Globalized Modeling and Signal Timing Control for Large-scale Networked Intersections

Hong Wang[†]
Energy and Transportation Science Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee, USA
wangh6@ornl.gov

Chieh (Ross) Wang
Energy and Transportation Science Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee, USA
cwang@ornl.gov

Meixin Zhu
Energy and Transportation Science Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee, USA
meixin92@uw.edu

Wanshi Hong
Energy and Transportation Science Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee, USA
wh3cv@virginia.edu

ABSTRACT

Traffic intersections are often the bottlenecks of traffic systems. Given a traffic network, an optimal traffic signal control strategy can result in smooth traffic flow and thus reduce energy consumption and environmental impact at intersections. This study aims to develop a new multi-input and multi-output (MIMO) traffic signal control method that can improve network-wide traffic operations in terms of delay and energy consumption. In this context, a 35-intersection network of Bellevue, WA is used as the basis for the development of the algorithm, where modeling and intersection controls in a globalized setting are established using MIMO linear control theory and high matrix formulation. The proposed control method is evaluated in a microscopic traffic simulation environment, VISSIM. Simulation results show that the proposed method has much shorter average travel delays in the network when compared with the delays of conventional pretimed and actuated controls.

CCS CONCEPTS

Traffic engineering algorithms, transportation.

KEYWORDS

Networked traffic flows, traffic signal control, linearized modeling, high matrix, MIMO controls.

ACM Reference format:

Hong Wang, Chieh (Ross) Wang, Meixin Zhu and Wanshi Hong. 2019. Globalized Modeling and Signal Timing Control for Large-scale Networked Intersections. In *SCC '19: The 2nd ACM/EIGSCC Symposium On Smart Cities and Communities Proceedings*

[†] Corresponding author.

1 Introduction

Traffic intersections are the bottlenecks of traffic systems. Given a traffic network, an optimal traffic signal control strategy will result in smoother traffic flow and a greener environment. Traditionally, there are two major traffic signal control methods: pretimed and actuated control. For isolated intersections, pretimed control uses fixed cycle lengths and green time durations, determined based on historical traffic patterns, which cannot handle the dynamics of real-time traffic conditions [3,8]. Actuated control presets minimum and maximum green times and passage time and utilizes loop detectors to sense the request of green phase in each approach. As a result, actuated control at isolated intersection is likely be more efficient than pretimed control [8].

At the network level, coordinated control strategies, be it pretimed or actuated, have been developed and implemented to optimize signal controls along a corridor or among a group of intersections in the real world. Similar to pretimed control at isolated intersections, coordinated pretimed signal control at the network level is limited because it uses of historical data rather than real-time traffic information. Examples of coordinated pretimed control include MAXBAND [2] and TRANSYT [4]. Coordinated actuated control, on the other hand, although can potentially be more efficient than pretimed control, can also be computationally expensive. Examples of coordinated actuated control include SCOOT [1] and RHODES [5]. As pointed out in the literature, many of the coordinated actuated control methods require complex computation for global optimization, which is not real-time feasible to be applied to large-scale traffic network.

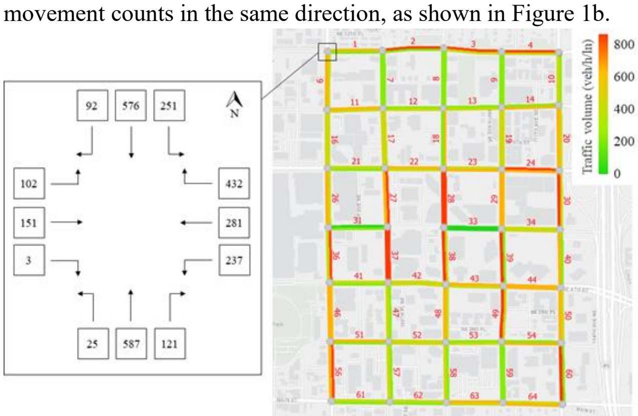
There is a need, therefore, to explore innovative control methods to improve the efficiency of signals at a large-scale traffic network. To address this need, this study aims to develop a simple traffic signal control method that not only can potentially improve network-wide traffic operations in terms of reduced delay and energy consumption, but also is more computationally feasible than existing methods.

2 Networked Intersection Area and Simulation

2.1 Traffic Data

This study focuses on the urban road networks with signalized intersections. Specifically, a grid road network from downtown Bellevue has been selected as the networked intersections area of this study. The study area covers from Main Street (the south) to NE 12th Street (the north) and from Bellevue Way NE (the west) to 112th Ave NE (the east). It includes 35 intersections and 57 major bi-directional road links, with average link length being 664.4 ft.

To replicate real-world traffic conditions, traffic count data by movements were collected for each intersection in the midday off-peak period (i.e., 1-2 pm). Figure 1a shows the traffic counts for the NE 12th Street (the north) and Bellevue Way NE intersection. Link traffic volumes were calculated by aggregating traffic movement counts in the same direction, as shown in Figure 1b.



(a) Traffic counts (b) Traffic volumes

Figure 1: Traffic count by movements and traffic volumes in the road network

2.2 Microscopic Traffic Simulation Model

In this study, VISSIM, a commonly used microscopic traffic simulation software for signal controls, was used to facilitate the development and testing of different traffic signal control methods [6,7,9,10]. The VISSIM traffic model shown in Figure 2 was developed based on the actual road geometries of the studied network area. This microscopic simulation model has been calibrated by the City of Bellevue with the actual traffic data that have been used for planning and management purposes in Downtown Bellevue.

Two baseline methods, i.e., the pretimed control and actuated control, were initially implemented in the simulation model. For pretimed control, the parameters are set as follows. The cycle length is set to be 90s, and the number of phases is selected as 2, where the east and west approaches share one phase, and the north and south approaches share the other phase). The yellow time duration is given as 3s, and all red time durations are set to be 2s. In this case, the green time duration for each phase can be changed before simulation and it ranges from 0s to 80s.It is also assumed that all the intersections are controlled by a single controller, indicating that the green times are the same. A pretimed control diagram with north-south phase green time of 40s is shown in Figure 3.

Figure 2: VISSIM simulation model for the studied traffic network

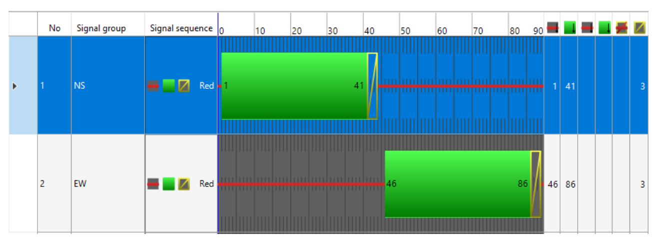


Figure 3: A typical pretimed control diagram with north-south green time being set to 40s

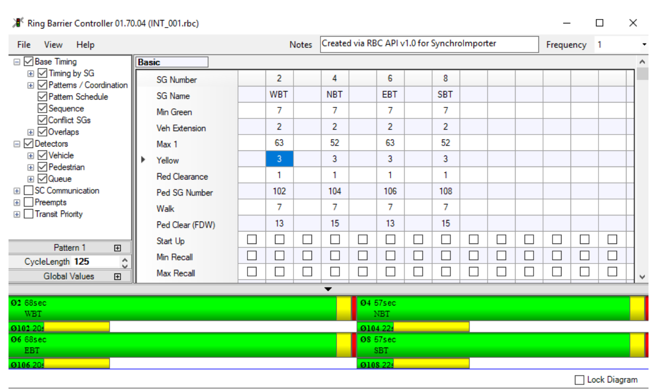


Figure 4: A typical actuated controller

For the actuated control, each intersection is controlled by a separate actuated controller with the "gap-out" method. The parameters are set according to the real-world setting from the City of Bellevue. Specifically, the minimum green time is set to 7s, the maximum green time varies from 50 to 60s, and the vehicle extension time is selected as 2s. A typical actuated controller is shown in Figure 4.

3 Traffic System Controller design

3.1 System Modeling

There are 35 intersections in the subject traffic network, and the green time allocation of each intersection can affect the performance of the whole system. Given a fixed cycle length, say 90s, we denote the north-south direction green time of intersection i as u_i, where $u_i \in [0\ ,80s]$ and $i = 1,2,\dots,35$. The upper limit of 80s is derived as follows:

$$\begin{aligned} total\ green\ time = {} & cycle\ length \\ & - 2(yellow\ time + all\ read\ time) \\ = {} & 90 - 2(2+3) = 80s. \end{aligned}$$

For each intersection, we have two delay measurements, i.e., the delay in the north-south (N-S) direction and the delay in the east-west (E-W) direction. In other words, there is a total of 70 delay measurements for the 35 intersections. For intersection i, the N-S direction delay is denoted by y_{2i-1} and the E-W direction delay is denoted by y_{2i}, where $i = 1,2,\dots,35$.

In this context, the traffic network can be represented by the discrete time input-output dynamic model:

$$y(k) = F(u(k-1)) \tag{1}$$

where $y \in R^{70}$ is the traffic delay of E-W and N-S direction at each node, $u \in R^{35}$ is the system control input, representing in particular the green signal period of N-S direction of each node, and k indicates the time steps. F stands for the nonlinear relationship between the delays and the green signal period, and it can be either a linear or nonlinear vector function. In this paper, only the linear model will be considered. This requires the linearization of system (1).

Since the traffic system is sampled at each traffic cycle, the sampled step size is therefore equal to the traffic cycle length. Assuming the nonlinearity of the traffic network is linearizable, one can simplify the above system with a linear model for $u \in [u_{min}, u_{max}]$ to obtain the following:

$$\Delta y(k) = H\Delta u(k) \tag{2}$$

where $H \in R^{70\times35}$ is the system matrix, Δy and Δu are the increments of y and u at linearized point u^*, respectively. Note that dynamic component of this control method has been ignored here for simplification.

3.2 Feedback Control Structure

The control objective is to design a controller for the simplified traffic system (2) to achieve tracking of an optimized travel delay time y^*. To achieve this control objective, we need to select the green signal period u(k) to achieve the following:

$$\Delta y(k) = -\Gamma(y - y^*) \tag{3}$$

where $\Gamma > 0$ is the controller parameter to be specified by user. By comparing the linearized model with equation (3), assuming the rank of matrix H equals to the number of its columns (i.e., high H-matrix), expected controller structure can be obtained to read:

$$u(k+1) = u(k) + \Delta u(k) \tag{4}$$

$$\Delta u(k) = -(H^T H)^{-1} H \Gamma(y(k) - y^*) \tag{5}$$

where $u(k) \in [u_{min}, u_{max}]$ is the required constraints.

3.2 Closed Loop System Analysis

To verify the performance of the proposed control strategy, we conducted a closed loop system analysis by applying (5) to (2), from which the following closed loop system equation can be obtained

$$\begin{aligned} y(k+1) - y(k) &= -H(H^T H)^{-1} H^T \Gamma(y - y^*) \\ &= -\Omega\Gamma(y(k) - y^*) \end{aligned} \tag{6}$$

$$\Omega = H(H^T H)^{-1} H^T \Gamma \tag{7}$$

The above equations indicate that if $\|I - \Omega\| < 1$ or $\max eig(I - \Omega) < 1$, the closed loop system given by (2) and (5) will be stable. In practice, this criterion needs to be satisfied when choosing Γ. Since the control signal is saturated, the asymptotic tracking of y^* cannot be generally guaranteed particularly when $y^* = 0$, albeit this would mean the minimization of the travel delays across the networked traffic flow area in Figure 2.

4 Estimating System H Matrix

To determine how u_i will affect all the delay vector $\{y_1, y_2, \dots, y_{70}\}$, we conducted a control experiment. Specifically, given an initial N-S green time g_0 (e.g., 40s) and a fixed simulation duration of 3600s, during 0 to 1800s, all the intersections were controlled by a pretimed control method with N-S green time being given by g_0. During 1800 to 3600s, the N-S green time of intersection i is changed to $g_0 \pm \Delta u$,with all the other intersectional control remain unchanged. By comparing with a baseline simulation where all the intersections were controlled by a pretimed control with N-S green time being g_0 from 0 to 3600s, we can estimate the impacts of changing u_i to all the delay components in the travel delay vector. In this study, $\Delta u = 5$s, and we various g_0 ranging from 5s to 75s with a step size of 5s were tested.

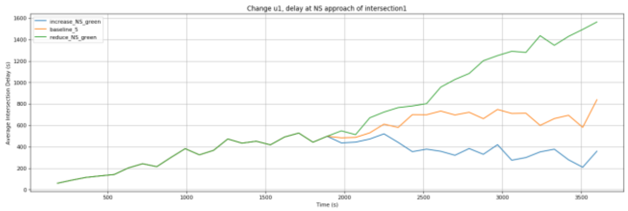


Figure 5: Travel delay of the N-S approach of the intersection 1 with different control strategies

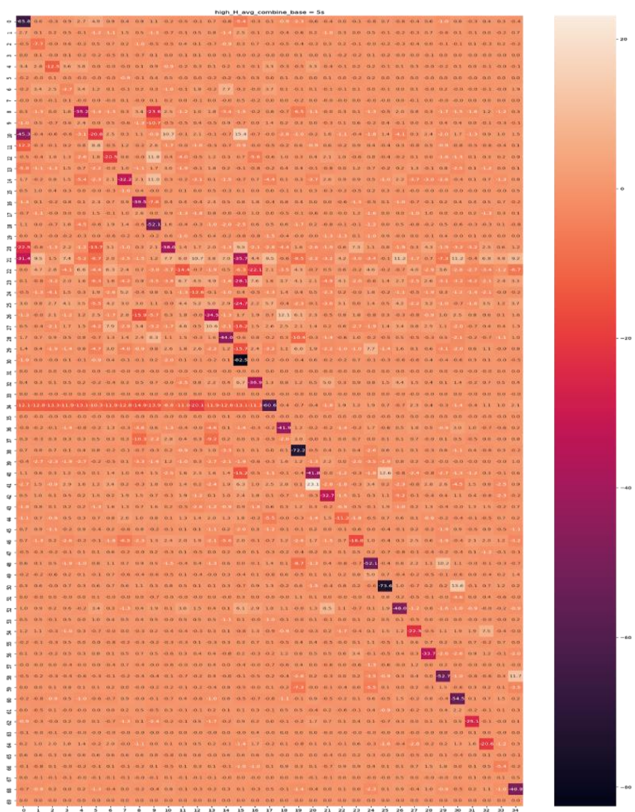


Figure 6: Estimated H matrix with initial N-S green time = 5

Figure 5 illustrates one example experiment in which the initial green time was 5s and the N-S green time of intersection 1 was increased/decreased by 5s halfway through the simulation. With these travel delay curves, the impact of u_1 to y_1 has been calculated by averaging the differences between changed delay measurements and the baseline delay measurement along the time horizon. This process is repeated to explore the relationship between any u_i and y_i. Figure 6 presents the estimated H matrix with initial N-S green time of 5s. The figure has 70× 35 cells. The number in each cell represents the value of the corresponding H matrix element. The color bar in the right part shows that smaller values are represented by darker colors. It can be seen that the diagonal elements have higher absolute values, indicating that an intersection's signal timing generally affect delays in itself more than any other intersections. With g_0 in [5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75], a separate H matrix was estimated for each individual g_0, resulting in a total of 15 H matrices.

5 Implementing the Control Method

To implement the proposed control algorithm obtained in (5), a separate signal controller has been used for each intersection, with cycle length being 90s. For each controller, 81 control programs were developed that respectively correspond to N-S green time of 0, 1, 2, …, 80. The results are shown in Figure 7.

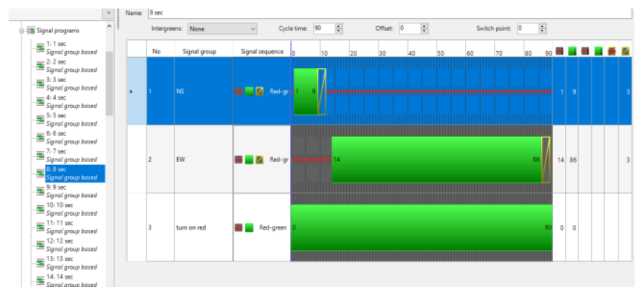


Figure 7: Illustration of signal control programs for a single intersection controller

During the simulation, an initial N-S green time g_0 and an updating interval of 90s were set. After every signal cycle (i.e., 90 seconds) of the simulation, the average vehicle delays at N-S and E-W approaches of each intersection were collected. Given a desired delay of 0s, the updated N-S green time at the next simulation interval can be calculated using equations (3) – (5) for each intersection. With the updated N-S green time, the corresponding signal control program (the nearest integer for the green time) can be selected to reflect the green time variation.

The simulation control and dynamic signal program updates have been implemented using VISSIM COM interface in Python. It should be noted that when calculating the updated green time, the nearest H matrix was chosen based on the green time in the previous cycle.

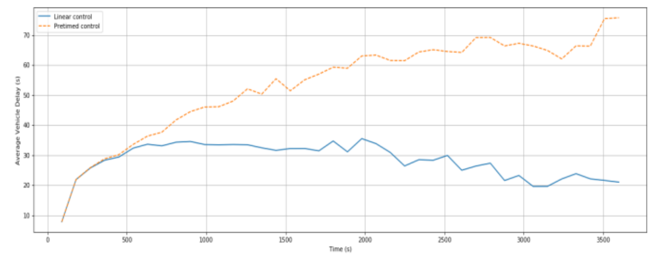
6 Simulation Results

We tested the proposed linear control algorithm with different initial N-S green times and compared its performance with the corresponding pretimed control (i.e., the green time = the initial green time and remains unchanged during the whole simulation). To choose an optimal parameter Γ, multiple Γ values were tested with initial green time being set to 60s. It was found that the linear control was able to achieve optimal average vehicle delay when Γ= 0.2. Table 1 summarizes the experimental results with different initial green times. As shown in Table 1, when compared with corresponding pretimed controls, the proposed linear control given in (5) results in shorter average vehicle delays if a proper Γ value is chosen. It is also noted that, when the initial green time duration is set to 40s and Γ is selected as 0.2, the linear control even outperforms the actuated control. It should be noted that the reason that initial green affects linear control (our method) performances is that for unbalanced initial green (e.g., 70s), we need to adjust the traffic situation from a very bad initial state. In this case, we will have large delays at the beginning of the simulation. When averaging across the whole simulation duration, we have large delays.

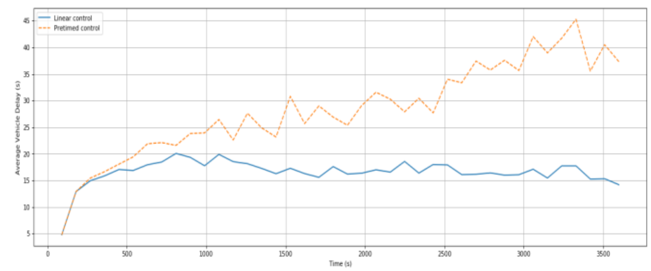
Table 1: Experimental results with different initial green times and control methods

Initial N-S green (s)	**Control**	**Gamma**	**Average Vehicle Delay (s)**
60	Pretimed	--	34.43
60	Linear	2	38.58
60	Linear	1	36.08
60	Linear	0.5	29.16
60	Linear	0.3	16.86
60	**Linear**	**0.2**	**16.00**
60	Linear	0.1	16.62
70	Pretimed	--	68.09
70	**Linear**	**0.2**	**28.20**
40	Pretimed	--	14.70
40	**Linear**	**0.2**	**12.42**
--	Actuated	--	17.62

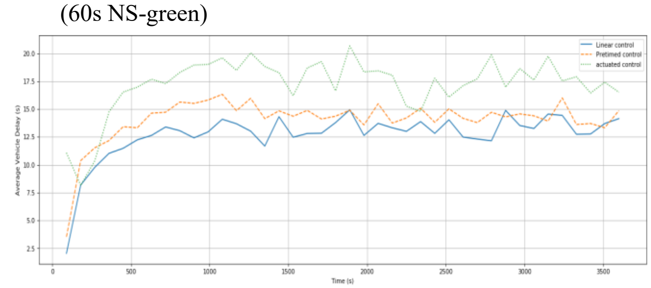
Figure 8 shows the vehicle delay changes along with the progression of the simulation time. It is apparent that the linear control method (blue line) has better performance than the pretimed baseline method (orange line), and it even performs better than the actuated control (green line) if the initial green time is set to 40s. Figure 9 shows how the traffic system looks like after 3000s of simulation. For the pretimed control (Figure 9a), there appeared to be long queues in E-W direction links, whilst the linear control produces (Figure 9b) resulted in much shorter queues.



(a) Initial green = 70s, Γ = 0.2, compared with pretimed control (70s NS-green)

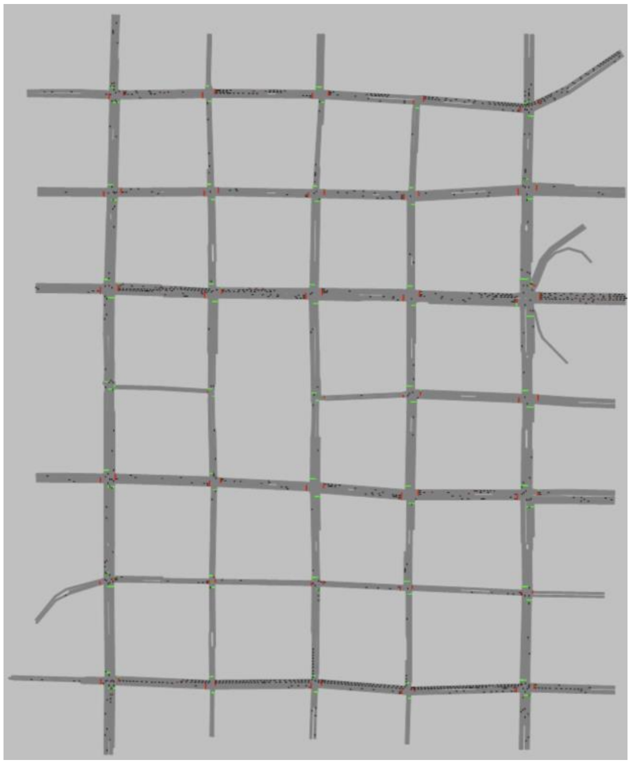


(b) Initial green = 60s, Γ = 0.2, compared with pretimed control (60s NS-green)

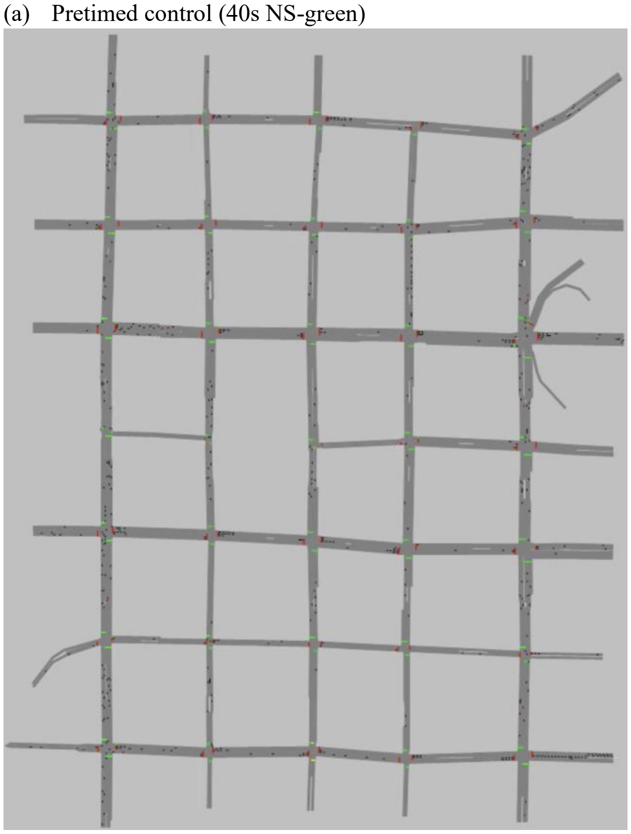


(c) Initial green = 40s, Γ = 0.2, compared with actuated control and pretimed control (40s NS-green)

Figure 8: Delay curves along the simulation process for pretimed and linear control



(a) Pretimed control (40s NS-green)



(b) Initial green = 40s, Gamma = 0.2, linear control

Figure 9: Simulation screenshot at 3000s

7 Summary and Moving Forward

A linear traffic system model was built to reflect how each intersection's signal control input will affect network-wide vehicle delay measurement. Based on the system model, a linear control method was proposed for network-wide traffic signal control. Results show that the proposed method outperforms corresponding pretimed control and even actuated control when proper initial green time is set.

For future research, various traffic flow conditions, especially during saturated flows like AM/PM peak periods will be tested using the proposed MIMO control system. Moreover, dynamic and stochastic control methods will be explored to improve the results.

ACKNOWLEDGMENTS

This research is part of the Systems and Modeling for Accelerated Research in Transportation (SMART) Mobility Consortium funded by the Energy Efficient Mobility System (EEMS) program of the Vehicle Technologies Office (VTO) of the Department of Energy. The authors would like to thank the input they received from the VTO office.

REFERENCES

[1] P B Hunt, D I Robertson, R D Bretherton, and M Cr Royle. 1982. The SCOOT on-line traffic signal optimisation technique. *Traffic Eng. Control* 23, 4 (1982).

[2] John D C Little. 1966. The synchronization of traffic signals by mixed-integer linear programming. *Oper. Res.* 14, 4 (1966), 568–594.

[3] M Papageorgiou, C Diakaki, V Dinopoulou, A Kotsialos, and Yibing Wang. 2003. Review of road traffic control strategies. *Proc. IEEE* 91, 12 (December 2003), 2043–2067. DOI:https://doi.org/10.1109/JPROC.2003.819610

[4] Dennis I Robertson. 1969. TRANSYT method for area traffic control. *Traffic Eng. Control* 10, (1969), 276–281.

[5] Suvrajeet Sen and K Larry Head. 1997. Controlled optimization of phases at an intersection. *Transp. Sci.* 31, 1 (1997), 5–17.

[6] Aleksandar Stevanovic, Peter T. Martin, and Jelka Stevanovic. 2008. VisSim-Based Genetic Algorithm Optimization of Signal Timings. *Transp. Res. Rec. J. Transp. Res. Board* 2035, 1 (2008), 59–68. DOI:https://doi.org/10.3141/2035-07

[7] Aleksandar Stevanovic, Jelka Stevanovic, Kai Zhang, and Stuart Batterman. 2009. Optimizing Traffic Control to Reduce Fuel Consumption and Vehicular Emissions: Integrated Approach with VISSIM, CMEM, and VISGAOST. *Transp. Res. Rec.* 2128, 1 (2009), 105–113. DOI:https://doi.org/10.3141/2128-11

[8] Tom Urbanik, Alison Tanaka, Bailey Lozner, Eric Lindstrom, Kevin Lee, Shaun Quayle, Scott Beaird, Shing Tsoi, Paul Ryus, Doug Gettman, Srinivasa Sunkari, Kevin Balke, and Darcy Bullock. 2015. *Signal Timing Manual - Second Edition*. National Academies of Sciences, Engineering, and Medicine, Washington, DC. DOI:https://doi.org/10.17226/22097

[9] Lihui Zhang, Yafeng Yin, and Shigang Chen. 2013. Robust signal timing optimization with environmental concerns. *Transp. Res. Part C Emerg. Technol.* 29, (2013), 55–71. DOI:https://doi.org/https://doi.org/10.1016/j.trc.2013.01.003

[10] Liang Zheng, Xinfeng Xue, Chengcheng Xu, and Bin Ran. 2019. A stochastic simulation-based optimization method for equitable and efficient network-wide signal timing under uncertainties. *Transp. Res. Part B Methodol.* 122, (2019), 287–308. DOI:https://doi.org/https://doi.org/10.1016/j.trb.2019.03.001