Hierarchical delay-based signal coordination for bicycles and motor vehicles traffic

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Abstract

A traffic control strategy is developed based on stop-time delay of traffic users to assign coordination between bicycles and motor vehicles by a fair distribution of stop-time delay in a complex urban area. To reach this goal, we implement a hierarchical coordination process for finding the optimal coordination interval in which the delay and number of stops of the whole network is minimized. Here, the coordination interval refers to the intervals in second required to implement the coordination and to evaluate the performance of the network. Therefore, different interval lengths are defined by integer multiples of cycle time and the coordination performance is evaluated for different traffic users and the network as well. SUMO, an open source microscopic traffic simulation software, is used for the simulation studies. The coordination performance is measured using the average delay and the number of stops. The investigation area is situated in the center of Munich and contains nine signalized intersections with separated bicycle lanes in the main direction. Traffic was added to the simulation network based on observed traffic volumes and turning ratios. The optimum coordination interval is achieved by minimizing the average delay and number of stops of the entire network while at the same time providing a balanced stop-time delay between different types of traffic users. The analysis of the results in the major direction indicates that by using the new algorithm in traffic control strategy, there would be a significant reduction of delay and number of stops for bicyclists while at the same time, the delay of the entire network is not higher than the one of the current states.

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1 Introduction

There are many reasons to motivate people to use bicycles for utilitarian trips. It could be used easily by majority of people as a means of transport with no noise and pollution. Bicycling requires physical activity, which provides valuable cardiovascular exercise and potential health benefits (Castro et al., 2019; Yuning Jiang, Mario Zanon, Robert Hult, & Boris Houska, 2017). Germany has a relatively high rate of bicycle usage. Almost 10 % of the trips in Germany carried out with the bicycle in 2008. It then increased to 13.7 % in 2012 and is predicted a modal split of 35 % by 2050 (Erhard et al., 2014). The sales of bicycles in Germany also show a positive trend, which implies the increasing interest in bicycling (Zweirad Industrie Verband, 2018).

On the other hand, traffic congestion in many cities is continuously increasing and activists in different mobility sectors are seeking new control strategies and methods to improve traffic conditions. Numerous studies focus on traffic signal coordination, optimization, or a combination of both as methods to improve traffic flow (Anagnostopoulos, Ferreira, Samodelkin, Ahmed, & Kostakos, 2016; Jin & Ma, 2017; Portilla, Valencia, Espinosa, Núñez, & De Schutter, 2016). Generally, a traffic coordination strategy increases the quality of traffic operation (Kaczmarek, Cichocki, & Jabkowski, 2009), reduces traffic jams and accident rates in urban areas and improves infrastructural usage . In the vast majority of cases, signal coordination, optimization, or prioritization methods only consider motor vehicles. However, as the modal share of bicycling is raising and the number of bicyclists becomes noticeable, new control strategies are needed to fairly accommodate different types of road users. Unfortunately, problems arise when implementing signal coordination, optimization, or prioritization methods to serve different types of road users with different physical and dynamic properties simultaneously. Bicycle and motor vehicle traffic starting at the same time at one intersection would not arrive at the next intersection at the same time due to different speeds and accelerations. For this reason, the offset time for the signal coordination would be different for the different road user types. This becomes more critical when intersecting minor roads require a certain amount of green time to prevent from queue formation. In this case, the share of green time for the major road segment under consideration cannot be easily increased. Therefore, the question is how to implement a coordination strategy that considers the needs of different types of traffic users.

Due to popularity of signal coordination and optimization strategies in transportation engineering, a great deal of research has concentrated on this topic. Yuning Jiang et al., (2017) focused on an optimal traffic control strategy for automated vehicles with a collision avoidance constraint. Zhou et al., (2016) suggested a traffic demand balancing control model working in parallel with optimization of an urban traffic network. A study by Nuli and Mathew (2013) evaluates the effect of a real-time coordination adaptive signal control through reinforcement learning on delay of the network. However, in these approaches there are no implementations of solving the optimal control problem by considering other traffic users such as bicyclists. In another study (Chen, Qian, & Shi, 2011), a multi-objective optimization model of signal timing is built and analyzed by genetic algorithm to minimize simultaneously delay and number of stops while considering the capacity of intersections. This model is based on signal timing optimization and considers both motorized and non-motorized vehicles. However, it only works on one intersection with undersaturated condition and the research did not consider analyzing a real complex network.

Generally, there are many types of approaches for the coordination of traffic signals, such as optimization of bandwidth along arteries and minimizing total delay (Zhang, Xie, Gartner, Stamatiadis, & Arsava, 2015). Since the models that are based on delay are usually computationally complex and imply a high degree of nonlinearity, a heuristic approach is presented here.

In the presented approach, the controller decides the coordination assignment based on cumulative stop-time delay for motor vehicles and bicycles within each coordination interval. To prevent from changing the offset orders of the phases within a cycle time and assuring all phases are served in a cycle time, the length of the intervals is selected based on integer multiples of cycle time. In this way, the offset changing time coincides with the beginning of the cycle time.

The approach is developed and evaluated using an example road segment located in the center of Munich, Germany.

2 Methodology

2.1 Case Study and Field Data Collection

This research focuses on 9 intersections located along the streets Leopoldstraße and Ludwigstraße in Munich, which connect the north of Munich with city center (Figure 1). This segment is located in densely-built urban environment where a significant number of bicyclists use separated bicycle lanes positioned parallel to the roadway. The intersections are spaced between 170 m and 380 m from each other and there are dedicated bicycle lanes on the South and Northbound. The segment runs from north to south with intersecting road from east to west. Due to many shops, restaurants, schools and universities in this area, there is an increasing demand for cycling.

The City of Munich provided the current traffic signal plans for the segment in which the cycle time of all intersections are based on a fixed 90-seconds interval.

By checking the pre-defined offsets and observing the simulation of the current situation, it is clear that a coordination strategy for motor vehicles is implemented on the traffic signals. Moreover, public transport is prioritized at the intersections. However, there is no specific traffic control coordination for bicyclists in the study area.

According to German guidelines for the design of streets and intersections (HBS, 2015; HSRa, 2005), the distance between coordinated intersections should be less than 750 (maximum 1000) m for motor vehicles and less than 200 m for bicycles to fully exploit the coordination; otherwise the platoon disperses. Therefore, regarding the distances in this project, they fulfil the geometric requirements for motor vehicles and partially for bicyclists. Because the length of the sections between intersections are not the same, the coordination is only feasible in one direction of travel.

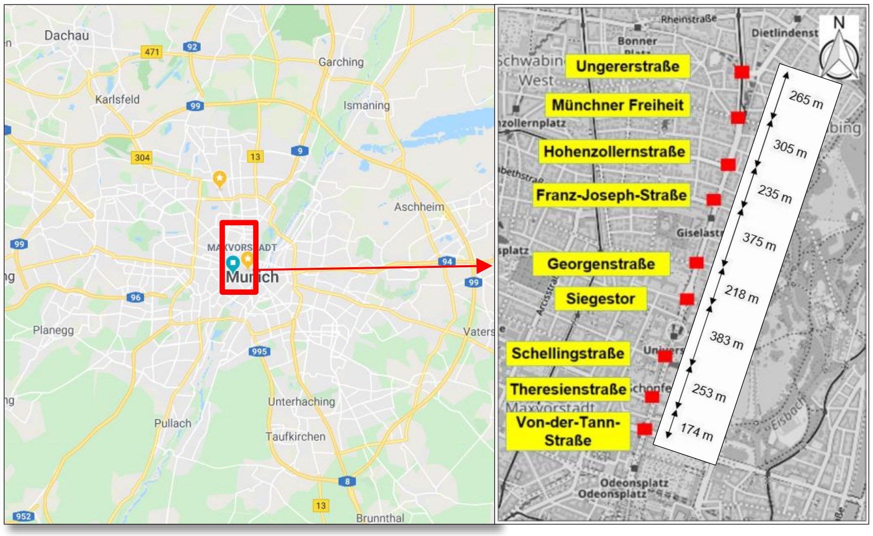

Figure 1: Map view of investigation area in Munich (Background image: OpenStreetMap)

Traffic data was extracted from video data recorded within two consecutive weeks for the afternoon peak hour and off-peak hour. In consideration of seasonal effects, video data was collected in June and July (2018), as bicyclist traffic volumes are high. Passenger cars, trucks, conventional bicycles, and cargo bicycles are considered as different types of traffic users. Pedestrians, parked vehicles and public transport are excluded from the scope of this research. Table 1 presents the characteristics of traffic users. These values are taken either by literature reviews, field measurement, or through calibration process.

Parameter	Bicycle		Passenger car	Truck
	Conventional Bicycle	Cargo Bicycle		
Max speed (m/s) [1,2]	6.2	5.8	13.9	11.1
Speed deviation (m/s)	0.15	0.16	0.12	0.15
Acceleration (m/s^2) [2,3]	1.8	1.8	2.3	0.8
Deceleration (m/s^2) [2,3]	4.0	4.0	5.5	3.0
Length (m)	1.6	2.4	5.0	10.0
Min Gap (s)	0.5	0.5	2.0	2.0
Minimum lateral gap (m)	0.5	0.5	0.6	0.6
Lateral alignment [2]	compact	compact	center	center
Sub-lane resolution (m)	0.2	0.2	0.2	0.2

[1] Schleinitz, Petzoldt, Franke-Bartholdt, Krems, and Gehlert (2017)

[2] Twaddle (2017)

[3] COWI (2012)

Table 1: Physical and dynamic properties of traffic users

2.2 Simulation Studies

Optimization of coordination is conducted using SUMO, an open-source multimodal traffic simulation software that is developed by the institute of transportation research at the German Aerospace Center (Alvarez Lopez, et al., 2018). The traffic control strategy is implemented using TraCI (Traffic Control Interface)(German Aerospace Center, 2020). Each scenario has 15 simulation runs and the evaluation period of each simulation run is 3600 s with 1800 s warm up time (total 5400 s). The cycle time of signalized intersections is fixed at T=90 s as the current state. Traffic data is extracted from video data and distributed on the network based on entering volume and turning ratios. Each simulation is assigned by a random seed to produce different arrival and departure variations.

We select traffic volume and travel time for the calibration and validation process of the model with two separate traffic datasets. The calibration of the model is implemented for off-peak hour to adjust the parameters of traffic users followed by validation of the network for peak hour traffic dataset. In the following the algorithm of the traffic control strategy and its implementation in simulation software is explained.

2.3 Traffic Control Strategy

The coordination strategy is the basis of this research and refers to a strategy in which several intersections are coordinated with each other, allowing the traffic to pass without stopping. This strategy requires similar cycle time for all coordinated intersections. Since the cycle time of all intersections in real conditions is the same (T=90 s), and to provide a comparable situation with other defined scenarios, the cycle time in simulation study is also kept the same for all scenarios. However, in a network with different types of traffic users (motor vehicles and bicycles) with dedicated lanes, the question is: to which traffic users the coordination should be assigned to get the optimum results for the entire network as well as to consider bicyclists in a fair process. To answer this question, the following method is implemented. The control strategy is depicted in **Figure** 2. Generally, when the distance between intersections is not the same, the coordination strategy is only feasible for one specific direction. The fairness is defined here by assigning equal weighting factors for motor vehicles and bicyclists.

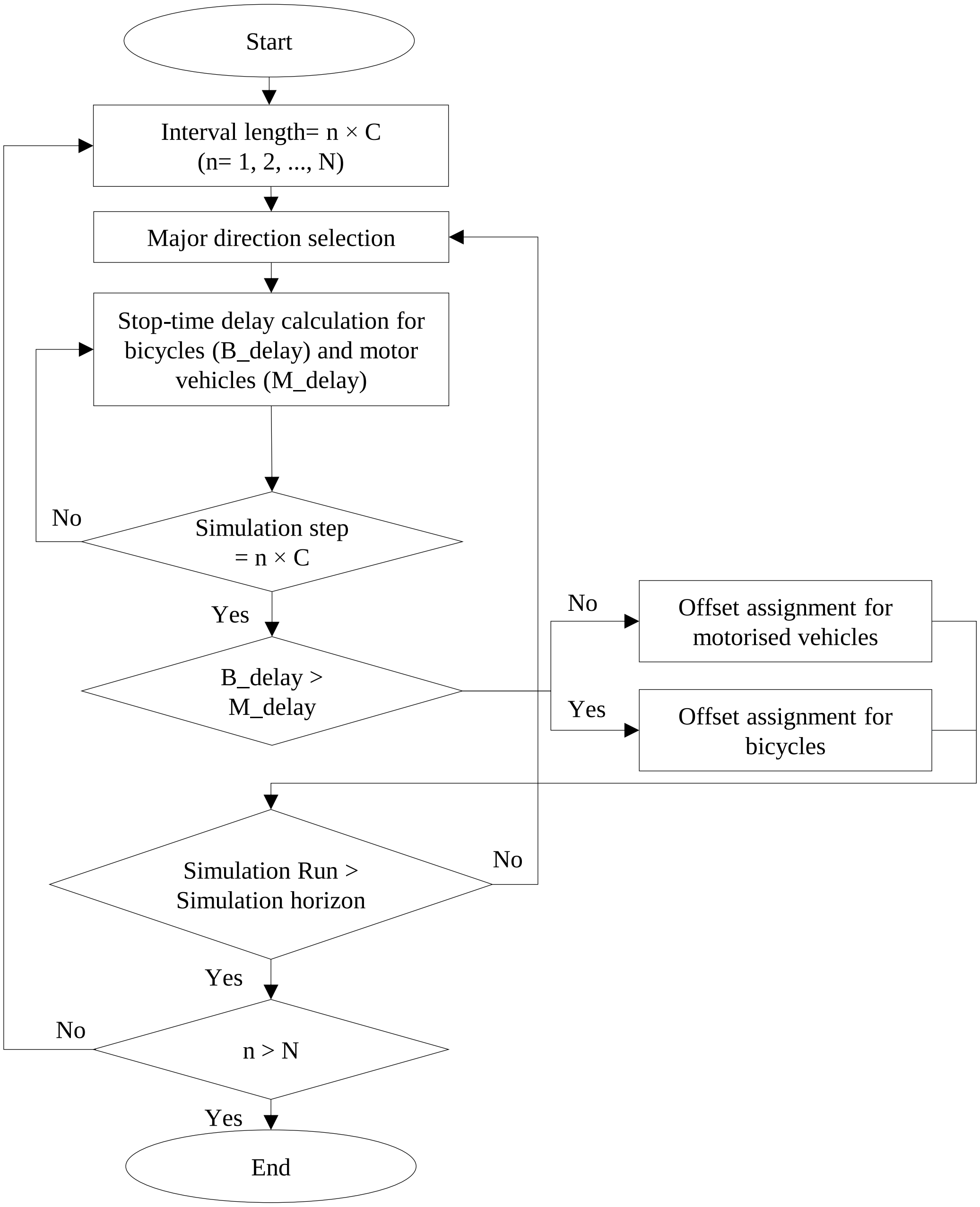

Figure 2: Flowchart of the algorithm of the new control strategy for signal coordination

The coordination direction is selected based on the major volume which could be time dependent. By observing the traffic volume in the network, North-to-South direction has the highest volume in afternoon peak hour for both motor vehicles and bicycles. Therefore, we regard this direction as the main direction in the coordination strategy of this study.

Then, we calculate the offsets separately for bicycles and motor vehicles based on progression speed so that a platoon of corresponding traffic users could travel along the entire network without stopping. For bicycles, we choose the progression speed by the average speed between the intersections in the simulated environment (without stopping). The progression speed of motor vehicles should be assigned between (90 – 100) % of the allowed speed (FGSV, 2001). Therefore, it is taken here by 90 % of the allowed speed. The distance between the intersections varies between 170 and 380 m. When the distance between intersections is more than 200 m, due to variation of bicyclists' speed as well as the difference between the speed of bicyclists and motor vehicles, implementation of a common coordination for bicycles and motor vehicles requires an adjustment of cycle time as well as increasing the length of green time assuring the passage of bicycle's platoons. However, since there is considerable traffic on cross streets, the cycle time and green time for them are kept constant to assure the green time of cross streets are as suitable as current state.

According to (1) we defined the term of interval length as a length of time to evaluate the measures of effectiveness of the network to make decisions for coordination assignment. With Cycle length C, we define the interval length I to:

$$\mathrm{I} = n \times \mathrm{C} \text{ with } n = \{1, \dots, 8\} \tag{1}$$

Moreover, the coordination interval is defined as the interval length in which the coordination process is implemented on the network. In this research, the coordination is implemented for each interval length individually.

During each coordination interval, the network will evaluate and compare the stop-time delay for both bicycles and motor vehicles. Take n = 5 for example, if the stop-time delay of bicyclists during an evaluation period 450 s (5×90=450 s simulation run) is higher than the one of motor vehicles, the controller switches to offset required for bicycles' coordination and this coordination lasts for the next 450 s. This process continues until the end of the simulation time.

3 Results and Discussion

The average delay and number of stops are selected as measures of effectiveness and the scenarios are compared with each other separately for bicycles and motor vehicles. These measures of effectiveness are calculated for the entire network and the scenarios are compared with each other to find the optimal coordination interval.

3.1 Average Delay

The effect of varying coordination intervals on the average delay for bicycles and motor vehicles is shown in Figure 3 and Figure 4.

Compared to the current state, by changing the interval length, the average delay of bicycles makes a minimum at interval length=630 s by almost 28% reduction (T-value = 40.627, P-value = 0.000). It increases afterwards slightly until the last interval length. Interestingly, the trend is the same for motor vehicles too. However, the delay of motor vehicles increases by almost 27% (T-value = -4.789, P-value = 0.000) at interval length= 450 s, showing the least increase through all interval lengths.

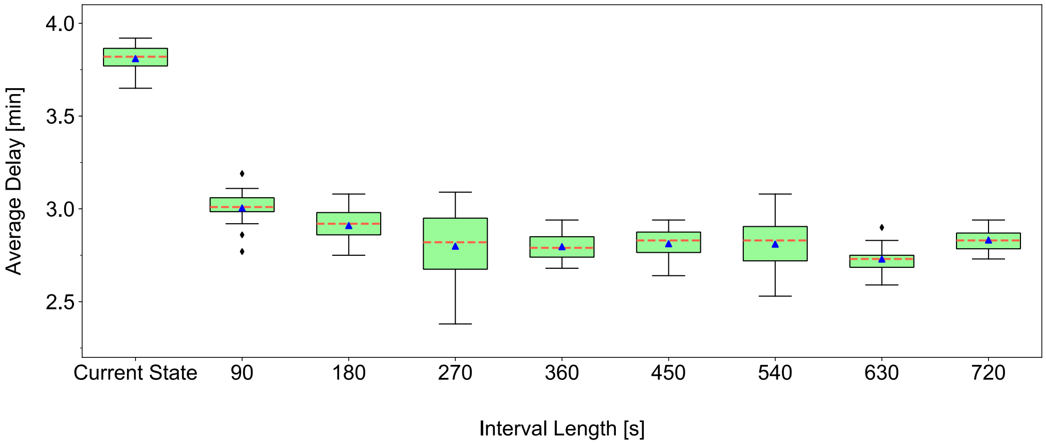

Figure 3: Average delay for bicycles at different coordination intervals

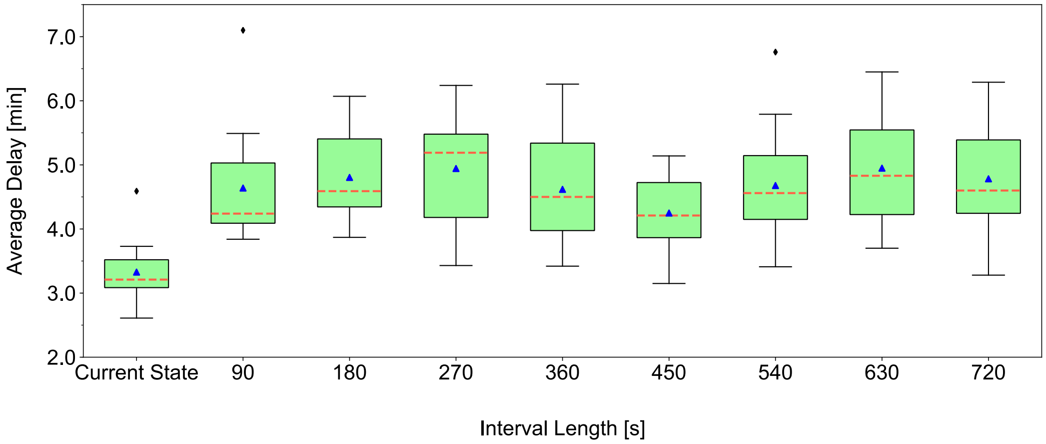

Figure 4: Average delay for motor vehicles by different coordination intervals

The current state scenario shows the highest average delay for bicycles and the lowest one for motor vehicles. It is important to mention that since the traffic control of the current state is designed to be more responsive to motor vehicles especially in peak hour, it contains the lowest average delay value for motor vehicles and the highest one for bicycles which implies that the coordination of bicycles was not of the priority for the planning of the network controllers in the current state.

3.2 Average Number of Stops

The number of stops for bicycles and motor vehicles are depicted in Figure 5 and Figure 6, respectively. Similar to the mentioned results for the average delay and compared to current state, the number of stops of bicycles is minimized at interval length= 630 s by almost 33% reduction (T-value = 41.668, P-value = 0.000). However, the number of stops for motor vehicles has increased in all coordination intervals and the lowest happens at interval length=450 s by nearly 54% higher than current state (T-value = -10.963, P-value = 0.000).

Moreover, the results of average delay and number of stops show two important interval lengths in which bicycles and motor vehicles show their minimum values, namely 630 s and 450 s, respectively.

On the other hand, the average travel time of bicycles and motor vehicles during changing the offsets varies from 630 to 735 s, and from 315 to 543 s, respectively. Since the mentioned interval lengths are within these travel times, one could conclude that there is a connection between required travel time for traffic users and their corresponding optimum interval lengths.

Sofar, the impact of the new control strategy on different traffic users are shown separately. Compare to current state, these results showed obvious improvement for bicycles and worsening situation for motor vehicles in delay and number of stops. However, the research question is not completely answered and it is still unclear if these changes are positively or negatively affected the network as a whole. To reach a better understanding about the network performance, these measures of effectiveness are aggregated for the whole network and are discussed in the next section.

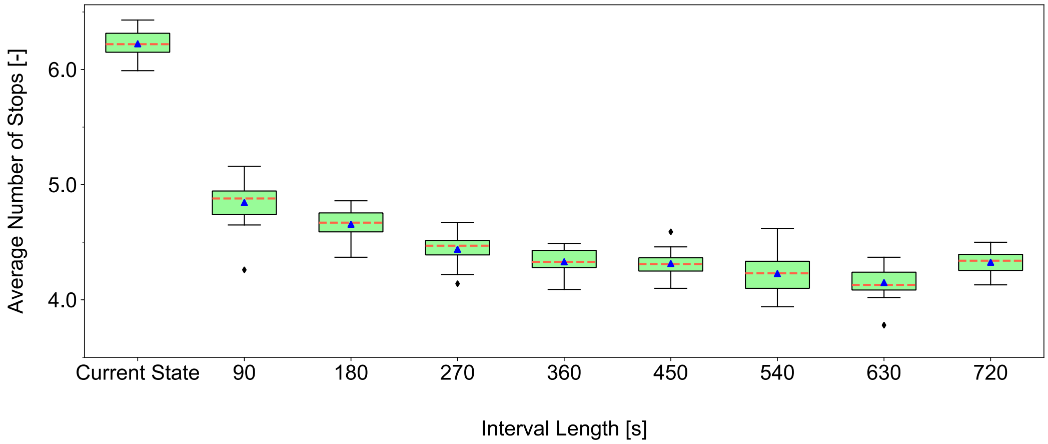

Figure 5: Average number of stops for bicycles by different coordination intervals

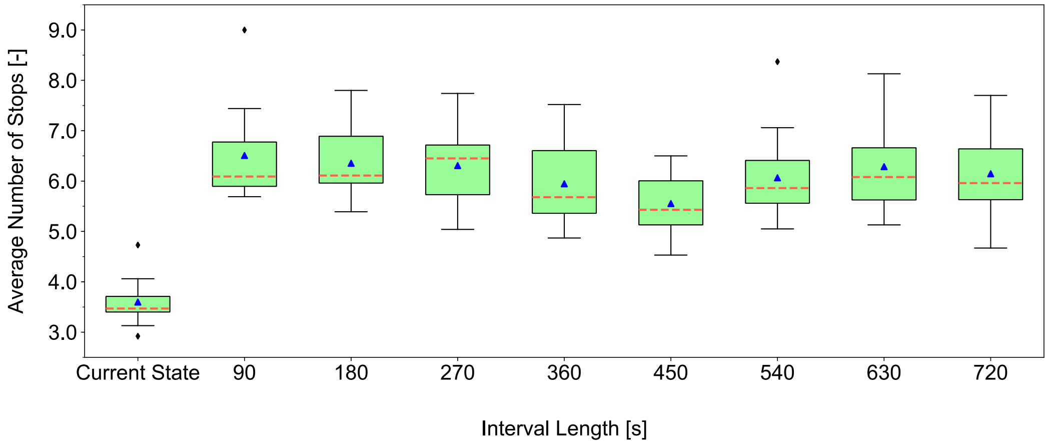

Figure 6: Average number of stops for motor vehicles by different coordination intervals

3.3 Assessment of the Network Performance

The average cumulative delay and number of stops for the whole network in major direction is depicted in Figure 7 and Figure 8, respectively.

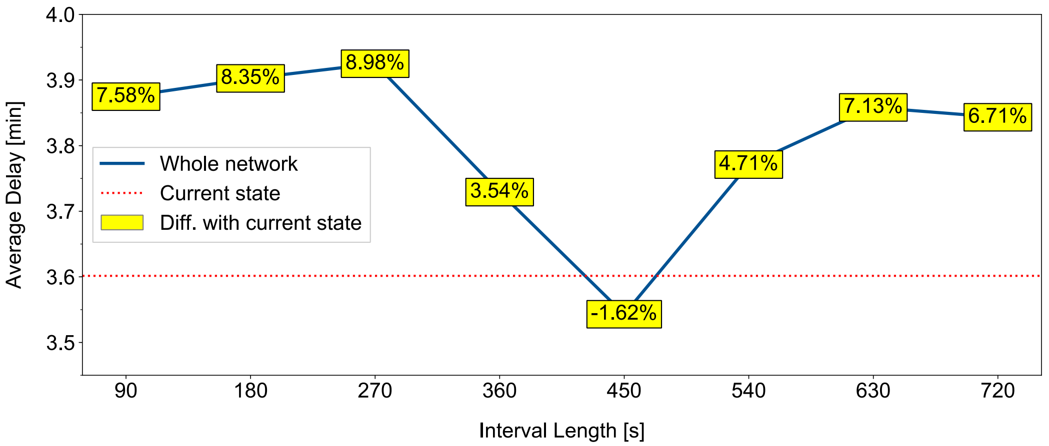

Figure 7: Average cumulative delay of the network (bicycles and motor vehicles) and its difference with current state [%] at different coordination intervals

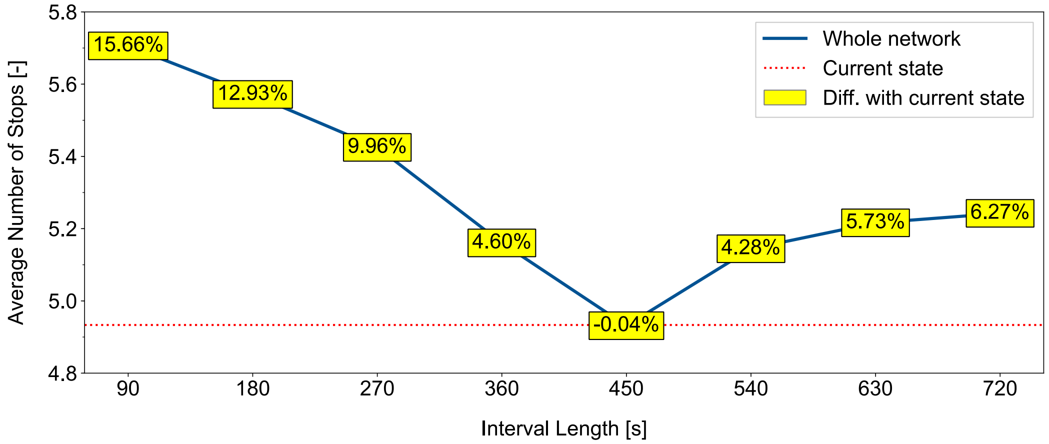

Figure 8: Average cumulative number of stops of the network (bicycles and motor vehicles) and its difference with current state [%] at different coordination intervals

As presented in these figures, compared to the current state, the scenario with the interval length=450 s reduces the average cumulative delay of the network by almost 1.62 % (T-value = 0.629, P-value = 0.534) and the average cumulative number of stops by nearly 0.04% (T-value = 0.026, P-value = 0.979). By considering the statistical values, it indicates that these changes are not significant. In other words, at interval length=450 s, the results of average cumulative delay and number of stops of the whole network is similar to the current state. As mentioned before in Figure 3 and Figure 5, the average delay and number of stops of bicycles at interval length=450 s significantly decreased by 26% (T-value = 35.085, P-value = 0.000) and 30% (T-value = 43.455, P-value = 0.000), respectively. Therefore, the coordination strategy at interval length=450 s could fairly change the performance of network control in favor of bicycles while at the same time, keeping the average cumulative delay and number of stops of the network similar to the current state. From bicyclist's perspective, this shows an outperforming of the new control strategy compared to the current situation. However, since the offsets of the network in the current situation was mostly designed to better coordinate motor vehicles, the new coordination strategy at coordination interval 450 s showed an increase in the average delay and number of stops of the motor vehicles by almost 27% (T-value = -4.790, P-value = 0.000) and 54% (T-value = -10.717, P-value = 0.000), respectively.

4 Conclusion

The stated procedure has a model-predictive structure based on stop-time delay to implement logical coordination strategies on multiple intersections of a network and to determine the optimal coordination interval based on selected measures of effectiveness. The coordination procedure is based on evaluation of the network on different interval lengths in which the controller could switch the coordination from one type of traffic user to another type. Through this procedure, interval lengths are defined by integer multiples of cycle time. The performance of the network as well as each type of traffic users are assessed through each interval length.

Bicycles and motor vehicles are two major types of traffic users in this study. The logic of the control strategy is based on comparing the average stop-time delay of bicycles and motor vehicles. However, choosing an optimal coordination interval to get the optimum result of network performance was not clear. In this research, the average stop-time delay of traffic users was chosen as indicator for offset assignment at different coordination intervals. The network performance is measured by average delay and number of stops.

This assessment shows that the average travel time between the first and last intersection in the network, that are parts of the coordination stretches, could play a key role on determining the optimum coordination interval and on improving the network performance. Naturally, we can see the major effects of a coordination in the network when the platoon of motor vehicles or bicycles could pass all signalized intersections without stopping. However, since the network is a mixture of bicycles and motor vehicles, any changes in the coordination of the network could affect positively some traffic users and negatively other ones. Therefore, due to the computational complexity of a delay-based model and its high degree of nonlinearity, this heuristic approach could show a solution to find a fair stop-delay-based coordination between different traffic users. This study implemented in an offline base. If required data are provided online, a live application of this approach is possible.

The extension of this method by considering queue-blocking effects and different volumes of traffic users will be regarded in future studies.

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