13th ITS European Congress, Brainport, the Netherlands, 3-6 June 2019

Paper number ITS-1758

Adaptive green wave with speed advice for automated vehicles

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Abstract

Advances in C-ITS can enable adaptive control- green wave function, promoting the state-of-the art in traffic control strategy and successful green wave. However, adaptive control can be problematic due to its flexibility that hinders a static speed advice. Therefore, automated vehicles facilitate this concept with wider dynamic speed advice range acceptance and higher compliance rate. This paper embarks on the promising experimental concept, employs the methodology of splitting platoons and simulates the N270 corridor in Helmond with four intersections. Green wave success rate of static control with speed advice is increased with 50.6% on average. Moreover, network impact for both static and adaptive control are lower.

Keywords:

GREEN LIGHT OPTIMAL SPEED ADVISORY (GLOSA), AUTOMATED VEHICLES, TRAFFIC MANGEMENT

Introduction

Traffic congestion is a serious problem, especially in high density urban areas, where disorders, such as delays, traffic collisions, pollutions and economic loss are more easily triggered. From a Traffic Management (TM) point of view, many technical and operational aspects regarding mobility that affect traffic efficiency, need to be improved. To deal with these non-optimal influences of the status quo, one approach is to regulate traffic flows with intelligent traffic control methodologies. Adaptive control based on a model of the approaching road links towards one individual intersection, to the end of seeking advantageous traffic performance locally, was developed. More details of the advantages and disadvantages of different control methodologies are discussed in the methodology section.

Another approach is to optimize network traffic flows by C-ITS means of GLOSA to synchronize traffic light control phases and to achieve green wave. Green wave is an influential part of an ITS and it plays an important role in easing traffic jams [1]. Similar to giving effective speed advice to vehicles, green wave is a trade-off between traffic control flexibility and success rate of the use case. The most effective strategy for a guaranteed green wave is static control, which is also the traditional approach. A static control configured with green wave has no flexibility on traffic light control phases and reduces benefits of green wave due to either congestion built up or unnecessarily long green duration.

To battle the aforementioned inefficient trade-off, first, we propose an adaptive control green wave system for automated vehicles in this paper. This system is based on automated vehicles following the speed advice from a static control green wave design (proposed in the experimental methodology section), under the assumption that GLOSA-based static speed advice has more possibilities when interacting with automated vehicles. For example, the range of acceptable speed limits can be further increased and platoons can be split and recombined when it is optimal. The motivation of this system is to combine the best of both worlds: accurate and individual platoon speed advice thanks to automated vehicles, complimented by the flexible and efficient control plan thanks to adaptive traffic control.

Second, we apply these improved concepts for creating a green wave directly to static control. Furthermore, the adaptive control green wave (AC-GW) and the improved static control green wave (ISC-GW) are implemented in SUMO microscopic simulation environment and adaptive traffic control - ImFlow (current traffic light control system operating on the case study network), to operate on four consecutive signal controlled intersections along a corridor road network. Finally, results of all four case study scenarios (with or without speed advice) are reported and compared, such as traffic efficiency and green wave success rate.

Theory

A typical signal schedule and traffic flow diagram is usually used to demonstrate and coordinate traffic light controls, creating continuous unimpeded traffic flow [2]. A unidirectional green wave simplifies the problem as any offset between intersections can be chosen. The only requirement is that the cycle time is synchronized. For bi-directional green waves, the offset in one direction needs to be equal to the offset in the opposite direction. Figure 1 presents an ideal bi-directional static control green wave (SC-GW) among three evenly distributed intersections. The bands of both directions perfectly overlap and vehicles arrive at the second intersection in the middle of the cycle.

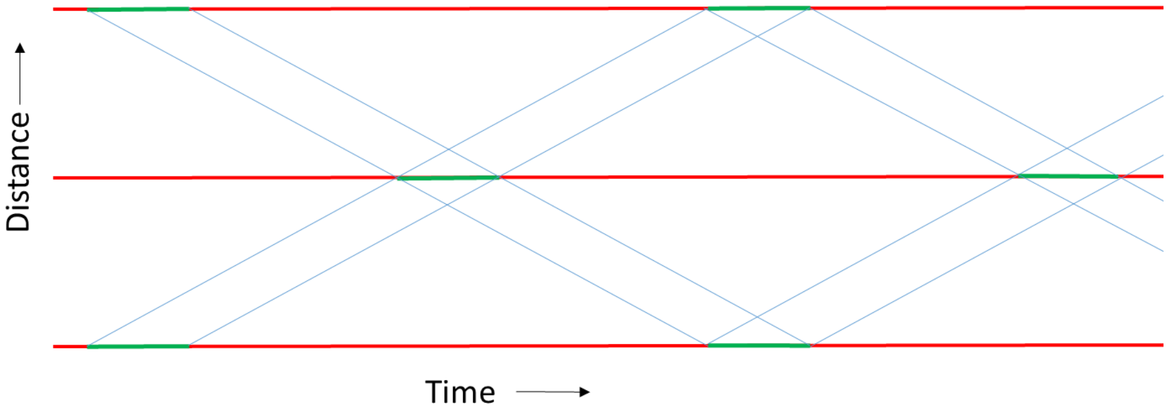


Figure 1 - Ideal bi-directional green wave

This design has two requirements: a) intersections are equally spaced, and b) the cycle time equals twice the travel time between the intersections. With longer distances between the intersections, this design can also be established if the travel time is half a cycle plus an integer amount of cycles. For an ideal bidirectional green wave, the following equation can be derived:

$$t_{i,i+1} = \left(n + \frac{1}{2}\right)C \quad with\, n \in (0,1,N) \tag{1}$$

In practice, it is very difficult to find networks that suffice the above conditions. A small extra offset can be created by leading or lagging left turns as described in [3] and [4]. But this method is often insufficient in creating overlapping green phases for bi-directions, which reduces network capacity, see Figure 2.

In specific for green wave, the platoon dispersion is also an important factor and often a problem for networks that are close to saturation. To give a smooth green wave, it should be taken into account that the front of a platoon moves at the speed limit, while the back is a bit slower. To prevent vehicles from just missing the green phase or being tempted to violate the red light, the green phase should be a bit longer for each consecutive intersection. These negative effect can be mitigated via platoon shaping using a speed advice. For non-cooperative vehicles, dynamic signs with speed advice are the exemplary solution, such as an ODYSA system [5]. This way the head of the platoon can be slowed down while the back can catch up. In this paper, the advice can be given more precisely and continuously using C-ITS, rather than only at several specific locations with the dynamic signs. A GLOSA application based on adaptive traffic control, would take over the role of platoon shaping in this study.

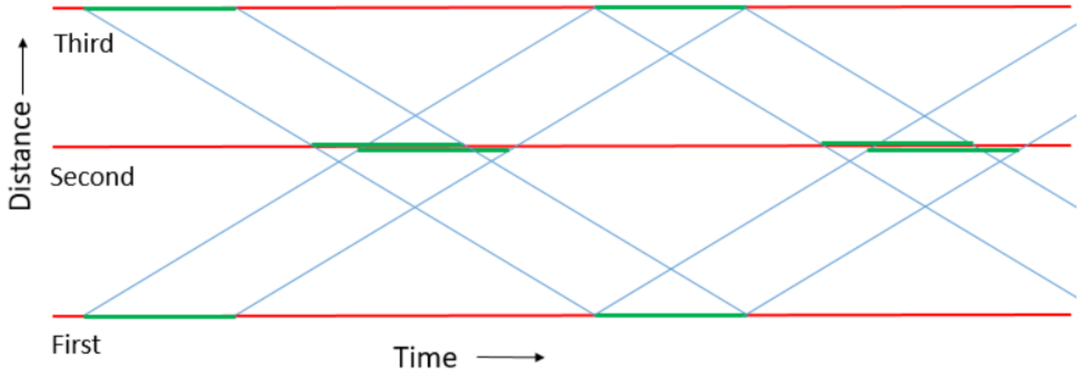


Figure 2 - Offset creation with lagging/leading left turns

In Figure 2, the second intersection is at 45% of the distance between the first and the third. Operationally speaking, this is about the maximum that can be compensated by assigning the left turns together with the non-conflicting main directions. If the design in Figure 2 is combined with speed advice lower than the maximum speed limit (see the discrepancy between dashed line and solid line), the second intersection can be moved closer to the third intersection as demonstrated in Figure 3:

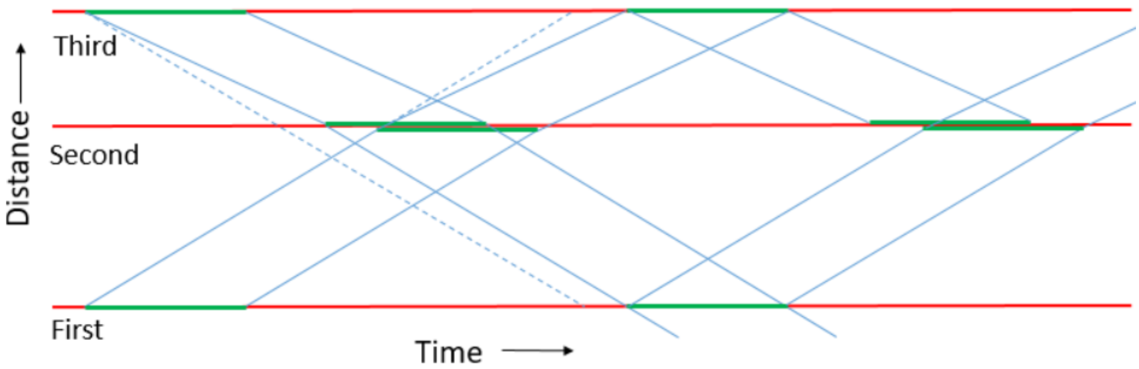


Figure 3 - Combination of lagging/leading left with speed advice

Figure 3 demonstrates that the second intersection is at 39% of the distance of the total distance between the first and the third. The dashed-blue lines are the vehicle trajectories with original speed and their corresponding solid lines are vehicle trajectories corrected by a lower speed advice. If a speed advice is further reduced to half of the maximum speed limit (for a road link with 50km/hr maximum speed limit, this would be the lowest acceptable speed advice), the second intersection could even deviate more, up to 33% of the total distance.

To sum up, Figure 2 and Figure 3 have the same total distance between the first and the third intersection; the cycle time also remains the same. From Figure 2 to Figure 3, the position of the second intersection can deviate from 45% to 39% with a speed advice of 40km/hr (shown with solid line in Figure 3), or even to 33% with a speed advice of 25km/hr. Other solutions such as increasing the cycle time or vehicles exceeding maximum speed limits, are inefficient and unsafe designs, especially when the main direction has a significant higher flow and takes up most of the cycle time. In this paper, these methods together with a new method of splitting platoons are combined in a methodological framework to battle the aforementioned problems, as shown in Figure 4.

Methodology

Experimental methodologies

Figure 4 illustrates the experimental methodology of splitting the platoon when the distances between two intersections are much further apart than the previous distances. In the theory section, a few methods have been introduced to tackle the coordination of static traffic controls aiming for green wave in real world road network. These methods based on the theory of static control cannot solve green wave problem entirely. From a traffic engineering standpoint, it is especially difficult to synchronize two opposite main directions to create bi-direction green wave because they are further apart than half a cycle time, such as from the second to the first intersection, or from the first to the second intersection, shown in Figure 4. To handle this, the platoons resulting from the green splits are separately controlled with two speed advice, so that the second half of the platoons are slowed down drastically to catch the next green split of the next intersection. This experimental method is enabled by automated vehicles facilitated with C-ITS traffic management measures. Automated vehicles can reach a specific, individual speed advice, which enables the speed advice with wider range and full acceptance. Furthermore, automated vehicles also play a vital role in platoon shaping. For example, the lead (automated vehicle) of the second half of the platoon can slow down and the followers (no matter they are automated vehicle or not) can encounter green wave.

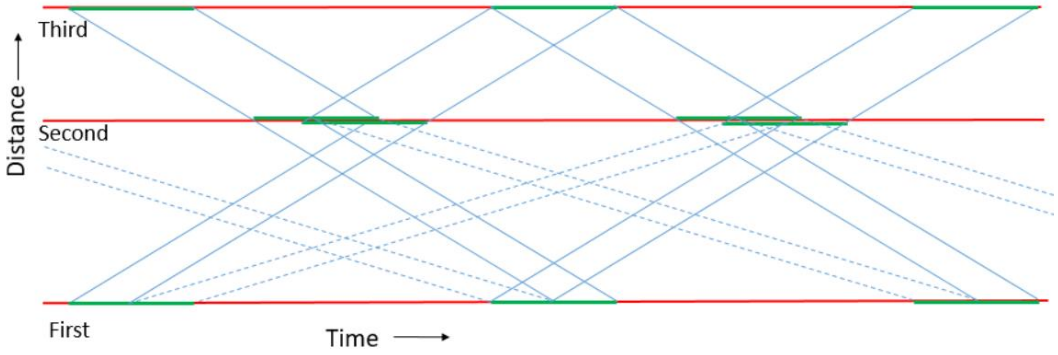


Figure 4 - Splitting platoon with speed advice

It should be noted that this example has relatively short green phases in the green wave, this is to keep the visualization comprehensible. With a longer green phase split, the difference in speed advice for second half of the platoon can be smaller. For example, with a 10 second green phase on a 60 second cycle, the second half of the platoon is delayed by 55 seconds, when there is 30 seconds of green time, this becomes 45 seconds.

Traffic control methodologies

The methodology section is the foundation of the simulation experiment later in this paper. Therefore, this section describes the methodologies of traffic control that are relevant to green wave.

The simplest form of traffic control is static or fixed-time control. Although it is simple with no sensor requirement, the maintenance costs can still be high due to the manual calibration effort required to keep the plans effective. Formulae and software tools [5] are available to calculate these plans, but for every significant change in traffic demand, the procedure has to be repeated.

The traffic control plans are calculated based on average flow, including a margin to cope with cycle-by-cycle demand fluctuations to prevent queues from forming. These margins are sometimes inefficient and they increase the delay time for all other traffic. When average demand fluctuates according to time of the day, multiple static programs are often loaded, which are switched on at the predefined times of the day.

Day-to-day differences can still cause unnecessary queues and System Activated Plan Selection (SAPS) is often used to cope with this. For this system, a few sensors are placed at strategic locations in the network to detect congestion and/or measure traffic volume. The system dynamically decides when to switch plans at real-time. Irrespective of the amount of static plans and the plan selection method, the mechanism of GLOSA with static controls are predictable but could impede the efficiency and even cause congestion. It's generally used as a low-cost solution or a very specific traffic management policy that requires such a green wave.

Semi-static control and adaptive control are considered the best traffic control solutions on the market. The choice on which particular system should be used, depends on the network and local standards. In general, more flexibility is used for smaller networks.

Actuated control is based on the presence of traffic from sensors detection. 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. If there is no traffic in all signal groups of a stage, this stage will be skipped. Gap detection is used for extension of green light beyond the minimum duration. This means as long as there is demand, the green duration will be extended until the maximum green time is reached, as illustrated in Figure 5 (The solid green rectangles represent the minimum green time and the hatched grey rectangles represents the optional time available for extension).

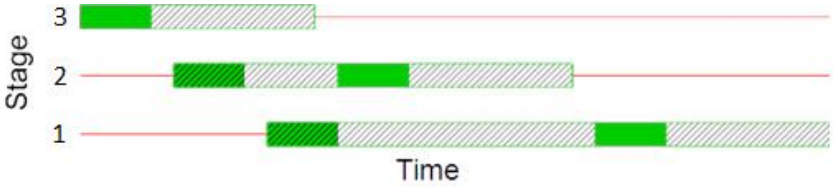


Figure 5- Actuated traffic control

Providing green wave with speed advice based on this data will be difficult since the plan stability of actuated traffic control is very low, as can be seen in Figure 5. The plan in the example has a minimum green duration of 6 seconds and a maximum of 20. There is 14 seconds uncertainty before the second stage starts and 28 seconds before the start of the third stage as the increasing hatched areas increase.

Semi-fixed time control that is based on a fixed time control plan, is the most commonly used for contemporary GLOSA solutions, such as ODYSA **Error! Reference source not found.**. The switching moment from green to red can occur between a configured minimum and maximum time, as illustrated in Figure 6. The solid green rectangles shows the guaranteed green and the hatched green shows the default configured green duration. Therefore, the maximum green is the total hatched plus solid green rectangles, while the minimum is the solid green rectangles. Comparing to the actual control, semi-fixed time control has a more constrained flexibility due to a fixed cycle time: the flexibility is not cumulative. But the plan stability is still problematic due to the uncertainty of the switching moment, which can lead to a jump in the speed advice of up to 60% in the example of Figure 6.

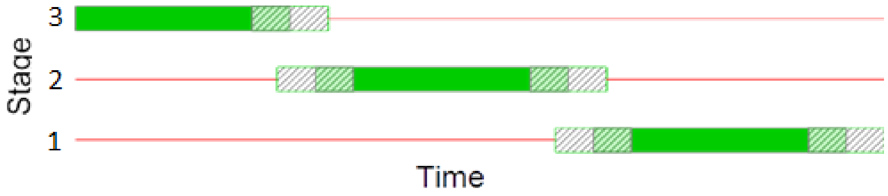
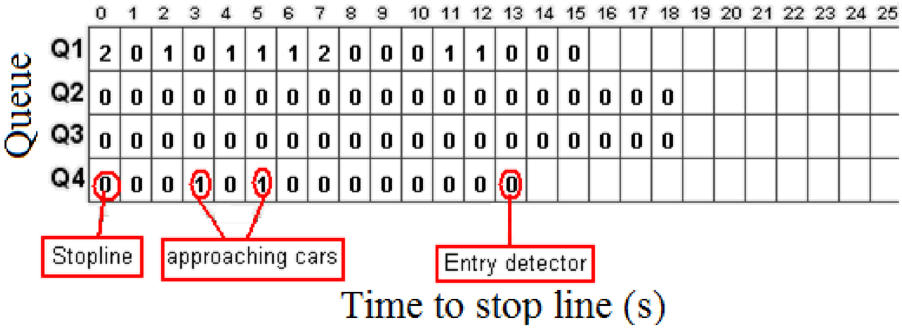


Figure 6- Semi-fixed time control dynamics

In operation, the original GLOSA application for semi-fixed control was developed to display speed advice on a static panel at approximately 500 m upstream of the intersection. The speed advice was intended to be used until approximately 100 m before the stop line where the driver starts to slow down more, anticipating a slightly delayed start of green.

Adaptive control was briefly introduced in the introduction section. Figure 7 shows a schematic view of a queue and arrival model. Vehicles enter the model when they are detected by the entry detector. The x-axis represents the vector of time that contains each cell, representing one second. In this example, the historical travel time from the entry detector for queue 1 (Q1) is 15 seconds and therefore the vector reaches up to t = 15. Every second, vehicles in the arrival pattern are moved one field closer to the stop line (indicated by the "0" column). The queues accumulate at the stop line and discharge with counts from the stop line detector. For Q1, after one second, the "0" in cell 1 gets added to the "2" in cell 0, resulting in a new "2"; the "1" in cell 2 shifts to cell 1, resulting in a new "1", and so on.



	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Q1	2	0	1	0	1	1	1	2	0	0	0	1	1	0	0	0										
Q2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0							
Q3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0							
Q4	0	0	0	1	0	1	0	0	0	0	0	0	0	0												

Figure 7- Queue and arrival flow modelling in adaptive control

In this paper, the adaptive control algorithm ImFlow [7] is used to set up simulation experiment. ImFlow uses the model of approaching and waiting vehicles to evaluate different possible control solutions. They are evaluated using a cost function that minimizes delay and stops for all traffic approaching the intersection. Calibration effort for this control method is minimal, since the algorithm optimizes the green duration by itself. Precise configuration of safety timings and detector location is required. Maintenance costs are minimal except for sensor maintenance. Throughput and delay for this control method are optimal, since every cycle can be precisely adjusted to cycle-by-cycle demand fluctuations. In case of congestion, the model knows which stages are most congested or could even cause spillback to other intersections and allocate most green time there while respecting a maximum waiting time. Adaptive control is the current state-of-the art, in contrast to semi-fixed time control, which allocates the spare time according to a first-come-first-serve principle and actuated control, which has a pre-configured amount of extra time for each stage.

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 (e.g. a pedestrian or bicycle approach with only a push button), signal priority and pre-emption calls.

Simulation Experiment

Simulation network

In light of the theory and methodology section, two types of experiments are set up in this case study: adaptive control (ImFlow) with experimental static speed advice and static control (the static control inherited in SUMO traffic simulator) with the same experimental static speed advice (the respective baseline is without speed advice). Both types of experiments take place on the network of Helmond, intersection 101, 102, 103 and 104.

Figure 8 shows the network topology in maps (left) and in SUMO simulation (right). The intersections for green wave study in this case study are listed under Figure 8. This network currently has adaptive traffic control system-ImFlow operating on the road stretch.

The network layout is suitable for green wave study due to the following characteristics: a) the corridor shaped network with consecutive intersections; b) for all four intersections, the highest traffic demands are on the corridor directions- signal group direction 8 (SG8:west-east) and signal group direction 2 (SG2:east-west); c) minor traffic demands on the other directions, such as north-south directions and pedestrian/cyclist directions; d) speed limit on the network is consistently 50km/hr.

On the other hand, the network layout, like all real world traffic network, poses the following challenges for green wave study: a) the various distances between adjacent intersections, for example, the distance between intersection 101 and 102 is 179m while the distance between intersection 103 and 104 is 485m; b) asymmetric distances between two adjacent intersections from stop line to the next stop line, for example, the distance between intersection 102 and 103 eastbound is 200m while the distance between intersection 102 and 103 west bound is 164m; c) different traffic demands and different traffic directions for cyclist and pedestrian, which result in long and various intergreen for conflicts between vulnerable road users (VRU) and vehicle directions.

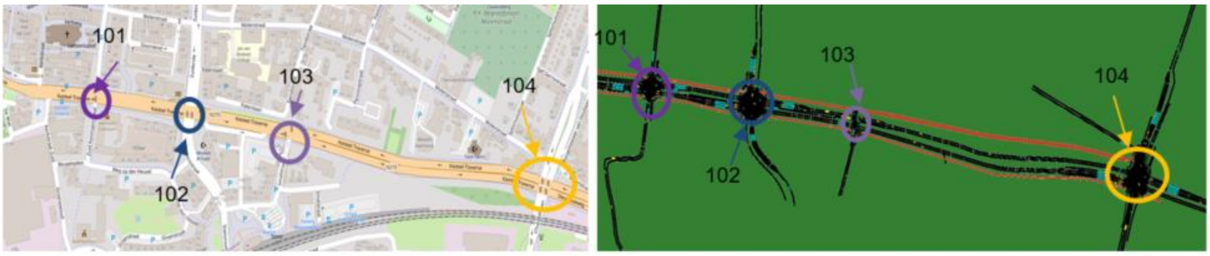


Figure 8- Case study of Helmond (left) and the simulation network in SUMO (right)

- Intersection 101, Zuid Koninginnewal/ Kasteel-Traverse
- Intersection 102, Zuidende/ Kasteel-Traverse
- Intersection 103, Penningstraat/Smalstraat/ Kasteel-Traverse
- Intersection 104, Churchilllaan/Burgemeester van Houtlaan/ Kasteel-Traverse

GLOSA design for fixed signal plan

According to the aforementioned real world network layout of the case study, the signal control on the main directions 8 and 2, as well as the distance between intersections are re-created in Figure 9.

X-axis is the distance, which resembles the network length and the intersection size. Y axis is the time, which has a fixed cycle time of 70 seconds for all four intersections.

In principle, this fixed plan adopts the theory for unevenly distributed networks. This fixed plan takes into account the calibrated demand of each direction at each intersection. Therefore, the minimum green times are satisfied to achieve no-congestion network. In addition, constraints such as intergreen, minimum green, minimum amber and red also comply with the traffic configuration currently in operation. Lastly, the green phases on direction SG8 and SG2 are maximized to achieve the optimal green wave.

After setting up the fixed time plan individually for each intersection, we can see from Figure 9 that the green time for SG8, SG2, and for each intersection are different. For example, it is relatively simple to achieve green wave on intersection 102 and 103 due to long and symmetrical green time on SG8 and SG2, while there are limited green time possibilities on intersection 101 and 104.

Afterwards, the light and dark green lines can be drawn to depict vehicle trajectories, aiming to achieve green wave. The dashed lines between intersection 101 and 102 indicate that the speed is adjusted lower than speed limit of 50km/hr to achieve green wave. In this case, the speed advice is 23km/hr on the SG8 direction (eastbound) and 18km/hr on the SG2 direction (westbound). This is quite slow, but with connected and automated vehicles, lower speed advice can be given since compliance is not an issue.

For adaptive control of this case study, the state plan of ImFlow considers the same calibrated demand and traffic constraints. Therefore, the signal stages and split of each stage are comparable as well. Since the goal of adaptive control is to achieve optimal traffic efficiency (low impact) instead of green wave, we adjusted the speed of road and vehicle speed between intersection 101 and 102 according to the fixed time plan. Assuming the adaptive control takes the new traffic arrival pattern and traffic speed into consideration, the adaptive plan would automatically adapt to achieve green wave when the underlying approach speed is already optimal.

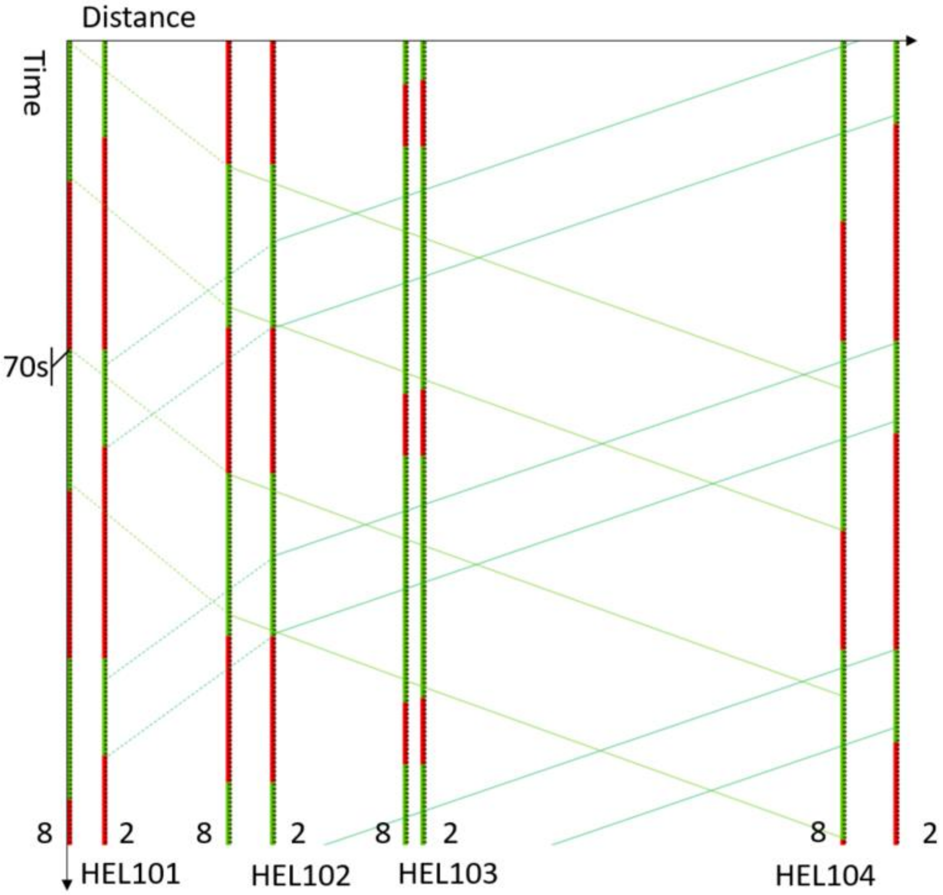


Figure 9- Fixed signal plan for the network, with maximum green wave bands.

Case study scenario set-up

In summary, four simulation scenarios are set up to perform green wave simulation experiment on the case study network, see Table 1.

Table 1- Case study scenario set-up

Scenario	**Description**
ImFlow Baseline	Current adaptive traffic plan in operation

ImFlow SA	Current adaptive traffic plan with speed advice, 23km/hr and 18km/hr between intersection 101 and 102
Static Baseline	Static traffic plan with no speed advice
Static SA	Static traffic plan with speed advice, 23km/hr and 18km/hr between intersection 101 and 102

To study the stops for red signals in the corridor itself, sets of E3 detectors (see SUMO wiki) are configured on the simulation network. A set of E3 detector (entry and exit) can detect the mean-vehicle-halt below a configured threshold, which can indicate the stops for red signal on one link or one stretch. It adds the possibility of filtering for vehicles that pass SG2 or SG8 on two or more consecutive intersections and not consider vehicles that entered from a side road.

In the case study network, eight sets of E3 detectors are configured, see the x-axis labels in Figure 11. The name of the E3 detector indicate the position, for example, 102SG8 means the detection of vehicle encountering red signal at intersection 102, direction SG8.

Result

The results of all four scenarios are collected after simulations experiments (10 runs per scenario and average results are used), see Figure 10.

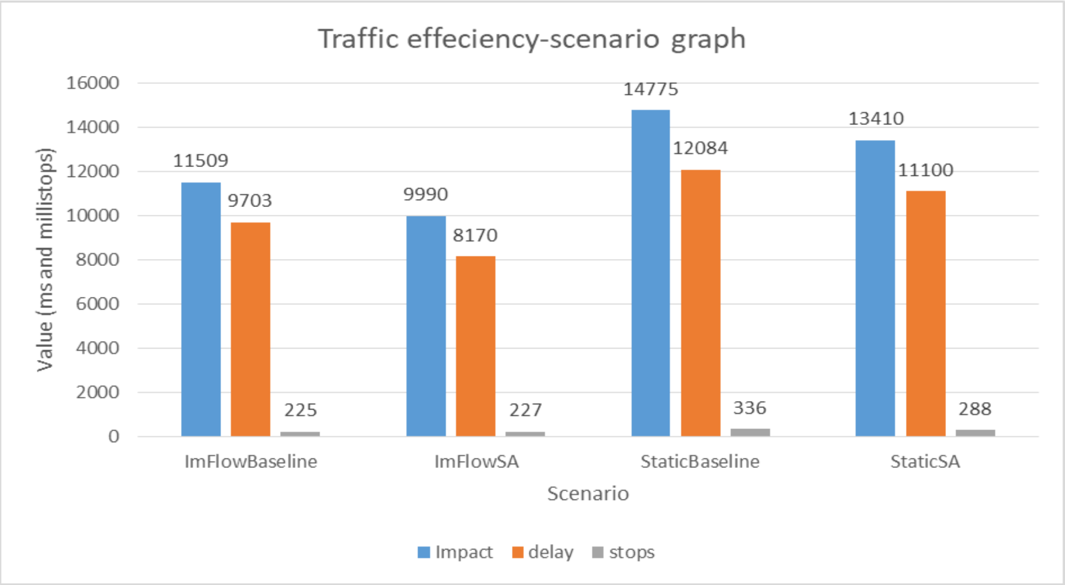


Figure 10- Impact, delay and stops comparison of four scenarios

As expected, the adaptive control (ImFlowBaseline) shows lower impact, delay and stops comparing to static traffic plan (StaticBaseline). The adaptive control with speed advice scenario demonstrates better network performance comparing to adaptive control, which is the contribution of less delay from speed advice.

The static plan with speed advice scenario shows an impact decrease of 9.2% comparing to static plan without speed advice. This can also be explained in the lower delay and stop, thanks to speed advice aiming for green wave.

The results of vehicles stopping for red are shown in Figure 11. For static plan, vehicles stop for red generally less with speed advice on (see the different between purple line and green line). While for adaptive control, the speed advice with ImFlow has some positive effects on some of the intersection and not on the others (see the different between blue line and red line).

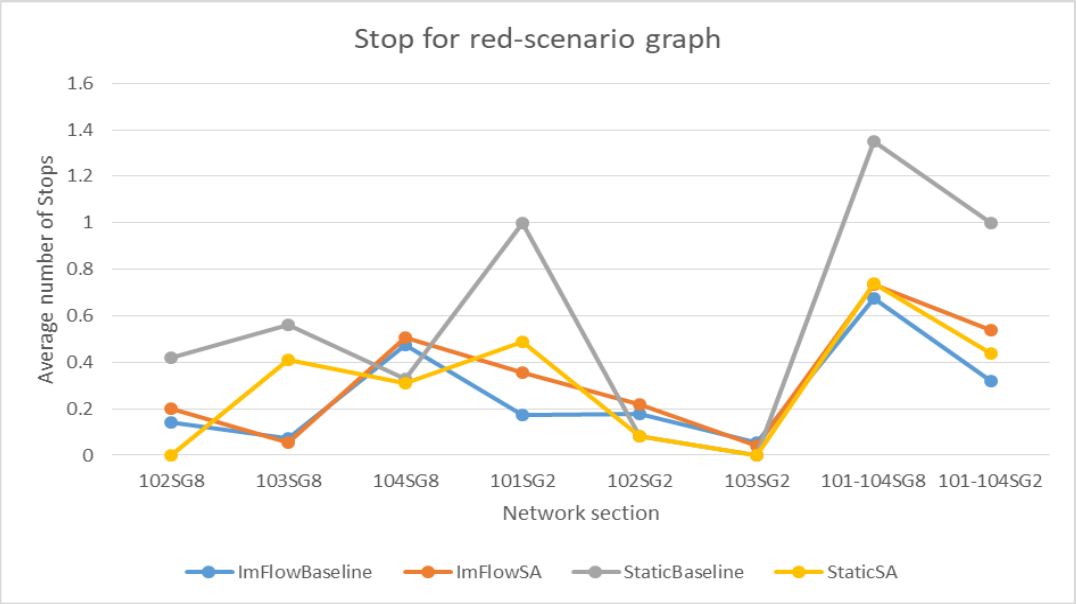


Figure 11- Stops for network subsections of four scenarios

To study the green wave improvement between with and without speed advice in static plan scenario, results are further demonstrated in Table 2. The positive increase from no advice to advice is significant while only two intersection/direction with already excellent green wave performance (due to fewer traffic directions in these two intersections) show no change.

Table 2- Case study scenario set-up

	102SG8	103SG8	104SG8	101SG2	102SG2	103SG2	101-104 SG8	101-104S G2
Static Baseline	0.42	0.56	0.33	1	0.08	0	1.35	1
StaticSA	0	0.41	0.31	0.49	0.08	0	0.74	0.44
Greenwave Improv.	100%	26.8%	6.1%	51%	0	0	45.2%	56%

Conclusion and future research

From the results, the following can be concluded:

1. Adaptive control leads in key performance indicators such as impact, delay and stops of the four scenarios, since it aims for traffic efficiency. The arrivals of vehicles, cyclist and pedestrian are evaluated at run-time and the lowest cost solution is chosen to optimize the network performance.

2. The static plan with speed advice scenario shows an impact decrease of 9.2% comparing to static plan without speed advice. This can also be explained in the lower delay and stop, thanks to speed advice aiming for green wave.

3. The results of the green wave plan are not significantly improved when it comes to stops in the corridor level for adaptive control with speed advice. As explained in methodology, the adaptive

control is flexible and optimal designed for lowest control cost for the whole network. But the control algorithm still has the same relative importance for stops of main direction, comparing to delay of other traffic vehicle directions and pedestrians/cyclists. Therefore, this result is according to expectation. It should also be noted that the stops are already lower than for static control with speed advice, resulting in less room for improvement. Delay is significantly reduced because traffic generally arrives more synchronized, leaving more green time for other traffic.

For the future research, we have observed that the platoons sometimes had to stop due to variations in queues of vehicles origination from upstream side roads for the static control solution during the simulation. Adding a dynamic GLOSA speed advice on top of that would also eliminate those stops. While the results for adaptive control are overall much better than for static control, the solution will not combine well with GLOSA-type speed advice. This will undermine the green band shaping, quickly restoring the old situation with unsynchronized platoon arrivals for large platoons arriving from the start of the corridor. Therefore, the static solution in combination with dynamic GLOSA has the highest potential to achieve maximum green wave performance. Additionally, platoon splitting will be applied for vehicles arriving at the first intersection of the corridor.

Acknowledgement

The paper presents results of the EU-funded project MAVEN project (Managing Automated Vehicles Enhances Network) under the Horizon2020 Framework Programme, Grant Agreement No. 690727.

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