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ART-UTC: An Adaptive Real-Time Urban Traffic Control Strategy

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***Abstract*—A novel signal control strategy for urban traffic networks, called ART-UTC (the abbreviated form of "Adaptive Real-Time Urban Traffic Control") is introduced. We propose an efficient algorithm for ART-UTC to determine the green priority of different rights-of-way at each intersection. The proposed algorithm takes into account the queue length on each link, the waiting time of the first vehicle in the queue, and the incoming traffic flow to the link. We also propose a law to determine the green times of each traffic light based on the queue length on the link that is controlled by that traffic light. An advantage of ART-UTC is that due to the simple computations involved, it can be used for real-time urban traffic control. To evaluate ART-UTC, two different urban traffic networks are simulated within the urban traffic simulator SUMO. The performance of ART-UTC is compared to the performance of a fixed-time traffic controller based on Webster's formulas and a vehicle-actuated traffic controller. The results show that by using ART-UTC, the total travel time of the vehicles, the average queue length on the links in urban traffic networks, and the average waiting time of the first vehicles in the queues on the links of the traffic networks are reduced significantly in the majority of the cases compared with the fixed-time and the vehicle-actuated controllers.**

I. Introduction

Populated cities suffer from growing difficulties due to the large number of vehicles and the resulting dense traffic on urban roads. Congested traffic causes waste of time and energy, pollutants in the air, and larger travel times, all of which have various physical and psychological consequences for urban populations.

Due to the high costs of expanding roads and traffic infrastructure, development of efficient control methods for traffic is considered as an alternative solution. A common way of urban traffic control is to use traffic signals. In particular, traffic-responsive control methods, which decide about the control policy online based on the current states of the intersections, have gained a lot of attention (see [1], [2], [3]). One important aspect of a traffic-responsive control approach is its computation speed. If computations take long, the produced control signal may not suit the current traffic situation anymore. Examples of traffic-responsive controllers include model-based and predictive optimization-based controllers, which minimize a performance criterion within a time window starting at the current control time step and spanning several control time steps in the future. The main issue with these controllers is their huge computation time.

In general, three classes of urban traffic controllers can be distinguished: fixed-time, vehicle-actuated, and adaptive controllers [4], where the second and the third class involve traffic-responsive approaches. A fixed-time traffic signal setting follows a fixed sequence of values that has been predetermined offline for different possible classes of traffic demands. A vehicle-actuated traffic controller adapts the traffic signal settings to the demand fluctuations, where traffic detectors are used to report the presence of a vehicle on the road. To decide whether a green phase should be terminated, the controller checks the time distance between consecutive vehicles. If the time distance is larger than a threshold, the green phase is terminated. Finally, an adaptive traffic controller optimizes the traffic signal settings at predefined or triggered control time steps.

Among these three classes, in practice, the fixed-time and the vehicle-actuated controllers are mainly used because of their lower computation time (see [5], [6], [7]). A main problem with these controllers, however, is that they are not optimized and do not provide the best possible performance for the traffic network. In this paper, we will develop an adaptive urban traffic controller that suits real-time applications. The rest of the paper is organized as follows: Section II discusses the state-of-the-art of different traffic signal control approaches. In Section III, we explain our proposed control strategy, ART-UTC. The proposed control strategy is evaluated compared with a fixed-time controller based on Webster's formulas and a vehicle-actuated controller, where the simulation results are given in Section IV. Finally, Section V concludes the paper and gives some suggestions for future work.

II. Traffic Signal Control: State-of-the-Art

TRANSYT (TRAffic Network StudY Tool) [8] developed at the Transport Research Laboratory in England, is a traffic simulation and optimization program for traffic signal settings. A recent version of TRANSYT is TRANSYT-7f [9], which was developed by the MCTrans Center of the University of Florida for the US Federal Highway Administration (FHWA). TRANSYT-7F can integrate the genetic algorithm and CORSIM (a microscopic traffic model) to provide a microscopic optimization procedure. TRANSYT-7F uses the genetic algorithm to generate a number of candidate traffic signal settings corresponding to the expected demand profiles, which are then evaluated using CORSIM and the setting that minimizes a predefined objective function is selected. The main issue with this approach is that the demand and traffic states are rarely exactly as expected, and a fixed-time controller does not adapt to unpredicted traffic situations.

SCOOT (Split Cycle and Offset Optimization Technique) [10] is a traffic-responsive control approach that optimizes the split, the offset, and the cycle time of traffic signals based on the last measured traffic states. SCOOT considers small increments for sets of preset traffic signal settings, such that the resulting control strategy suits the current average traffic state. Therefore, SCOOT shows its best performance when there are small variations in the traffic flow, while for large variations in the traffic flow SCOOT may not be very efficient.

An adaptive optimization-based control approach that can be used for urban traffic control is Model Predictive Control (MPC) [11]. At each control time step, MPC minimizes a predefined objective function within a prediction window spanning several time steps in the future. A model of the traffic network is used by MPC to estimate the future state of the traffic network, based on the measured current state. MPC can handle both state and input constraints (e.g., a maximum number of vehicles per lane, a maximum waiting time per vehicle, etc.). The main challenge of MPC is the huge computation time required for solving the optimization problem at every control time step. For application of MPC in urban and freeway traffic networks (see [2], [12], [13]).

III. Adaptive Real-Time Urban Traffic Control (ART-UTC)

In this section, we introduce the proposed urban traffic control algorithm, ART-UTC. All the optimization procedures are offline. Hence, the proposed algorithm has a very low computation time, which makes it suitable for real-time control applications. Next, we present the assumptions and preliminary information that will be used later.

A. Preliminaries and Assumptions

- We consider a separate traffic signal for each right-of-way at an intersection. Hence, since a specific link can embed multiple rights-of-way in an intersection, it may be controlled via multiple traffic signals.
- All traffic signals that are activated and deactivated at the same time are kept in a set B_i, which we call a *block*. Therefore, $B_{i,j} = \{s_{1,i,j}, s_{2,i,j}, \ldots, s_{n_{\mathrm{B},j},i,j}\}$ indicates that the activation periods of all traffic signals $s_{\ell,i,j}$, for $\ell = \{1, 2, \ldots, n_i\}$ coincide. Note that $j \in \{1, \ldots, n_j\}$ is the intersection index (with n_j the total number of intersections in the urban traffic network), $i \in \{1, 2, \ldots, n_{\mathrm{B},j}\}$ denotes the block number at the j^{th} intersection, $n_{\mathrm{B},j}$ is the total number of blocks at the j^{th} intersection, and $s_{\ell,i,j}$ is the ℓ^{th} traffic signal in the i^{th} block of the j^{th} intersection. Note it this is the task of a traffic engineer to decide about the structure of these blocks. In this paper, we will consider a structure that corresponds to the typical traffic regulations in The Netherlands (see Figure 1).
- Each traffic signal is assigned to a block (even a single entry block if needed).
- A traffic signal cannot belong to two different blocks at the same time. In a general case, we may consider time-varying blocks. However, in this paper we assume that the blocks are fixed during the entire control procedure.
- The proposed control scheme follows a decentralized architecture (no interactions among different intersections).

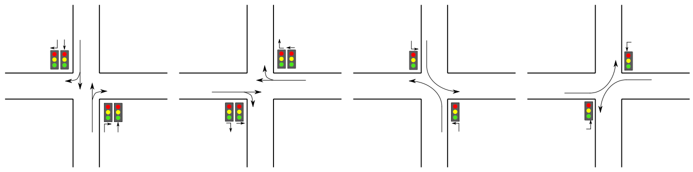

Fig. 1: Different rights-of-way based on the standard traffic regulations in The Netherlands: a traffic signal is assigned to each right-of-way. Traffic signals in each plot will be activated simultaneously and represent one block.

- Average queue length on the links, average waiting time of the first vehicle in the queues, total emissions ($\mathrm{TE}_{\mathrm{CO}_2}$) of CO_2 in [kg], and total travel time (TTT) of the vehicles in [h] are considered as control objectives.

B. ART-UTC Algorithm

The proposed algorithm determines the green priority for different rights-of-way in an urban intersection. Later we propose a formula for determining the green times.

The following parameters should initially be provided:

- The threshold $\tau_{\ell,i,j,}$ for the waiting time of the first driver in the queue on a link that is controlled by the traffic signal $s_{\ell,i,j}$.
- The threshold $\xi_{\ell,i,j}$ for the queue length on a link that is controlled by the traffic signal $s_{\ell,i,j}$.
- The queue weighting factor, $w_{\mathrm{q},j}$, for the j^{th} intersection.
- The link occupancy weighting factor, $w_{\mathrm{n},j}$, for the j^{th} intersection.
- The maximum green time $g^{\max}_{\ell,i,j}$ corresponding to the traffic signal $s_{\ell,i,j}$.
- The minimum green time $g^{\min}_{\ell,i,j}$ corresponding to the traffic signal $s_{\ell,i,j}$.
- The green time extension g^{ext}_j for all traffic signals corresponding to the j^{th} intersection.

The threshold for the waiting time, $\tau_{\ell,i,j,}$, can be initially determined by considering this parameter, together with $\xi_{\ell,i,j,}$, g^{ext}_j, and the other predefined parameters as the optimization variables of a minimization problem that considers a typical fixed-time control strategy and the different objectives of ART-UTC (e.g., $\mathrm{TE}_{\mathrm{CO}_2}$ and TTT). The threshold $\xi_{\ell,i,j,}$ for the queue length on a link can also be computed similarly via an offline optimization procedure, taking into account that the optimization variable should be constrained not to exceed an upper bound which is a percentage of the capacity of the link. The minimum green time can be determined considering the minimum time needed for a vehicle in front of a queue to cross the intersection, and the maximum green time can be obtained via the statistical data of an intersection, and taking into account the safety and comfort considerations for different rights-of-way in an intersection.

For the sake of simplicity, we have considered fixed queue and occupancy weighting factors for all the right-of-ways and for the green time extensions in a specific intersection. Extension to a general case, where each right-of-way has a separate queue and occupancy weighting factor, and each block has a green time extension can simply be done easily. At control time step k the following inputs are needed:

- The queue length $q_{\ell,i,j}$ on the link that is controlled by the traffic signal $s_{\ell,i,j}$.
- The waiting time $t^{\text{wait}}_{\ell,i,j}$ of the first vehicle in the queue on the link that is controlled the traffic signal $s_{\ell,i,j}$.
- The total number of vehicles $n_{\ell,i,j}$ on the link that is controlled by the traffic signal $s_{\ell,i,j}$.

The steps of the proposed algorithm at control time step k are:

Step 0. For each block, the algorithm computes the average value of the total number of vehicles on all links that are controlled by the traffic signals in the block. If this average is the largest for that block that currently has a green phase, the green time for the block is extended for g^{ext}_j time units. Otherwise, the algorithm goes to Step 1.

Step 1. To evaluate the traffic state of different blocks, the algorithm gives the first priority to the normalized queue length, $q_{\ell,i,j}(k)/\xi_{\ell,i,j}$, as follows: if one and only one block in the j^{th} intersection includes traffic signals that correspond to a normalized queue length that is equal to or larger than 1, then the green phase for that block is activated. Otherwise, if none of the blocks includes traffic signals corresponding to a normalized queue length larger than or equal to one, or if more than one block satisfies this condition, then the algorithm goes to Step 2. Note that if the block that currently has a green phase is selected by the algorithm in Step 1, the green time of the block will be extended for g^{ext}_j time units.

Step 2. The second priority is given to the normalized waiting time, $t^{\text{wait}}_{\ell,i,j}(k)/\tau_{\ell,i,j}$. In case one and only one block with a normalized waiting time of 1 or larger exists, then the green priority is given to that block. Otherwise, if no or more than one block exists that satisfies this condition, then the algorithm goes to Step 3. In case the block that currently has a green phase is selected by the algorithm in Step 2, the green time of the block will be extended for g^{ext}_j time units.

Step 3. For each traffic signal $s_{\ell,i,j}$, an evaluation function $\epsilon_{\ell,i,j}(k)$ is defined as follows:

$$\epsilon_{\ell,i,j} = w_{\text{q},j}\frac{q_{\ell,i,j}(k)}{\xi_{\ell,i,j}} + w_{\text{n},j}\frac{n_{\ell,i,j}(k)}{C_{\ell,i,j}} + \frac{t^{\text{wait}}_{\ell,i,j}(k)}{\tau_{\ell,i,j}}, \tag{1}$$

where $C_{\ell,i,j}$ is the capacity of the link that is controlled by the traffic signal $s_{\ell,i,j}$, and $w_{\text{q},j}$ and $w_{\text{n},j}$ are called the queue and the occupancy factors. The average evaluation function for each block is

$$\bar{\epsilon}_{B_{i,j}} = \text{mean}\left\{\epsilon_{\ell,i,j}\right\}, \qquad \forall\ s_{\ell,i,j} \in B_{i,j}. \tag{2}$$

Then the green priority is given to the block with the largest value of $\bar{\epsilon}_{B_{i,j}}$.

C. ART-UTC Green Time Calculation

At every control time step k, ART-UTC computes the green time $g_{B_{i,j}}$ of the block $B_{i,j}$ that has received the green priority, taking into account the queue lengths on all links that are controlled by the traffic signals in the block. First, a green time is computed for each traffic signal $s_{\ell,i,j}$ in the block $B_{i,j}$ separately, i.e., for each ℓ such that $s_{\ell,i,j} \in B_{i,j}$ we have

$$g_{\ell,i,j}(k) = \max\left\{g^{\min}_{\ell,i,j}, \min\left\{g^{\max}_{\ell,i,j}, \gamma_1\left(q_{\ell,i,j}\right)^{\gamma_2}\right\}\right\}, \tag{3}$$

with $\gamma_1 > 0$ and $0 < \gamma_2 < 1$ control parameters that can be tuned adaptively during the control procedure. Moreover, this green time increases by the queue length; however, this increase does not follow a linear trend, i.e., if the queue length increases, the average green time that is allocated to each vehicle in the queue decreases (since $\gamma_2 < 1$). The main reason for this choice is as follows: suppose that the average distance between the entrance and exit of the intersection is almost the same for all the vehicles in the queue. When the traffic signal turns green, the first vehicle in the queue starts from a zero speed at the entrance of the intersection and accelerates to reach the exit of the intersection. A vehicle that is somewhere in the middle of the queue will have a higher speed than the first vehicle when reaches the entrance of the intersection. Therefore, the time that is needed for this vehicle to exit the intersection is less than the time needed for the first vehicle in the queue. The green time for block $B_{i,j}$ is

$$g_{B_{i,j}}(k) = \max_{\{\ell | s_{\ell,i,j} \in B_{i,j}\}}\left\{g_{\ell,i,j}(k)\right\}. \tag{4}$$

IV. Simulation and Results

A. Urban Traffic Networks for the Test Example

We consider two different urban traffic networks to implement and compare the proposed control strategy, ART-UTC, with a fixed-time controller based on Webster's formulas, and a vehicle-actuated controller. The first one called 'traffic network 1' is represented in Figure 2, and consists of 14 single-lane links, 4 controlled intersections (each having two different rights-of-way), and correspondingly 8 traffic signals. Two blocks are considered per controlled intersection. Traffic network 1 has 4 entrances and 3 exits, and the entering flows via the 4 entrances are indicated by $\alpha^{\text{enter}}_1, \ldots, \alpha^{\text{enter}}_4$. All links have an equal length of 500 m.

The second urban traffic network, called 'traffic network 2', (see Figure 3) in total has 13 double-lane links, with 5 controlled intersections, 3 of which have 12 rights-of-way (regular crossroads) and the other two (T-junctions) have 6 rights-of-way. Therefore, there are 48 traffic signals that should be controlled in total. Considering the standard regulations of The Netherlands (see Figure 1), for each intersection four blocks can be considered. The network has 6 entrances and 6 exits, where the entering flow are indicated by $\alpha^{\text{enter}}_1, \ldots, \alpha^{\text{enter}}_6$. The Eastern and Western links (illustrated by horizontal lines in Figure 3) have a length of 300 m and the Northern and Southern links (illustrated by the vertical lines in Figure 3) have a length of 200 m.

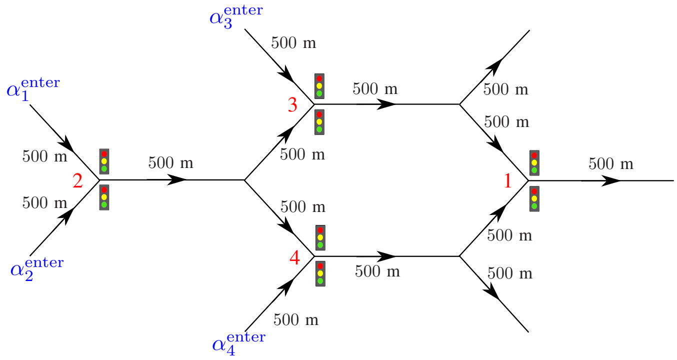

Fig. 2: Traffic network 1: 4 entrances, 14 single-lane links, 3 exits, 4 controlled intersections, 8 traffic signals.

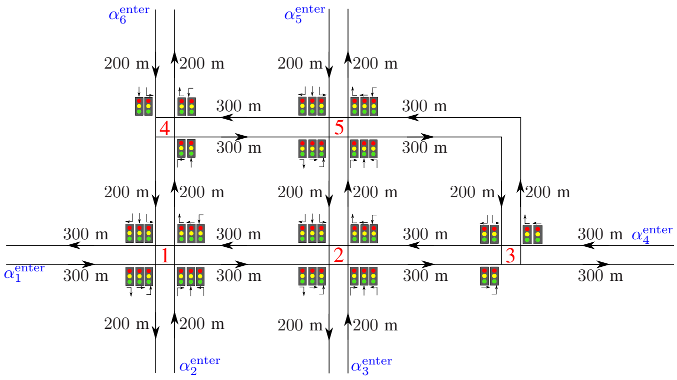

Fig. 3: Traffic network 2: 6 entrances, 13 double-lane links, 6 exits, 5 controlled intersections, 48 traffic signals.

Both networks have been implemented in the traffic simulation software SUMO (Simulation of Urban MObility) [14].

B. Controllers for Comparison with ART-UTC

Fixed-time Controller: We consider a fixed-time controller based on Webster's formulas [15] for the cycle times and green times. Webster [15] proposes a formula for the optimal traffic cycle time that minimizes the overall delay of the vehicles at the intersection, and explains how to distribute this cycle time among different green phases. The proposed formula for estimation of the optimal cycle time c_j^{web} at the j^{th} intersection is $c_j^{\text{web}} = \dfrac{1.5\theta_j + 5}{1 - \rho_j}$, where θ_j is the total lost time (sum of the inter-green periods) per cycle for the j^{th} intersection, and $\rho_j = \sum_{p=1}^{n_{\text{p},j}} \max\limits_{l \in \mathbb{L}_{j,p}} \left\{ \frac{\alpha_{l,j}}{\alpha_{l,j}^{\text{sat}}} \right\}$, where $n_{\text{p},j}$ is the total number of phases at the j^{th} intersection, $\mathbb{L}_{j,p}$ is the set of all lanes of the intersection for which phase p is a green phase, $\alpha_{l,j}$ is the volume on link l of the intersection, and $\alpha_{l,j}^{\text{sat}}$ is the saturation flow rate of lane l. Finally, the total green time $c_j^{\text{web}} - \theta_j$ is divided among all the phases p, $p \in \{1, \dots, n_{\text{p},j}\}$ of the j^{th} intersection using $g_{p,j}^{\text{web}} = \max\limits_{l \in \mathbb{L}_{j,p}} \left\{ \dfrac{\alpha_{l,j}}{\alpha_{l,j}^{\text{sat}}} \right\} (c_j^{\text{web}} - \theta_j)$.

Vehicle-Actuated Controller: A vehicle-actuated controller uses information about the current demand on a link from detectors, and alters the cycle time and/or green time of the corresponding traffic signals based on a predefined control logic. The vehicle-actuated controller used in this paper uses the control system designed with the software package RWS-C regelaar, developed by Rijkswaterstaat (the Department of Infrastructure and Environment in the Netherlands), which is extensively used for urban traffic control in The Netherlands. There is a set of control parameters that should be tuned before the controller can be used for a traffic network.

C. Test Conditions

To assess the performance of ART-UTC in comparison with the other two controllers, we consider similar traffic flows and initial traffic states for all simulations (which are repeated three times for each traffic network: with ART-UTC with the fixed-time controller based on Webster's formulas, and with the vehicle-actuated controller as the controllers). Each simulation starts from an empty network. Then some vehicles enter and travel in the networks under identical situations (including input flows, turning rates, speeds, and other factors that may affect the traffic state) for 500 [s]. During the first 500 [s] the traffic moves freely with no control. Next, the simulations are run for 2000 [s] for each of the three controllers. To simulate various traffic scenarios (under-saturated, saturated, and over-saturated), at every 500 [s] we have considered variations in the input flow (an input flow that results in an over-saturated traffic scenario first, and then decreases for a while, and again increases moderately, and finally drops to a very small input flow). We repeat all the simulations for input flows that are 90% of the first input flows.

D. Parameter Tuning for ART-UTC

For computation of the green times, ART-UTC needs to know γ_1 and γ_2 (see (3)). We have used a grid search to find an optimal value for these parameters minimizing the TTT of the vehicles. The range of the grid for γ_2 was considered [0.1,1] with a step size of 0.1, and for γ_1 it was [1,10] with a step size of 1. The parameters γ_1 and γ_2 are mostly affected by the time each vehicle in the queue needs to pass the green signal (and hence the total number of vehicles that pass a green signal in one cycle). We assume this number is independent of the intersection geometry and the level of traffic saturation, and use the same values for γ_1 and γ_2 for both traffic networks 1 and 2.

To find optimal values for $w_{\text{n},j}$ and $w_{\text{q},j}$ (see (1)), due to the large number of optimization variables (two variables per intersection) and the complex nature of the optimization problem with a large expected number of local minima, the genetic algorithm (in the Global Optimization Toolbox 7.5, MATLAB) was used. The population size and the generation number were 200 and 10, and the TTT of the vehicles was the optimization cost function. The values used for different parameters of the ART-UTC algorithm for the case study are $g^{\text{ext}} = 15$ [s], $g^{\max} = 50$ [s], $g^{\min} = 10$ [s], yellow time = 4 [s], queue threshold on a link = 60% of the link's capacity [veh], waiting time threshold = 60 [s], $c_1 = 4$, and $c_2 = 0.7$. Also w_{q} and w_{n}, for traffic network 1, intersections 1, 2, 3, and 4, are 177, 123, 182, 14, and $9.2 \cdot 10^3$, $17.7 \cdot 10^3$, $9.7 \cdot 10^3$, $4.4 \cdot 10^3$. These parameters for traffic network 2, intersections 1, 2, 3, 4, and 5 are 74, 34, 26, 96, 89, and $4.4 \cdot 10^3$, $3.45 \cdot 10^3$, $2.8 \cdot 10^3$, $4.6 \cdot 10^3$, $4.3 \cdot 10^3$.

E. Results and Discussions

To compare the performance of different controllers, the TTT of the vehicles in the traffic networks, the average queue lengths on the links, the average of the waiting times of the first vehicles in the queues on different links of the traffic networks, and $\mathrm{TE}_{\mathrm{CO}_2}$ have been considered.

The results of the 6 simulations are illustrated in Figure 4: for the regular demand profiles, ART-UTC always outperforms the fixed-time and the vehicle-actuated controllers for both traffic networks 1 and 2. In particular, ART-UTC reduces the average queue length and the average waiting time of the first vehicles in the queues significantly w.r.t. the other controllers. Considering the average queue length, the improvement made by ART-UTC for traffic network 1 is 67% w.r.t. the vehicle-actuated controller and 29% w.r.t. the fixed-time controller. For traffic network 2, the improvement is almost 61% w.r.t. both the vehicle-actuated and the fixed-time controllers. From the results for traffic network 1, the fixed-time controller outperforms the vehicle-actuated controller, except for $\mathrm{TE}_{\mathrm{CO}_2}$. For traffic network 2, the vehicle-actuated controller usually has a better performance than the fixed-time controller, except for the average waiting time of the first vehicles in the queues, where the fixed-time controller shows 37% of improvement w.r.t. the vehicle-actuated controller.

For 90% of the regular demands, for traffic network 1, the fixed-time controller always shows the best performance. ART-UTC outperforms the vehicle-actuated controller considering the average queue length and the average waiting times of the first vehicles in the queues, but for TTT of the vehicle and $\mathrm{TE}_{\mathrm{CO}_2}$, ART-UTC has the worst performance. This can be explained by the way ART-UTC distributes the green time among different traffic signals (see (3) and (4)). In these formulas, the focus is on the number of vehicles in the queues. For traffic network 2, for 90% demand profile, ART-UTC outperforms the other controllers considering the TTT of the vehicles and the average queue length.

In general, considering the measured values of $\mathrm{TE}_{\mathrm{CO}_2}$, none of the controllers affects these emissions satisfactorily. Comparing the two traffic networks 1 and 2, ART-UTC has the maximum effect on reduction of the TTT, the average queue length of the vehicles, and $\mathrm{TE}_{\mathrm{CO}_2}$ for traffic network 2. This might be because each intersection has two blocks only, while the number of blocks in traffic network 2 are 4. Hence, for traffic network 1, ART-UTC cannot significantly take advantage of its main characteristic, i.e., changing the block phases, for performance improvement.

V. Conclusions and Future Work

We have proposed an adaptive real-time urban traffic control algorithm called ART-UTC for urban traffic signal control. The performance of the developed control strategy has been compared with those of a fixed-time controller based on Webster's formulas and a vehicle-actuated controller inspired by the urban traffic control system in The Netherlands. Two different traffic networks have been used for the case study. The simulation results illustrate the efficiency of the proposed control strategy w.r.t. the other two controllers in reducing the TTT of the vehicles, the average queue lengths on the links, and the average waiting time for the first vehicle in the queues. The computation time for 2500 [s] in SUMO was about 14 [s] for the first urban traffic network, and 26 [s] for the second one. This shows the proposed approach is fast enough for real-time applications in practice.

For future work, one can consider ART-UTC in a distributed control architecture (including interactions among controllers), an extension of the formulas for green time computation considering more effective factors, and more extensive simulations on larger traffic networks.

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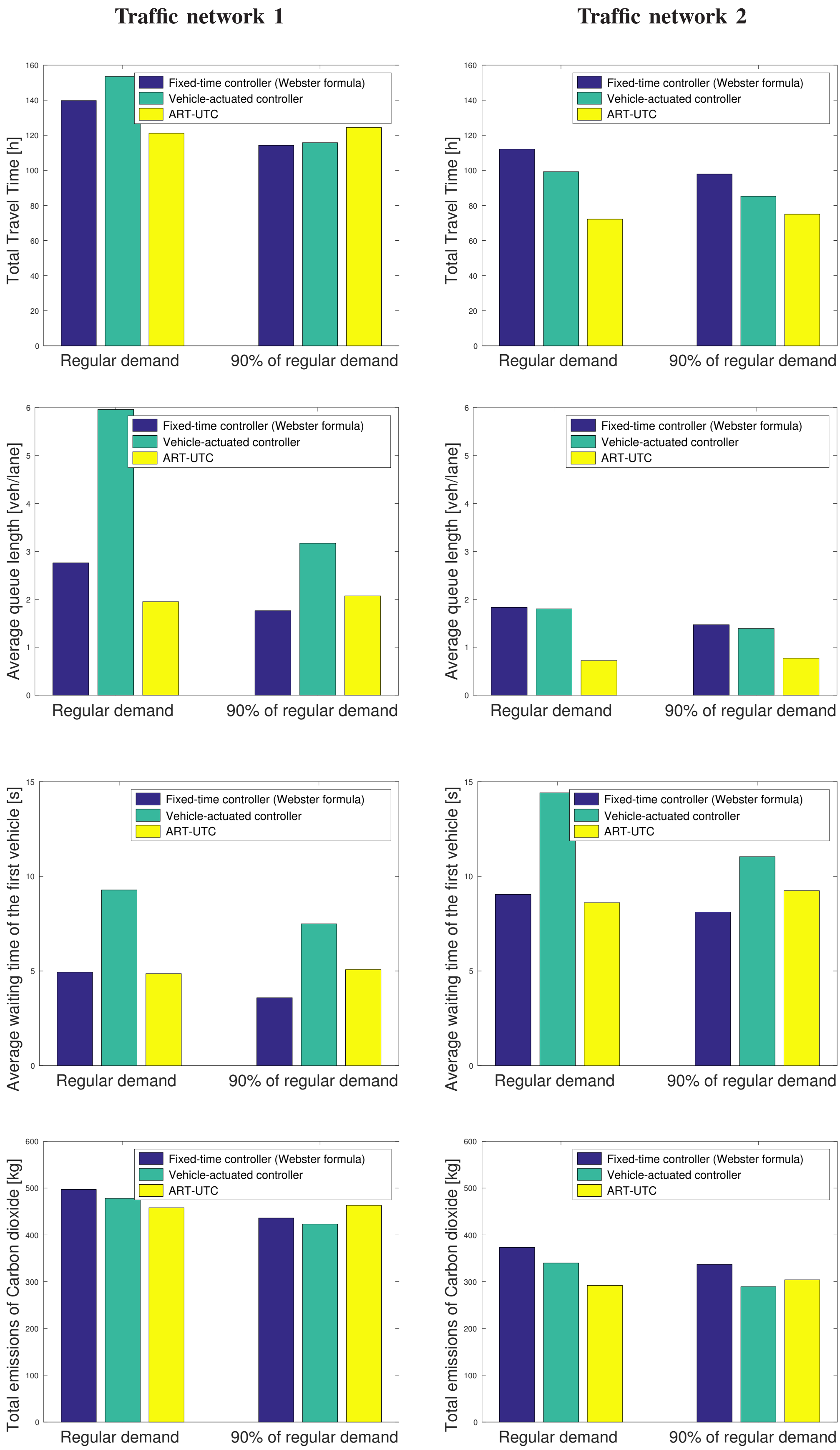

Fig. 4: Simulation results for different evaluation criteria for traffic networks 1 and 2