 20% can be observed for almost all sub-scenarios of scenario1-5. This feature is an effective way to configure more predictability for GLOSA for those signal groups because it can be customizable down to the level of a signal group at an intersection. Simulations for scenario 5 (six intersections with GLOSA) are conducted the most. Optimistic result of Scenario 5, with extension level (*SBW*=720, *EL*=1) shows a 9.65% decrease comparing to Scenario 5, without extension level (*SBW*=720, *EL*=0). Combining with Figure 4, it demonstrates that when *SBW* is at extreme high value, doesn't bring much benefit to further lowering *FOM_unified*. Setting *EL* to 1 can still have a better result.

Conclusion and further research

This paper investigates the GLOSA function for cyclists green wave on multiple intersections and demonstrates the related impacts on all traffic participants on the network. It shows 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 the cyclist's behaviour 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 configuring more importance to predictability. The results also showed that consecutive intersections are more effective and very closely spaced intersections are less effective.

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 rigid plan of no extension in the next stage, shows that green wave for cycling is feasible with ImFlow 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 first before configuring the importance of predictability in the algorithm.

Future research on this topic can be carried out on this aforementioned attention point, to study if more flexibility of adaptive control can be kept regarding the trade-off between flexibility and predictability.

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