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A semi-decentralized control strategy for urban traffic

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Abstract

We present in this article a semi-decentralized approach for urban traffic control, based on the TUC (Traffic responsive Urban Control) strategy. We assume that the control is centralized as in the TUC strategy, but we introduce a contention time window inside the cycle time, where antagonistic stages alternate a priority rule. The priority rule is set by applying green colours for given stages and yellow colours for antagonistic ones, in such a way that the stages with green colour have priority over the ones with yellow colour. The idea of introducing this time window is to reduce the red time inside the cycle, and by that, increase the capacity of the network junctions. In practice, the priority rule could be applied using vehicle-to-vehicle (v2v) or vehicle-to-infrastructure (v2i) communications. The vehicles having the priority pass almost normally through the junction, while the others reduce their speed and yield the way. We propose a model for the dynamics and the control of such a system. The model is still formulated as a linear quadratic problem, for which the feedback control law is calculated off-line, and applied in real time. The model is implemented using the Simulation of Urban MObility (SUMO) tool in a small regular (American-like) network configuration. The results are presented and compared to the classical TUC strategy.

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Keywords: Traffic control, cooperative ITS, traffic modelling.

1. Introduction

Recent advances in information and communication technologies improve vehicular traffic in urban road networks by enabling the development of innovative urban traffic control strategies. While the traffic control in urban road networks is still done by setting traffic lights, intelligent transportation systems (ITS) are being tested in many cities. Various agents in the road network will be able to communicate from vehicle to vehicle (V2V) or from vehicle to infrastructure (V2I) for example. Big data sets, with different levels of information (microscopic, macroscopic) will be processed in real time and adaptive control strategies will be applied. The whole process of urban traffic control needs to be redefined in order to take into account this development.

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We think that several levels of information need to be distinguished in the big amounts of data that will be made available by ITS, and that the whole information cannot be optimally exploited with a unique centralized or distributed traffic control system. In our opinion, a multi-level control system needs to be developed in order to optimally use each level of information for the corresponding control level. Macroscopic information could be transmitted to the centralized controller, while the microscopic one could be used by the local controller, which should operate in a short time horizon, compared to the high-level controller. Multi-level control schemes have been recently proposed; see for example (Ramezani et al., 2015; Varaiya, 2013). In (Ramezani et al., 2015), the control uses macroscopic fundamental diagrams (MFD) (Geroliminis and Daganzo, 2007; Daganzo and Geroliminis, 2008; Farhi et al., 2005, 2007; Farhi, 2008, 2009; Farhi et al., 2011).

Using traffic lights, the main urban traffic parameters are: phase specification, split, cycle time, and offset. Fixed time urban traffic control (UTC) strategies appeared in the 1950s with coordination of signals that optimizes the offsets. These strategies use historic datasets, and therefore, are unable to adjust to changing conditions. The most well-developed and widely used UTC system is TRANSYT (Robertson, 1969). With advances in detection, communication, data processing, and control strategies, traffic responsive UTC systems appeared, where centralized and distributed systems are distinguished. Among the main centralized ones, we cite SCOOT (Hunt et al., 1981; Bretherton et al., 1998), SCATS (Lowrie, 1982), RHODES (Head et al., 1992), MOTION (Busch, 1996), and TUC (Diakaki, 1999). For distributed responsive UTC, we cite UTOPIA (Donati et al., 1984), PRODYN (Farges et al., 1990), OPAC (Gartner, 1991). Other UTC systems define an intermediate level of centralization.

Traffic responsive UTC systems use feedback controls on the state of the traffic and permit by that, to meet traffic demand. Moreover, the control may be set in such a way to be robust, in the sense that it responds rapidly to disruptions. Furthermore, such controls are automatically adaptive to works and operations, and so installation and maintenance costs are reduced.

We propose in this article an extension of the traffic responsive urban control strategy TUC (Traffic Urban Control) (Diakaki, 1999; Diakaki et al., 2002, 2003). Our extension introduces a kind of decentralization in the optimization of the right of way assignment. We introduce a contention time window inside the cycle time, where the traffic light is yellow for antagonistic stages that alternate a priority rule during this time period. A TUC-based centralized control determines the optimal split of green, red and yellow lights at the levels of every junction. A decentralized system manages the traffic of antagonistic stages during the yellow signal, taking into account the characteristics of each junction. By doing this, we aim to reduce the red time inside the cycle, increase the capacity of the network, and reduce users' delays. The traffic management during the yellow times would be realized based on vehicle to vehicle (V2V) and/or vehicle to infrastructure (V2I) communications. We present in this article preliminary results of this semi-decentralization on a small American-like city. The results demonstrate the efficiency of this extension with respect to the classical TUC control. On a selected scenario of traffic demand, we show that the semi-decentralized TUC controls better the traffic, in the sense that it is able to respond efficiently and rapidly to congestion.

2. A short review of TUC

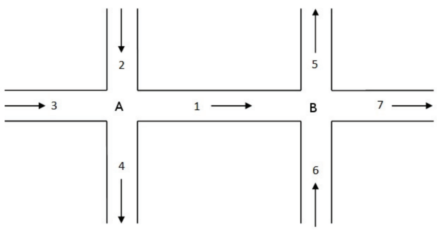

Fig. 1. Academic example explaining the TUC strategy.

TUC (Diakaki, 1999; Diakaki et al., 2002, 2003) is a coordinated control strategy based on a store-and-forward approach. It can be implemented for large-scale networks, in real time, even under saturated traffic conditions. The split control part of TUC varies the green-stage durations of all stages at all the junctions of a urban network around given nominal values, and under a simplified traffic dynamics. The objective is to avoid oversaturations and spillbacks of link queues. In order to briefly explain the approach, let us consider the small network of Figure 1, with the following notations.

c	cycle time duration, in seconds.
k	discrete time index, corresponding to a duration of kc sec.
$x_i(k)$	number of cars on link i at discrete time k.
$\bar{x}_i$	constant nominal number of cars on link i.
$\Delta x_i(k)$	$= x_i(k) - \bar{x}_i$.
s_i	saturation flow on link i.
$g_i(k)$	green time duration for link i during the kth cycle.
$\bar{g}_i$	constant nominal green time duration for stream i.
$\Delta g_i(k)$	$= g_i(k) - \bar{g}_i$.
$u_i(k)$	$= (g_i(k)/c)s_i$ average outflow from link i during the kth cycle.
$d_i(k)$	arrival demand flow to link i at discrete time k.
$\bar{d}_i$	constant nominal arrival demand flow to link i.
$\Delta d_i(k)$	$= d_i(k) - \bar{d}_i$.
α_{ij}	turning movement ratio from link i to link j

The definition of $u_i(k)$ assumes sufficient demand on link i. Note that the oscillations of vehicle queues in the links due to green/red communications, and the effect of offset for consecutive junctions cannot be described by the model.

According to Figure 1, the number of cars on link 1 is updated as follows.

$$x_1(k+1) = x_1(k) + d_1(k) + \alpha_{21}(k)s_2(k)g_2(k) + \alpha_{31}s_3(k)g_3(k) - s_1g_1(k).$$

Then, by introducing the nominal amounts, and by using vectorial notations, we get :

$$\Delta x(k+1) = \Delta x(k) + B\Delta g(k) + D\Delta d(k), \tag{1}$$

Assuming that the variations of the arrival demand flows on every link inside the cycle time sum to zero, we get the following linear system :

$$\Delta x(k+1) = \Delta x(k) + B\Delta g(k), \tag{2}$$

Bounds for minimum green times and maximum storage capacity of links must also be considered.

The criterion is the following, where λ is a discount factor, and where an infinite time horizon is considered.

$$J = \frac{1}{2}\sum_{k=0}^{+\infty} \frac{1}{(1+\lambda)^k}\left(\|\Delta x(k)\|_Q^2 + \|\Delta g(k)\|_R^2\right), \tag{3}$$

where Q and R are non-negative definite, diagonal weighting matrices. The first term on (3) aims to minimize the risk of oversaturation and the spillback of link queues, while the second term is used to influence the magnitude of the control.

The control bounds are treated externally of the LQ problem solving. The solution for such problems consists in solving an algebraic Riccati equation, which then leads to the following optimum feedback control :

$$g(k) = \bar{g} - Lx(k). \tag{4}$$

where L is the gain matrix; see (Diakaki, 1999; Diakaki et al., 2002, 2003) for more details.

3. Semi-decentralization

The model we present here is an extension of the classical model presented above. Instead of considering only green and red time durations in a cycle time (in addition to the lost time, which we consider implicit here and for which we assign the orange colour), we also consider yellow time durations. The objective here is to reduce the red time duration. To do that, we divide this duration into two time periods : red and yellow. By that, when a stage is assigned a red or a yellow time, the antagonistic stage is assigned a green light.

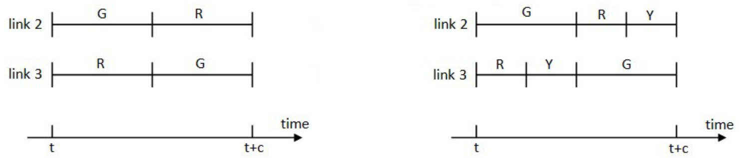

Fig. 2. The cycle time in the classical model, and in the new model. G: green, R: red, Y: yellow.

We notice here that our model is an extension of the classical TUC model, because it is sufficient to set the yellow times to zero to get the classical model.

In order to explain the model, let us consider the left side junction of the example of Figure 1. Only two stages can be considered here, each of them with only one stream. One stage is associated to link 2 and the other to link 3. In this case, and in the classical TUC model, at every cycle k, we only have one independent control variable on that junction, which is the green or red duration of any of the two streams. All the other time durations are dependent variables. We consider $g_2(k)$: the green time duration of link 2 as the independent control variable, then the dependent variables can be easily obtained as follows :

- $r_2(k) = c - g_2(k)$: red duration of link 2
- $g_3(k) = r_2(k)$: green duration of link 3
- $r_3(k) = g_2(k)$: red duration of link 3

By considering yellow time durations, we need to choose three independent control variables, among six variables. For example the following three independent control variables can be considered.

- $g_2(k)$: green time duration for link 2
- $y_2(k)$: yellow time duration for link 2
- $y_3(k)$: yellow time duration for link 3

The other three dependent control variables are given as follows (see figure 2) :

$$r_2(k) = c - g_2(k) - y_2(k), \quad r_3(k) = g_2(k) - y_3(k), \quad g_3(k) = c - g_2(k). \tag{5}$$

3.1. The dynamics

Let us consider the following additional notations.

- s_i : saturation flow on link i.
- $q_J^{\max}$: capacity (maximum flow) of junction J.
- $Q_{ij}(k)$: total flow going from link i to link j at time k.
- Q_i^{out} : total flow exiting from link i, at time k.
- γ_J : friction coefficient on junction J.

Let us write the traffic dynamics on link 1 of Figure 1 with the new control model.

$$x_1(k+1) = x_1(k) + d_1(k) + Q_{21}(k) + Q_{31}(k) - Q_1^{out}(k),$$

$$Q_{21}(k) = \alpha_{21}s_2(g_2(k) - y_3(k)) + \gamma_A\alpha_{21}s_2y_3(k) + \gamma_A(q_A^{\max}y_2(k) - s_3y_2(k)). \quad (6)$$

$$Q_{31}(k) = \alpha_{31}s_3(c - g_2(k) - y_2(k)) + \gamma_A^{\max}\alpha_{31}s_3y_2(k) + \gamma_A(q_A^{\max}y_3(k) - s_2y_3(k)). \quad (7)$$

$$Q_1^{out}(k) = s_1(g_1(k) - y_6(k)) + \gamma_B s_1 y_6(k) + \gamma_B(q_B^{\max}y_1(k) - s_6y_1(k)). \quad (8)$$

In (6)-(8), we introduce a new parameter γ_J (for junction J) which we call here a friction coefficient, and which expresses the bother between vehicles entering into the junction from antagonistic stages during the contention time window. For example, in (6), during the contention time window of length $y_3(k)$ (see Figure 2) the amount of vehicles passing from link 2 to link 1 through junction A (see Figure 1) is $\alpha_{21}s_2y_3(k)$ multiplied by γ_A, $(0 \leq \gamma_A \leq 1)$ in order to decrease this amount due to the friction of those vehicles with the ones entering from link 3.

The dynamics (6)-(8) are still linear on the variables x_i, g_i and y_i. We notice here that the dynamics is written with only independent controls. As it has already been explained above, on junction A, for example, the independent controls are g_2, y_2 and y_3. As in the classical TUC model, we consider nominal demands $\bar{d}_i$, nominal numbers of cars $\bar{x}_i$ and nominal independent controls $\bar{g}_i$ and $\bar{y}_i$. The choices of $\bar{x}$ and $\bar{g}$ can be done by the same way as in the classical TUC model. One way to choose $\bar{y}$ is to take $\bar{y}_i = c - \bar{g}_i$. This is equivalent to say that the nominal red time is zero. This choice can also be dependent on the junction design. Then it is very easy to derive a linear dynamics similar to (2). For the criterion we take exactly the one of (3), written with the new (independent) control variables Δg_i. Again, a linear quadratic problem is obtained, and the optimal control is derived by solving a Riccati equation as in the classical TUC model.

4. Numerical example

In this section, we apply the control model presented above, on a small regular (American-like) network of four horizontal and four vertical roads, with alternated directions, as shown in Figure 3.

For the saturation flow values, we take the recommended ones in urban networks ($s_i = 1800 veh./h, \forall i$, as shown in Table 2), without corrective factors; see for example (Cohen, 1993). To compute the optimal cycle, we consider here a fixed cycle time that we approximate to 60 seconds, using the Webster Method (Webster, 1958): $c = (1.5T + 5)/(1 - Y)$, where T is the total lost time per cycle, Y is the junction load. The cycle time is then projected onto the interval $[40s, 90s]$.

4.1. Model implementation and Simulation Tools

We used SUMO, see for example (Behrisch et al., 2011), and its interface TRACI (Wegener et al., 2008) to simulate and implement the model. The source code has been written in Python. The main tasks were :

- build the network topology and the demand using SUMO tools and original configuration files.
- design an algorithm and the source code architecture that enable the construction of the B matrix in equation (2).
- implement the contention time window and the associated priority rule.
- solve Riccati equation, and at every cycle, measure the state, and apply the control on the traffic light signals.
- analyze the simulation data outputs, including state and control vectors, by rendering graphical results.

The time contention window is implemented as follows. On a given junction, and inside such contention time window, we consider first vehicles in incoming edges. We compute the distances from those vehicles to the junction. In order to avoid conflicts, at a given time in the time window, if the distance of the first vehicle on the link with yellow stage, to the junction, is less than m, and if the distance of the first vehicle on a link with green antagonistic stage, to the junction, is less than M, we slow down the first vehicle on the link with yellow stage.

In general, the vehicles moving on an approach with a green stage (priority approach) pass through the junctions without checking for the antagonistic approaches. However, the vehicles moving on the approaches with yellow stages slow down at $m = 15$ meters before the junction to check if there is any vehicle coming from an antagonistic approach with green stage.

In our case, we chose $m = 15$ meters and $M = 50$ meters. Our choice takes into account the reaction time of the drivers in SUMO, and also the simulation step length.

We plan to implement this conflict management using a communication simulator, for example the Network Simulator (McCanne et al., 1997).

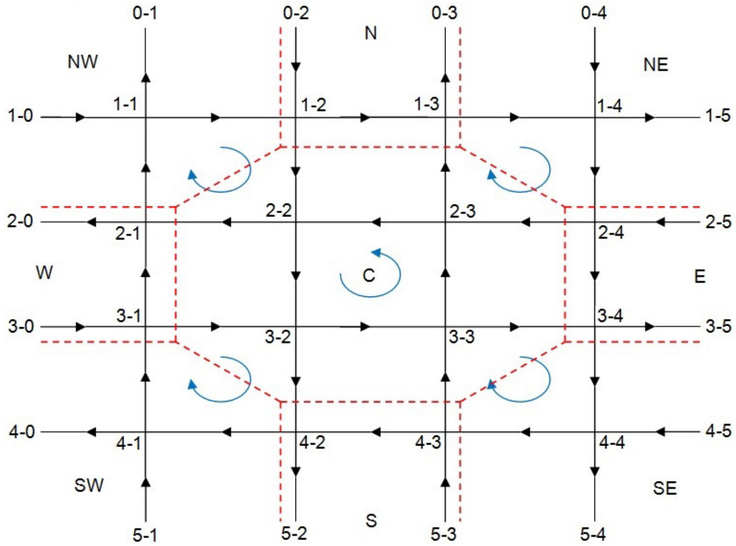

Fig. 3. Regular network example.

4.2. Network configuration

We discuss here, the configuration of the network of Figure 3. In this network, circuits are formed. We distinguish two types of circuits. The central circuit in which vehicles turn in the anticlockwise direction, and the other four circuits in which vehicles move in the clockwise direction. As already shown in (Farhi, 2008; Farhi et al., 2011), the car-densities on the circuits of links are determinant in the stage transition of a vehicular network. Indeed, if a circuit is full of vehicles, then a deadlock occurs and spreads on the network.

In the network we consider here, the central circuit (which we call here the main circuit) is critical compared to the other four circuits, (which we call here the secondary circuits). Indeed, the secondary circuits have exits that are not constrained by any output supply, and they are closer to the borders.

In case of congestion, we need to clear out vehicles from the main circuit in order to improve the traffic, so that the number of vehicles we take out is bigger than the one we take into the circuit. Hence, for that circuit, the controller needs to favour the vehicles coming from the left side at the level of the four junctions around the main circuit. For example, if we take symmetric turn ratios, half of vehicles leaving the approaches are likely to leave the circuits, while the other half of vehicles are likely to remain in the circuit. However, when the way is given to the vehicles coming from right, half of those vehicles are likely to enter the circuit, while the other half is likely to not enter the circuit. For the secondary circuits, in case of congestion, the control shall favour vehicles coming from the right side links at the level of the junctions associated to those circuits, in order to clear them out.

The four junctions of the main circuit are shared with other secondary circuits. We think that the control needs to foster the evacuation of the main circuit with respect to the secondary circuits. Therefore, the control should favour the vehicles coming from the left side approaches to the main circuit.

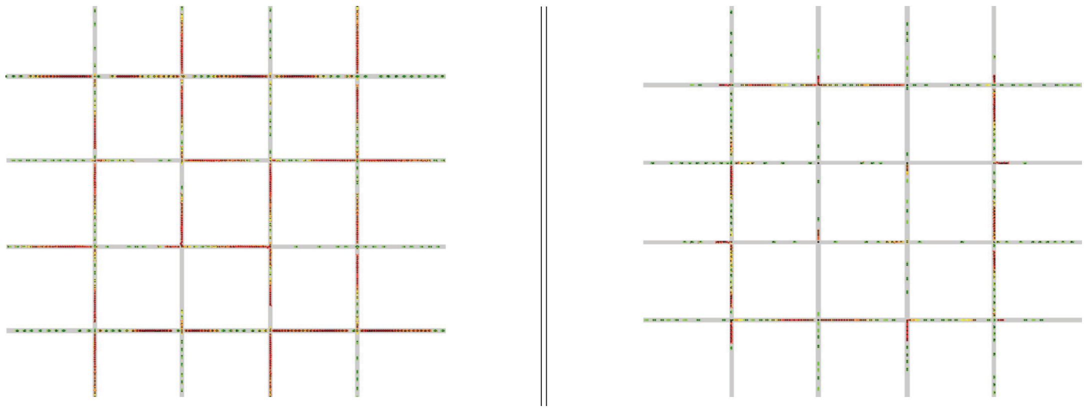

Fig. 4. The state of the traffic at the end of simulation. The vehicles' colours correspond to their speed. On the left side: Centralized TUC. On the right side: semi-centralized TUC.

4.3. Preliminary results

We present in this section the preliminary results we obtained. For the traffic demand, we took the scenario of Table 1. In this scenario, we have some traffic demand inside the network. This permits us to attain saturated and congested stages. In the other side, the traffic demand from and towards the center zone is low comparing to that from and towards the boundary zones. This choice makes the states of the traffic controllable in the central zone of the network.

Table 1. The traffic demand.

	Center zone	Other zones
Center zone	0	40 (veh/h)
Other zones	40 (veh/h)	250 (veh/h)

The other parameters are given in Table 2, where

- r is a positive scalar such that $Q = I$ and $R = rI$, with I the identity matrix,
- g_{i-min} is the minimal green time duration on link i,
- l_i is the length of link i.

Table 2. The values of other parameters.

r	λ	$\bar{x}_i$	s_i	$\bar{g}_i$	g_{i-min}	c	l_i	α_{ij}
0.5	0.1	10.5 veh/m	1800 veh/h	30 s	4 s	60 s	300 m	0.5

In Figure 4, we give the state of the traffic at the final time of simulation. The evolution over time of the running vehicles in the network is given on Figure 5, where we compare the classical TUC control with our semi-decentralized control by varying the value of the friction parameter γ in $\{0.3, 0.5, 0.7\}$. We see that with our semi-decentralized control, the car-density is limited in order to optimize the capacity of the network. The best result is obtained with $\gamma = 0.3$.

In Figure 5, we also compare the two controls in term of the cumulated ended (served) cars through the time, and in term of the average travel time of cars in the network. We see clearly that our control improves the whole capacity of the network. Indeed a congestion appeared at a time around 1000 seconds. We observe that as long as the simulation runs, the two controls clear the congestion, but the semi-decentralized control do it very rapidly compared to the centralized one. We see clearly that the difference between the number of running vehicles decreases over time, but, even at the final time of simulation (which is 6 hours here), this difference is still important. Figure 4 tells clearly that the state of the traffic with the two controls is different (fluid with the decentralized control, and saturated with the centralized one). Figure 5, where we compare the cumulated ended vehicles as well as the average travel time of the cars through the network, confirms these results.

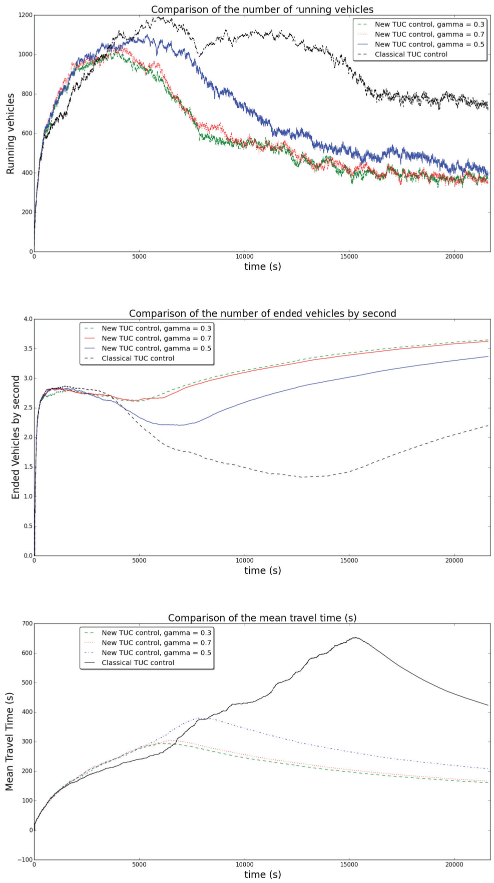

Fig. 5. Comparison of the new TUC strategy presented in this article with the classical one, in terms of the running vehicles on the network, by time unit.

In Figure 6, we give the results of simulation for the semi-decentralized control. We show on the first row the time-average number of vehicles in the circuits of the network. On the second (resp. third) row of that figure, we show the control (in term of durations of the green, the yellow and the red times) for the approaches coming from the left side (resp. right side) of the circuit junctions. The left side column of the figure corresponds to the main circuit (the circuit of the central zone), while the right side column corresponds to the secondary circuits (the circuits on the boundary of the network).

We observe on the first row of Figure 6 that the main circuit is more cleared out than the secondary circuits. This observation confirms our intuition given above. We see in the second and third rows of Figure 6 that the control frees the approaches coming from the left side of the junctions' main circuit and limits the flow on the antagonistic approaches of the same circuit, while it does the opposite for the secondary circuits.

Figure 6 shows another important result, which is that the yellow time is almost fully used (i.e. the red time is almost zero) in the case of free traffic flow, while the red time appears with important values in case of congestion. This result is very important because it confirms the importance that the activation as well as the duration of the local control (the contention time window with yellow times) are both controlled by the centralized control, which optimizes them in function of the state of the traffic in the network.

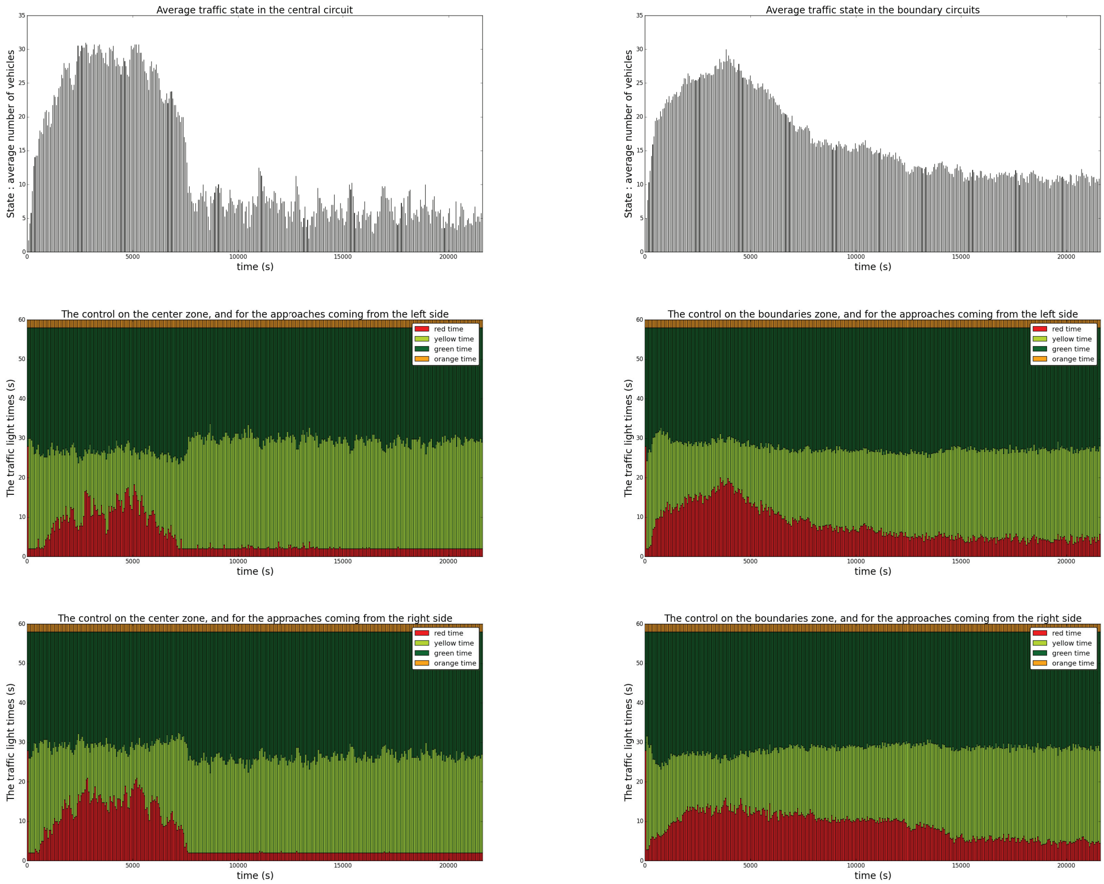

Fig. 6. The control in terms of the traffic light times into the cycle time, through the simulation time, on different zones (center and boundaries), and for approaches coming from left or right sides.

5. Preliminary conclusions

We presented in this article a TUC-based approach for the control of urban traffic. By defining a time contention window inside the time cycle, we introduced a little of decentralization of the control. We have implemented and simulated the new control on a small American-like network. The traffic has been simulated using the Simulation of Urban MObility tool while the control has been implemented with Python. We are aware that we need more investigations in order to validate our assertions. For that we will improve the implementation of our control by better managing the contention time window, in particular using communication network simulators. On this small network, we showed that our approach is effective in terms of many parameters including the total network capacity as well as the average travel time. Another important result we obtained is the confirmation that the centralized control optimizes the activation as well as the duration of the decentralized control (the contention time window) in function of the state of the traffic in the network.

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