Signal Plan Stabilization to Enable Eco-Driving

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***Abstract*— Eco-driving applications have high potential to significantly reduce pollution in urban environment. Speed advice for vehicles approaching traffic lights, allowing them to pass through an intersection during the green interval, is one of such applications. This paper compares several control methods with respect to traffic efficiency, plan stability and the resulting speed advice performance. A novel control method is introduced, which is specifically designed for maintaining efficient traffic control while adding stability to the control plan. The method is an extension to the current adaptive algorithm. The results show a large improvement between static and actuated control with 19% reduction of negative impact, and a further 11% reduction is achieved with adaptive control. While semi-fixed time control is currently the default solution for speed advisory systems, the stabilized adaptive controller outperforms this solution in both stability and traffic efficiency. The chance for stopping at the traffic light was reduced from 73% to 47% with a 14% better traffic efficiency.**

Keywords—Traffic control, speed advice, eco-driving, traffic management

I. Introduction

Traffic is one of the major contributing factors to pollutant emissions, which can cause health problems for people especially in congested urban environments [1]. Apart from measures to stimulate a modal shift to modes of transportation alternative to car usage and promotion of clean vehicles, eco-driving is the most promising solution. These can be implemented through in-vehicle systems, or in cooperation with the ICT infrastructure. In dense urban areas, traffic lights are one of the dominant factors for traffic flow dynamics. Solutions in these areas should therefore be efficiently sought in cooperation with traffic light controllers.

A commonly used application for eco-driving is Green Light Optimal Speed Advisory (GLOSA). However, this application requires a predictable traffic control plan to be effective and accepted by users. This contradicts with the requirement of adaptability to the dynamics of traffic demand. Static control strategies are ideal for GLOSA, but are not able to deal with changes in traffic demand. This will cause congestion leading to even more negative environmental impacts.

Scientific research in the domain of traffic control for cooperative (and future automated) transport systems is limited. Researchers from academia often do not specify the control system, or assume that such system exists. Most previous studies only target the sustainability evaluation of eco-driving through simulation. Several commercial speed advice products are on the market, which use semi-fixed time. However, no scientific reference was found to such systems. Studies, such as [2] and [3] showed that cooperative traffic control systems require substantial penetration rates of equipped vehicles, typically above 20%, in order to assure their functionality. However, they did not specify the control algorithm used. The EU-funded project Drive C2X (FP7) intensively explored V2X (i.e. vehicle to anything (relevant)) technologies and assessed the potential impact and user perception of cooperative systems, including GLOSA [4]. Stebbins, et al. [5] generalised the speed advice given to a vehicle, by optimising primarily for delay over the entire trajectory instead of suggesting an individual speed, regardless of initial conditions. The algorithms developed focused on minimising delay, and help to reduce fuel usage and emissions by conserving kinetic energy. In addition, Stebbins. et al. [6] used a microscopic, car-following traffic model instead of macroscopic, fluid-mechanical traffic models). It proposed that the optimal control schedule that minimises delay can be found via model predictive control (MPC) with suitable state space reduction techniques. Blokpoel and Niebel has investigated traffic light control (TLC) systems. Three algorithms were analyzed through micro-simulation: SWARM, ImFlow and extended ImFlow (from the perspective of stabilising green planning, to enable GLOSA) [7].

This paper aims to contribute to the area of traffic control algorithms in the context of cooperative and automated transport. It will first discuss the background theory of relevant control strategies: static, actuated, semi-fixed time, adaptive and stabilized adaptive. This is followed by a section where the research methods for the simulation are described. The results section will apply the simulation methods to each control strategy and analyse their plan stability and its effects on GLOSA applications. Finally, conclusions will be drawn, and further research will be presented.

II. Traffic Control Theory

A. Static control

The simplest form of traffic control is static or fixed-time control. Even though little intelligence is required inside the controller cabinet nor any investment for sensor technology, the maintenance costs can still be high. This is due to the manual calibration effort required to keep the plans effective.

Formulae and software tools [8] are available to calculate these plans, but for every significant change in traffic demand, the procedure has to be repeated.

The plans are calculated based on average flow and include a margin to cope with cycle-by-cycle demand fluctuations and prevent queues from forming. This does imply most of the time these margins are unnecessary and 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 on by the clock.

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. With this input, the system dynamically decides when to switch between several pre-configured plans.

Irrespective of the amount of static plans and the plan selection method, the dynamics for GLOSA are the same. The control strategy is perfectly predictable, but has a risk of forming congestion, which impedes the efficiency of a speed advice.

B. *Actuated control*

Actuated control is based on sensors detecting whether traffic is present or not. Typically, two functions for detection 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. This is illustrated in Figure 1. The solid green rectangles represent the minimum green time and the hatched rectangles the optional time available for extension.

Investment costs of actuated control are higher due to the required sensors. Apart from added sensor maintenance, the calculation of the signal plans require much less updating. The traffic engineer sets the minimum green time based on safety requirements, since in general drivers do not expect very short green durations. The maximum green time is based on the maximum desired cycle time. This may require rebalancing when traffic demand changes considerably.

The plan stability is very low as can be seen in Figure 1. The plan in the example has a minimum green duration of 6 seconds and a maximum of 20. This means that there is 14 seconds uncertainty when the next stage starts and 28 seconds for the start of the third stage as is indicated by the increasing hatched areas. Providing speed advice based on this data will be nearly impossible.

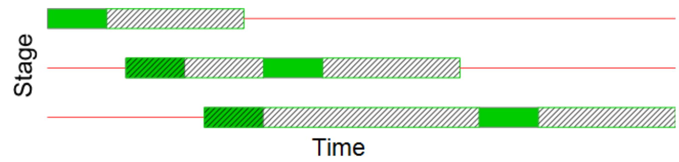

Figure 1: Actuated control dynamics

Figure 2: Semi-fixed time control dynamics

C. *Semi-fixed time control*

Most commonly used for contemporary GLOSA solutions are semi-fixed time control strategies, like for ODYSA [9]. These are based on a fixed time control plan, but the switching moment can occur between a configured minimum and maximum time. This is illustrated in Figure 2, which shows the guaranteed green with solid green rectangles, default green is indicated with hatched light green and the maximum allowed flexibility with just a hatched box. A default green time of 20 seconds is used, while both at the beginning of a stage and at the end there is a flexibility of (-3, 3) seconds. Meaning the absolute minimum and maximum green times are 14 seconds and 26 seconds respectively.

Important for the stability is that there is a fixed cycle time. This means the flexibility is not cumulative, i.e. if the first stage is extended up to $t = 23$ seconds, the second cannot reach the maximum green time of 26 seconds anymore. It would have to extend to the maximum switching moment to reach the default green time of 20 seconds. This also shows a weakness of this method in congested situations. If the first stage is slightly congested it will use up all flexibility, even if the second stage is heavily congested.

Despite the constrained flexibility, the plan stability is still problematic, due to the moment the decision is taken. Until the previous stage enters the (light green) hatched area, there is still 6 seconds uncertainty for the switching moment. Only once the switch is initiated, there is certainty. The amber time is left out of the figures to keep them easy to understand, but is typically 3 seconds. This is followed by typically 2 seconds of all-red clearance time before the next phase can start. Therefore, until 5 seconds before the start of green there is a 6-second uncertainty for the moment of switching.

The original application for this system was to display speed advice on a static panel at approximately 500 m upstream of the intersection. The advice is therefore intended to be used until approximately 100 m before the stop line when the driver starts to slow down, anticipating on a slightly delayed start of green. For connected and automated vehicles, the potential is much bigger as they can receive continuous updates of the speed advice. This control strategy for them,

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would imply a sudden decrease of time to green prediction from 8 to 5 seconds (green starts early) or a freeze of 3 seconds when reaching 5 seconds to green. This can lead to a jump in the speed advice of up to 60%.

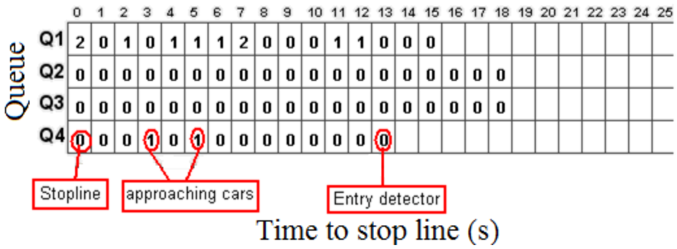

Figure 3: Queue and arrival flow modelling in adaptive control

D. *Adaptive control*

Adaptive control is based on a model of the approaches towards the intersection. In Figure 3, a schematic view of the queue and arrival model is shown. Vehicles enter the model when they are detected by the entry detector. The x-axis represents the distance to the stop line in travel time. In this example the travel time from the entry detector for 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, which is indicated by the "t = 0" column. The queues accumulate at the stop line and discharge with counts from the stop line detector.

In this work, the adaptive control algorithm ImFlow [10] is used. ImFlow uses the model of approaching and waiting vehicles to evaluate different possible control solutions. They are evaluated using a costs 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 cycle time. This 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 preconfigured 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) and signal priority calls.

E. *Stabilised adaptive control*

The adaptive algorithm allows for adding new elements to the cost function. A patent for a new algorithm adding such plan stabilization was applied. This should make the control algorithm more suitable for GLOSA, without deteriorating the average traffic delay significantly. The implementation of this cost function (C) is further explained in the following formulae:

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

$$d = TTG_{t-1} - TTG_t - T \quad (2)$$

The configured weight for stability (SBW) allows the traffic engineer to configure the importance of stability with respect to the other control targets. The deviation (d) is calculated using the difference between the time to green (TTG) of two consecutive time steps. The time period of a time step (T) is used for the expected decrease of the TTG. The cost is quadratic with respect to the deviation because higher deviations are increasingly worse for the driver acceptance of a speed advice. Furthermore, the cost is inversely proportional to the TTG of the last time step. This is because the closer to green, the more impact a change in the plan has. This last element is a major improvement compared to semi-fixed time strategies that allow for flexibility around the stage transition and could therefore change the prediction very close to the actual moment of the transition.

An added advantage of a configurable cost function element is that it can be activated on a per signal group basis. The through direction of the main road generally has the largest amount of traffic and, therefore, the highest benefit of GLOSA and plan stabilization. Other directions can be more flexible because they do not require a cost for plan stability. In this way the controller is able to combine the best of two aspects: stability for the main direction and flexibility for the others. This is shown schematically in Figure 4; only the third stage has a fixed start of the green. The other stages are completely flexible and even their order could be changed if this is more optimal for the traffic flow (i.e. first stage 2, then 1 and finally 3).

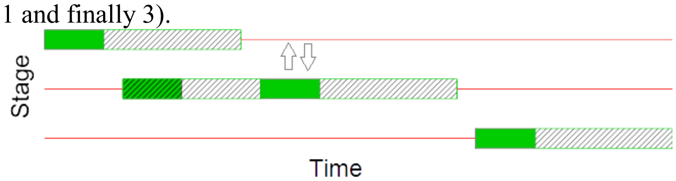

Figure 4: Stabilized adaptive control dynamics

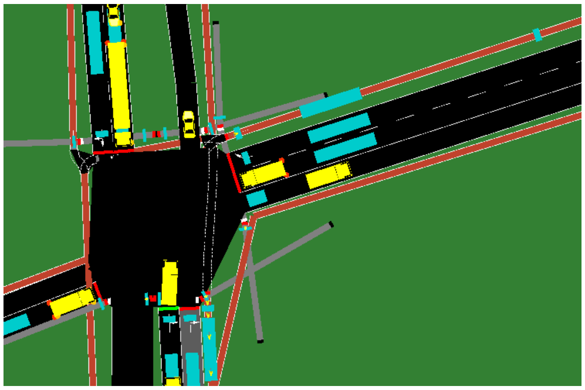

Figure 5: Simulation network of Groningen, The Netherlands

III. SIMULATION METHOD

To compare the performance of the various control strategies introduced in the previous section, a network using the Simulation of Urban Mobility (SUMO) [11] was used. The simulated intersection is depicted in Figure 5 and is located at Parkweg/Paterswoldseweg in Groningen, The Netherlands. The intersection is not saturated with a total traffic flow of approximately 1,250 movements per hour. The largest share of the traffic are the bicycles approaching the intersection from the south with a volume of 350 per hour.

The bicycles of this signal group will have GLOSA and plan stabilization (when applicable) enabled. The developed method will also be implemented for cyclists in the field at this intersection. For the overall performance of the network, it is most important that the largest stream of traffic receives the speed advice. In addition, the number of signal groups with plan stabilisation is limited to one. Adding more would impede flexibility more and could negatively impact the performance of the network.

The speed advice is directly applied to traffic participants using the TraCI interface of SUMO. Speed advice is applied from 200 m before the stop line and is subject to a range of 6-20 km/h for cyclists. Slower or faster speeds are not considered realistic.

The simulations are performed with 10 runs of 2 hours per traffic control strategy to build statistically significant data. During the simulation delay time and the amount of stops are tracked for every traffic participant. Overall averages are reported in the results section for impact, delay and stops. The impact is a measure to quickly review the performance of a simulation scenario in one glance. It is defined by the following formula:

$$impact = \frac{\sum_{i=0}^{i=I} delay_i + 8\ stops_i}{I} \tag{3}$$

The formula sums over all traffic participants (I) and calculates the average impact. It can be applied to the total network or to a single signal group. The most interesting signal group is the one where the GLOSA service is applied. Therefore, this signal group will be reported separately as well.

The simulation network has sufficient space for vehicles to enter the network even in case of long queues due to congestion. However, in case there is severe congestion, the total throughput of the simulation is also measured and used as a control. When a scenario has significantly lower throughput than another, the other numbers cannot be compared anymore because one or more signal groups had too few traffic entering the network. This makes it easier for the controller to serve the other traffic with low delay and results in an unfair comparison because the solution would be unacceptable in the field.

For evaluating the plan stability and GLOSA performance, multiple measures are used. Firstly, the prediction of *TTG* is logged during the entire simulation. Afterwards, the actual *TTG* can be calculated by stepping back from the moment the light turned green. These two values cannot be compared directly as the traffic light controller does not give a prediction, when there are no approaching bicycles. Additionally, when $TTG > 60$ seconds, it is considered too far in the future to be relevant. In most situations, traffic participants would still be at an upstream intersection. Therefore, these cases are filtered out of the statistics.

A mean square error (MSE) is calculated as a good indicator for overall reliability of the data and is commonly used in many fields of science. However, this measure equally penalizes deviations close to the actual moment of switching as well as close to 60 seconds *TTG*. Therefore, the mean relative error (MRE) was added, which divides the error by the remaining *TTG* and expresses this as a percentage. A last stability 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:

$$pc = \left. \sum_{t=1}^{T} \frac{\alpha\ TTG_{t-1} - TTG_t}{min(TTG_{t-1}, TTG_t)} 100\% \middle/ \sum_{t=1}^{T} \alpha \right. \tag{4}$$

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

The PC measure serves to estimate the users' perception of the system. A sequence of predictions for *TTG* of for example 55,44,53 that should have been 50,49,48 would have an equal MSE as a sequence of 55,54,53. All predictions are 5 seconds too high. However, the user will see the prediction jumping around in the first case and will quickly discard the information as unreliable. Therefore, a low value for this PC is important for users' perception.

The GLOSA performance itself is measured by the number of stops of the bicycles receiving the speed advice. Fewer stops means more successful advice. It should be noted that reducing this number to zero will be impossible in the current scenario, because bicycles arrive in the network with a Poisson arrival process. This means even without a speed advice, some will not stop because they arrive exactly during green. This percentage is approximately equal to the share of the total green time for the specific signal group, minus the time required for the queue to clear. With a speed advice, a considerable amount will still approach the intersection at a moment that a potential speed advice would be above the maximum speed they can achieve or below a minimum comfortable speed.

IV. RESULTS

The results for traffic efficiency are presented in Table 1. Total throughput of the scenarios varied by 0.5%. This is still within the boundaries of the expected variation due to the Poisson arrival process. Therefore, all control strategies can be considered acceptable. Two sub-scenarios for the stabilised ImFlow configurations have been simulated, one with normal weight on plan stability in the cost function (1) and a high weight (5). To indicate the effects of GLOSA advice on overall traffic the No Speed (NS) scenario of regular adaptive ImFlow control was also simulated.

Table 1: Traffic efficiency results

Scenario	**Measure (average over 10 runs)**		
	Impact (s)	***Delay (s)***	***Stops***
Static	43.2	36.7	0.81
Semi-fixed	37.4	31.0	0.80
Actuated	36.2	29.6	0.84
Stabilised 5	35.6	29.7	0.73
Stabilised 1	32.7	27.0	0.71
Adaptive	32.8	27.0	0.72
Adaptive NS	33.6	27.0	0.83

As expected, the static control strategy has the worst performance. Generally, too much green is given to prevent congestion due to cycle-by-cycle variations in traffic demand. This does imply the amount of stops is slightly lower than for the actuated controller, since there will be some vehicles that can pass the green light while there is no queue. In such cases the actuated controller is likely to have cut off the green already. Semi-fixed time comes in second closely followed by actuated control. Adding flexibility reduces the impact significantly by up to 19% for actuated control.

Looking at the adaptive control scenarios using ImFlow, another impact reduction of up to 11% was found compared to actuated control. Interesting is to see the impact was reduced by adding speed advice to the adaptive control strategy (notice that all other scenarios have speed advice). This is due to the reduction of the amount of stops. With stabilized control the advice is more successful. This creates well-shaped high-density platoons approaching the intersection, which leads to better green phase utilization. Therefore, with a well-functioning speed advice the controller has more green time available for other directions, positively impacting overall network performance.

The formula in (1) showed there is a possibility to configure the *SBW* weight for how important stability is. For "stabilised 1" the weight was set to 1 and for "stabilised 5" the weight was set to 5. More stability leads to less flexibility and therefore the higher impact for stabilised 5 could be expected.

Table 2: Plan stability results

Scenario	**Measure (average over 10 runs)**		
	MSE (s^2)	***MRE (%)***	***PC (%)***
Static	0	0	0
Semi-fixed	62	41.89	3.82
Actuated	182	84.67	7.62
Stabilised 5	22	7.95	2.66
Stabilised 1	17	15.01	3.52
Adaptive	46	25.86	5.76

The results for plan stability are presented in Table 2. Static control has perfect predictability and actuated gives little useful information for speed advice. Semi-fixed time control has complex results, the MSE and PC are low compared to regular adaptive control, but the MRE is very high. This can be explained by the moment errors occur. At a *TTG* value of e.g. 2 seconds an error of 2 seconds is 100%, but only contributes 4 s^2 the MSE. Similarly, if the countdown is simply 4-3-2-0, the PC is still relatively low since the only penalized value is the transition from 2 to 0. The MRE penalizes all incorrect values. This is exactly what occurs for semi-fixed time control, the last correction is made in the final seconds and counts heavily for the MRE. It is also important for the performance of GLOSA, as these last-moment changes have the largest consequences for the speed advice.

For adaptive control the PC and MRE values exactly follow the expectations. It also confirms the theory that increasing weight on the stabilization increases the stability at the cost of traffic efficiency. It also becomes clear that much higher stability can be achieved with this cost function than with semi-fixed time control, while still achieving better traffic efficiency. The higher MSE for stabilised 5 may be unexpected, but can be explained by the fact that the cost function stimulates making corrections in smaller steps, even at higher *TTG* values. If the correction is made anyway, then the MSE is higher. For lower *TTG* values the plan is not changed anymore, which results in the lower MRE. Both effects together lower the PC value.

Table 3: GLOSA performance results

Scenario	Measure (average over 10 runs)	
	Bike delay (s)	***Bike Stops***
Static	46.2	0.75
Semi-fixed	33.4	0.73
Actuated	31.0	0.81
Stabilised 5	29.6	0.49
Stabilised 1	27.7	0.47
Adaptive	30.6	0.54
Adaptive NS	30.0	0.94

The results for GLOSA performance are presented in Table 3. Clearly, giving an advice reduces the chance to stop greatly: from 94% to 54% for adaptive control. The delay of the cyclists increases by giving speed advice, but only when there is no stabilization. This means that a very small share of the cyclists slowed down too much for an advice. Afterwards this was corrected, but still could not let the cyclist ride through the green light. These cases would frustrate the users and certainly impair user acceptance of the system. For stabilized control the delay time actually reduced, which means these cases did not occur. A surprising result is that stabilised 5 outperforms stabilised 1. This can be explained by the fact that the control algorithm could still make small adjustments to group more cyclists together in a green phase with lower weight on stability. An open question, however, is how much of these adjustments would be acceptable by actual road users, since the simulations were carried out with 100% acceptance rate.

Similarly, the better predictability of static control also did not lead to a lower amount of stops. For static and semi-fixed time control this can also be explained by the longer cycle time due to lower control efficiency. With this there are less opportunities for cyclists to receive an advice that is within the range of acceptable speeds. Actuated control has high flexibility and therefore low delay time, but the predictability is so low that speed advice is rarely successful.

V. Conclusion

This paper compared several control methods with respect to plan stability and GLOSA performance. The comparison was carried out using a SUMO simulation network of a solitary intersection. Specific measurements were introduced to evaluate the stability in detail. Apart from already available control strategies, the paper introduces a new control method, which is specifically designed for maintaining efficient traffic control while adding stability to the control plan. The method adds a cost function element to the adaptive control algorithm ImFlow. This gives the traffic engineer the possibility to tune the trade-off between traffic efficiency and plan stability.

The results showed a large improvement between static and actuated control with an impact reduction of 19%. A further 11% reduction could be achieved with adaptive control. While semi-fixed time control is currently the default solution for such systems, the stabilised adaptive controller actually outperforms this solution in both stability and traffic efficiency. The chance for stopping at the traffic light was reduced from 73% to 47% when comparing semi-fixed time control to stabilised adaptive control with a 14% better traffic efficiency. The configurable weight showed a clear effect on the trade-off between traffic efficiency and plan stability. It can be concluded that the stabilized adaptive control opens many new opportunities for eco-driving by making speed advice possible while maintaining near-optimal traffic efficiency.

Further research is required for user acceptance to be able to configure the weight for plan stability correctly. In addition, the speed advice modelling can be improved, e.g. to include occasional non-compliance. Furthermore, the plan stability weight and the relationship between MSE-MRE and PC can be further investigated.

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