Traffic Signal Optimization for Oversaturated Urban Networks: Queue Growth Equalization

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***Abstract*—This paper develops a signal optimization algorithm that aims to equalize queue growth rates across links in oversaturated urban roadway networks and thus postpones queue spillbacks that form at the localized sections of networks. The performance of this algorithm is evaluated by simulating traffic conditions with optimized signal settings on an idealized 3 by 3 roadway network under various oversaturated demand scenarios. The simulation experiments show that the algorithm can delay queue spillbacks by distributing queues over upstream links that would otherwise be underused. The findings from the experiments also show that the signal settings optimized by the queue growth equalization (QGE) algorithm outperform those optimized using the conventional signal optimization software, TRANSYT-7F, for all the performance measures examined in this paper, i.e., compared with TRANSYT-7F, the QGE results in higher outflows, higher vehicle miles traveled, shorter delays, less sensitivity to various demand scenarios, and delayed queue spillbacks. In addition, the algorithm is computationally light to provide a promising groundwork for large-scale signal optimization.**

***Index Terms*—Optimization, road transportation, signalized intersection, traffic control.**

I. Introduction

TRAVEL demand in urban areas has rapidly increased over the past decades along with the growths of population and economic activity; however, transportation infrastructure has only slowly expanded due to the limited space available in urban areas. Hence, urban transportation networks have become more crowded and repeatedly develop into gridlock [2], [10], [12]. Gridlock is a state of severe congestion that brings traffic in the network to a standstill. This state often arises when a local queue spills back and spreads over the network, thereby restricting traffic movements in all other directions [5], [6], [23]. In any urban transportation network, traffic signal settings have a significant impact on the activation and evolution of urban gridlock, as well as on the capacity of the network, because they determine the rate of queue growth and the occurrence time of spill-over [23], [28].

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Since Webster [18], there have been extensive research efforts to develop methods of traffic signal setting. The majority of those are for undersaturated transportation intersections, in which links have only endogenous queues; neither queue spillover nor gridlock is anticipated in such links [7], [10]. In oversaturated conditions, on the other hand, queues that form in other intersections may have effects on traffic conditions in distant links via queue spill-overs. In this condition, no closed-form expression can be formulated for network delay and throughput as functions of signal parameters because the state of one intersection can be affected by the traffic signal settings at other intersections.

Specifically for oversaturated networks, Gazis [12], Gazis and Potts [13], Green [14], Michalopoulos and Stephanopoulos [36], [37] and Chang and Lin [44] proposed methods to minimize delay by optimizing signal timings of oversaturated intersections. Park *et al.* [4] adopted the genetic algorithm (GA) to optimize signal timings of oversaturated intersections and validated their method with an arterial of four intersections. Girianna and Benekohal [31], in order to maximize the number of vehicles processed by a network, formulated a traffic signal problem for oversaturated conditions as a constrained dynamic optimization problem. Chang *et al.* [43] developed a dynamic method that searches for a solution such that the possibility of progression is maximized. Chang *et al.* [25] proposed a signal control optimization scheme that can maximize throughput while managing queues in the system in oversaturated conditions. The aforementioned algorithms reflect traffic dynamics within networks in formulating objective functions and constraints. However, those formulations often require computationally demanding procedures such as GA when searching for optimal solutions. This computational burden can introduce a drastic limitation in applying these methods to large-scale, complicated urban networks.

Another approach to the design of signal timings for oversaturated networks is to embed traffic simulation models in such a way as to realistically reflect the evolution of congestion over the network. Lo [20], [21] employed the Cell Transmission Model (CTM) to represent traffic dynamics for traffic signal optimization, and reported that the optimized signal timings were able to improve traffic conditions. Lertworawanich *et al.* [35] applied CTM to a goal programming technique with multi-objectives. The formulation was solved using GA for signal timing setting. Several studies have attempted to use micro-simulation to evaluate traffic states [23], [30]. Design of signal timing in oversaturated networks requires extensive searching for optimal solutions in a larger domain due to the exogenous nature of oversaturated networks. Although recent studies [38],

[41], [42] have developed algorithms that can efficiently combine traffic simulation and optimization procedure, embedding a simulation model generally further worsen the computational burden and prohibit the efficient search for optimal signal timing.

For the optimal operation of traffic signals in large-scale urban networks, it is necessary to develop a more computationally efficient algorithm. The present study proposes an algorithm that aims to equalize queue growth across the network in oversaturated conditions (Section II). This equalization of queue growth can delay queue spill-over from congested links by holding vehicles in upstream links where queue storage space is available (i.e., minimizing the difference in queue growth rates among all approaches at all intersections). Such re-allocation of queues postpones the onset of gridlock and therefore sustains high network capacity for a longer period of time. To validate the proposed method, traffic signal settings were optimized for a 3×3 grid-type network in three different oversaturated scenarios; results were then compared with those from the widely-used commercial software TRANSYT-7F. This comparison demonstrates that the proposed method, using our own measure of effectiveness, is superior to TRANSYT-7F in oversaturated conditions and can reflect the essential phenomena of oversaturated networks with greater numerical simplicity and efficiency (Section III). It is feasible to apply the proposed algorithm to real-world large-scale urban networks with complicated demand, though this implementation will require further work (Section IV).

II. Traffic Signal Optimization: Queue Growth Equalization (QGE)

A. New Measure of Effectiveness (MOE)

In this paper, an oversaturated network is defined as a network that includes one or more oversaturated intersections (i.e., not the entire network). Thus, one or more intersections experience higher demand than capacity, and queues formed at those oversaturated intersections spill over into the entire network. In oversaturated conditions, queues forming in a downstream link can deteriorate the performance of the adjacent upstream links. Because in oversaturated conditions queues do not completely dissipate within a signal cycle, it is important to properly manage the queue growth rate at each intersection to avoid spill-over or even gridlock. If the optimized amount of green time is allocated to minimize the difference between discharging capacity and traffic demand at each link, it will be possible to balance the rates of queue growth (or equalize them in an ideal case) in a network and therefore minimize the risk of a spill-over due to localized, intense demand. If this strategy for queue growth equalization (QGE) is successfully performed, maximum utilization of road infrastructure can be achieved at the network level.

For a quantitative measure of queue growth equalization, a network is decomposed into nodes and links. Each node represents an intersection that is operated by traffic signals, which can be assigned for each directional movement using a 2-phase, 3-phase, or 4-phase operating system. Previously, various strategies were developed to control the operation of traffic signals and, therefore, manage queues at oversaturated intersections [1], [12], [15], [18], [19], [34], [40]. The findings from this cohort of studies are intriguing because the network performance can be substantially enhanced by proper queue management via traffic signal control. However, these strategies are unable to optimize network-wide traffic signals. Hence, a new measure of effectiveness (MOE) is developed to quantify the degree of QGE in the network of interest, as follows:

$$\begin{aligned}
&(\text{Degree of QGE}) \\
&\quad = \sum_{link}\sum_{move}(\max(\text{inflow rate-discharging capacity}, 0))^2 \\
&\quad = \sum_{i=1}^{n}\sum_{j=1}^{3}\left(\max\left(\alpha_{i,j}\dot{Q}_i^{in} - l_{i,j}\dot{q}_{i,j}^{out}t_{i,j}, 0\right)\right)^2 \qquad (1)
\end{aligned}$$

where subscripts i and j denote the ith link and the jth turning-movement (1 for a left turn, 2 for straight, and 3 for the right turn), respectively; $\alpha_{i,j}$ represents the split ratio of traffic demand in the ith link to the jth movement, $l_{i,j}$ is the number of lanes assigned for the jth movement in the ith link, $\dot{Q}_i^{in}$ is the total inflow rate (vehicles/hour) in the ith link, $\dot{q}_{i,j}^{out}$ is the per-lane per-hour discharging capacity (vehicles/hour/lane) for the jth movement in the ith link, and $t_{i,j}$ is the sum of the signal phase ratios for the jth movement in the ith link (i.e., $0 \leq t_{i,j} \leq 1$); max(A, B) returns the larger value between A and B. With max($\bullet, \bullet$), Eq. (1) considers only capacity deficit cases (i.e., queue-growing links), which are more critical from the viewpoint of the network performance and therefore can be used to effectively balance queue growth rates in the network. It should be noted that, in Eq. (1), both the inflow and outflow in the ith link can be controlled by changing $\dot{Q}_i^{in}$ and $t_{i,j}$, respectively, to achieve queue "growth" equalization by penalizing their difference. Based on the conservation of traffic flow, the total inflow rate in the xth link, $\dot{Q}_x^{in}$, can be assumed to be a summation of the discharging capacities of the adjacent upstream links through the relevant movement to the xth link as in

$$\begin{aligned}
\dot{Q}_x^{in} &\cong \sum_{adj} l_{adj,rel}\dot{q}_{adj,rel}^{out}t_{adj,rel} \\
&= \dot{Q}_x^{in}(t_{adj,rel}) \qquad (2)
\end{aligned}$$

where the subscripts adj and rel denote the adjacent upstream links and the relevant turning movement, respectively. Equations (1) and (2) imply that link-wise queue growth equalization can be achieved only if both adjacent upstream and downstream traffic signals are considered.

Hence, if optimized traffic signals that minimize Eq. (1) at the network level are determined, wider, smoother transitions (or zero difference in an ideal case) of queue growth in a network can be achieved even under localized oversaturated conditions, as shown in Fig. 1. This can help vehicles to "gradually and uniformly" accumulate at the network level and thereby postpone a spill-over (or even gridlock) in the given network. As a result, the total outflow from the network can remain high for a longer duration, which implies that we can approach the system optimum of the network.

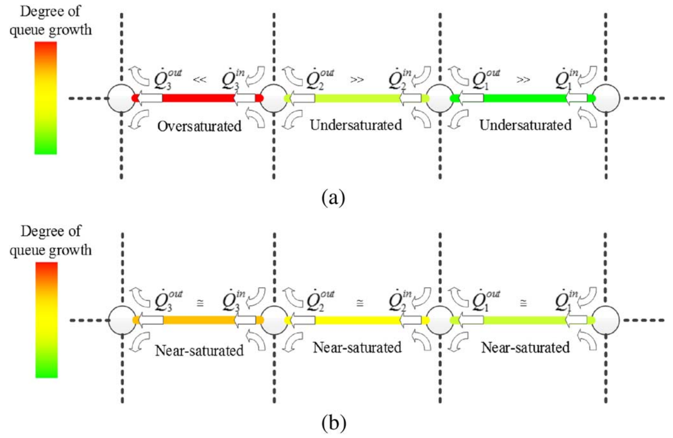


Fig. 1. Conceptual comparison of traffic congestion with and without queue growth equalization. (a) Contour of the degree of queue growth without queue growth equalization. (b) Contour of the degree of queue growth with queue growth equalization.

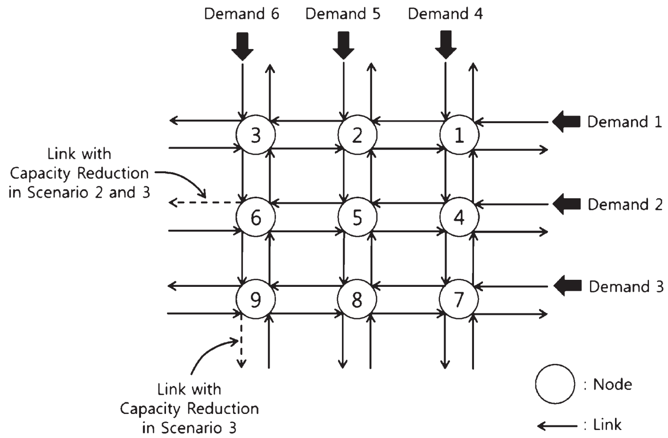


Fig. 2. Roadway network for simulation.

B. Signal Optimization Formulation Based On Queue Growth Equalization

Using the new MOE proposed in the previous section, traffic signal optimization for oversaturated networks can be formulated as follows:

$$\begin{aligned}
\text{minimize} \quad & f(\Phi)=\sum_{i=1}^{n}\sum_{j=1}^{3}\left(\max\left(\alpha_{i,j}\dot{Q}_i^{in}-l_{i,j}\dot{q}_{i,j}^{out}t_{i,j},0\right)\right)^2 \\
\text{subject to} \quad & g(\Phi)=\sum_{m=1}^{c}\Phi_{k,m}=1 \qquad \text{for all } k \\
& 0\le\Phi_{k,m}<1 \qquad \text{for all } k \text{ and } m
\end{aligned} \tag{3}$$

where $\Phi_{k,m}$ denotes the ratio of the mth signal phase time to a cycle length at the kth node (i.e., $0 \le \Phi_{k,m} \le 1$), and $\sum_{m=1}^{c}\Phi_{k,m}=1$ means that the summation of the signal phase ratios at the kth node should be one for signal completeness. In Eq. (3), the design variables are the signal phase ratios at the node k, $\Phi_{k,m}$; then, $t_{i,j}$ can be represented using a linear function of $\Phi_{k,m}$ as

$$t_{i,j}=t_{i,j}(\Phi_{k,1},\,\Phi_{k,2},\ldots,\Phi_{k,c}) \tag{4}$$

where c denotes the total number of signal phases at node k.

Considering the chain rule of differentiation with Eqs. (2) and (4), the sensitivities of the objective and constraint functions with respect to the design variable $\Phi_{k,m}$ can be derived as follows:

$$\begin{aligned}
\frac{\partial f(\Phi)}{\partial \Phi_{k,m}} &= \begin{cases}
\sum_{i=1}^{n}\sum_{j=1}^{3} 2\left(\alpha_{i,j}\dot{Q}_i^{in}-l_{i,j}\dot{q}_{i,j}^{out}t_{i,j}\right) \\
\left(\alpha_{i,j}\frac{\partial \dot{Q}_i^{in}}{\partial t_{i,j}}\frac{\partial t_{i,j}}{\partial \Phi_{k,m}}-l_{i,j}\dot{q}_{i,j}^{out}\frac{\partial t_{i,j}}{\partial \Phi_{k,m}}\right) \\
\qquad if\ \alpha_{i,j}\dot{Q}_i^{in}>l_{i,j}\dot{q}_{i,j}^{out}t_{i,j} \\
0 \\
\qquad if\ \alpha_{i,j}\dot{Q}_i^{in}\le l_{i,j}\dot{q}_{i,j}^{out}t_{i,j}
\end{cases} \\
\frac{\partial g(\Phi)}{\partial \Phi_{k,m}} &= 1.
\end{aligned} \tag{5}$$

It should be noted that $\partial t_{i,j}/\partial \Phi_{k,m}$ in Eq. (5) becomes zero unless the link i and node k are connected to each other. This leads to significant computational efficiency in calculating Eq. (5). During optimization, in order to provide the network-wide balanced queue growth rates, Eq. (3) searches for the optimal set of signal phase ratios with the sensitivities obtained from Eq. (5). Thus, only one-time optimization is necessary for all intersections if the traffic demands on the boundary of a network are set to be constant. Considering that Eq. (3) is a nonlinear constrained optimization and that further application will be a large-scale network, the modified method of feasible direction (MMFD) was chosen as an optimization algorithm. MMFD has been well known to provide reliable convergence in various engineering problems [46]; it also uses less computer memory than do other algorithms, which is critical for its application to a large-scale network. It is also noteworthy that QGE is easy to extend to a larger network because a new MOE is formulated link-wise with a small number of parameters, as shown in Eqs. (1) and (2).

III. Simulation-Based Experiments for Validation

In this section, simulations were conducted to validate the performance of the proposed signal optimization described in Section II. The network used in the simulations is composed of 48 links and 9 nodes, as illustrated in Fig. 2. Each link has one lane with invariant capacity; its length is 1 km. At each node, there is a four-phase signal of four links for sending and receiving flows. At each sending link, there are three possible movements: permissive left-turn, straight, and right-turn. For simplicity, it is assumed that green time for each sending link simultaneously serves the three movements and that cycle times are equal at all intersections. Because the optimized green times at intersections are not necessarily the same, the starts of green times are different across intersections.

The network is loaded with inflows at six access links that are located at the right and top input links of the network (Fig. 2). From the input links, vehicles arrive uniformly at a constant rate in each scenario. Traffic demand patterns—amount of traffic volume into the network and split ratio at each node—are predetermined depending on the demand scenario. Under the given demand patterns, traffic signal timings were optimized using both the proposed signal optimization and the conventional signal optimization package, TRANSYT-7F (ver 8.2). Signal timings optimized by both algorithms were separately input into the traffic simulation software, CORSIM, to evaluate traffic conditions for comparison.

Three demand scenarios were designed to progressively validate the performance of the proposed algorithm. The first scenario examines whether the algorithm determines optimal traffic signal timings that are already known (Section III-A). With demand patterns identical to those in the first scenario, the second scenario purposely imposes a bottleneck on a single, outward-bound link by restricting the capacity of the link (Section III-B). The final scenario was established to evaluate a more complicated case in which the demand patterns are non-uniform and multi-directional, and in which two links have reduced capacity (Section III-C).

A. Scenario 1: Uniform Demand With No Bottleneck and Uni-Directional Flow

In this scenario, demand in the network was assumed to be uniform at 1,000 vehicles/hour (vph) of the top-to-bottom and right-to-left directions with no-turning movements. The capacity at each link was set at 2,000 vph per lane. Under this setup, the network will not have any queues if traffic signal timings at each node are equally allocated to top-to-bottom and right-to-left directions (i.e., bottom-to-top and left-to-right signals are set at zero).

Traffic signal timings were optimized using both QGE and T-7F. As expected, both methods determined traffic signal timings that are exactly half of a cycle time for both top-to-bottom and right-to-left directions. Since vehicles were able to pass each node within a single cycle under the signal settings, delay and accumulation occurred only at intersections as vehicles waited for the next green.

B. Scenario 2: Uniform Demand With a Single Bottleneck and Uni-Directional Flow

In this scenario, a single bottleneck was imposed by reducing the capacity of the horizontally outward-bound link from node 6 (labeled in Fig. 2) by half. All other inputs remained the same as those in Scenario 1. In this situation, a queue forms at the link with the lowest capacity and propagates upstream toward nodes 6, 5, and 4, sequentially. The horizontally spilled queues then constrain the top-to-bottom traffic flow that passes through those nodes, and initiate queues vertically upstream. As a result, the congestion that spreads over the network eventually diminishes network outflows and therefore increases delays.

After optimization of this scenario using QGE and T-7F, the performances of the two signal settings were evaluated and compared by simulating traffic flow. Computation time for QGE was 7.92 minutes while that for T-7F was 22.42 minutes.

Fig. 3. Elapsed time (sec) of queue spill-over at each link for QGE and T-7F in Scenario 2. (a) QGE; (b) T-7F.

For traffic simulation, CORSIM[1] was used with an one-hour simulation duration. Average total outflow from the network was 4,610 vph for QGE and 3,790 vph for T-7F. Because the total demand for the network is constant at 6,000 vph, total delay can be calculated using queueing analysis at 695 vehicle·hrs for QGE and 1,105 vehicle·hrs for T-7F. A comparison of these measures shows that the network performs better in terms of network delay and discharging rate when signal timings from QGE are implemented.

The simulated experiment also demonstrates that the total network outflow diminishes by constraining traffic flows in the top-to-bottom direction as the queue spills over the upstream nodes (i.e., nodes 6, 5, and 4). Therefore, if the occurrence time of queue spill-over is defined as the moment when vehicle accumulation in the link reaches close to the jam density (i.e., 120 vehicles/km in this paper), it can be a key indicator of outflow reduction. Elapsed time of queue spill-over for the network is illustrated in Fig. 3. The red lines indicate the spill-over links; the elapsed times of spill-over are noted next to the red lines.

With the signal settings determined by T-7F [Fig. 3(b)], all inward-bound links at the top input links of the network spilled over and thus inflows through the links were constrained. This phenomenon might have occurred due to the objective function formulated in the T-7F–delay minimization "with" the network–because this formulation can lead to a solution that minimizes the total delay within the network by restricting inflows at input links (Park *et al.*, 2001). Another set of spill-over links are those connected horizontally from node 6. It is important to note that with signal settings determined by QGE, the queue that formed near node 6 grew more slowly and therefore the occurrence time of spill-over was postponed. This is because the signal settings with QGE are designed to balance queue growth in the network by holding inflows toward node 6 at the upstream links.

To examine the evolution of queues over the network, the normalized accumulation (i.e., accumulation at any given moment divided by accumulation in jam) was computed and

[1]CORSIM is a computer program that can simulate the blockage of an intersection due to queue spill-over. It is quasi-officially used by the U.S. Department of Transportation (USDOT) (US DOT, 1996), and many research papers have validated the performance of signal control strategies by CORSIM (FHWA, 1996; Sacks *et al.*, 2002; Owen *et al.*, 2000).

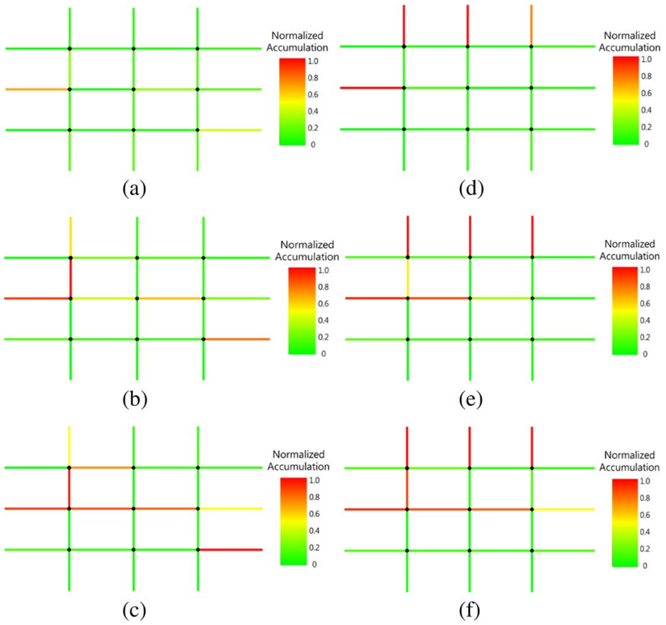


Fig. 4. Accumulations over the network at the elapsed times of 1,000 seconds, 2,000 seconds, and 3,000 seconds for QGE and T-7F in Scenario 2. (a) QGE at 1,000 seconds; (b) QGE at 2,000 seconds; (c) QGE at 3,000 seconds; (d) T-7F at 1,000 seconds; (e) T-7F at 2,000 seconds; (f) T-7F at 3,000 seconds.

displayed in the grid network at the elapsed times of 1,000 seconds, 2,000 seconds, and 3,000 seconds, as can be seen in Fig. 4. The line colors correspond to the magnitude of the normalized accumulations: the darker the shade, the higher the normalized accumulation. Fig. 4 depicts different queue formations for QGE and T-7F signal settings. The queues under the signal settings of QGE gradually saturated the links away from the bottleneck (i.e., the outward link from node 6), as shown in Fig. 4(a) to (c); QGE distributed vehicles over the network to postpone queue spill-over. Meanwhile, queues under the signal settings of T-7F formed horizontally upstream of the bottleneck and started to fill the links in the vicinity of the bottleneck [See Fig. 4(d) to (f)].

To examine this in more detail, time-series profiles of accumulations in the two links (i.e., the link from nodes 5 to 6 and the link from nodes 4 to 5) are provided in Fig. 5. With the signal settings of T-7F, the surges in accumulation of the two links occurred "sequentially." In Fig. 5(b), the line With white rectangles reached an accumulation of 110 vehicles prior to 1800 seconds in the link from nodes 5 to 6. Shortly after the white rectangles reach 110 vehicles, grey circles start to rise. This indicates that the spill-over from the downstream link was closely followed by a surge in accumulation of the link from the upstream link.

On the contrary, the two links became fully saturated "almost concurrently" with the signal settings of QGE, as shown in Fig. 5(a). This is because the vehicles accumulated more gradually in the downstream link, as depicted by the moderate slope of the white rectangles in Fig. 5(a). This earlier but more gradual queue growth toward the upstream link consequently postponed the occurrence time of spill-over in the downstream link (i.e., the link from nodes 5 to 6). This mechanism was able to equalize the queue growths in the two links and delay spill-

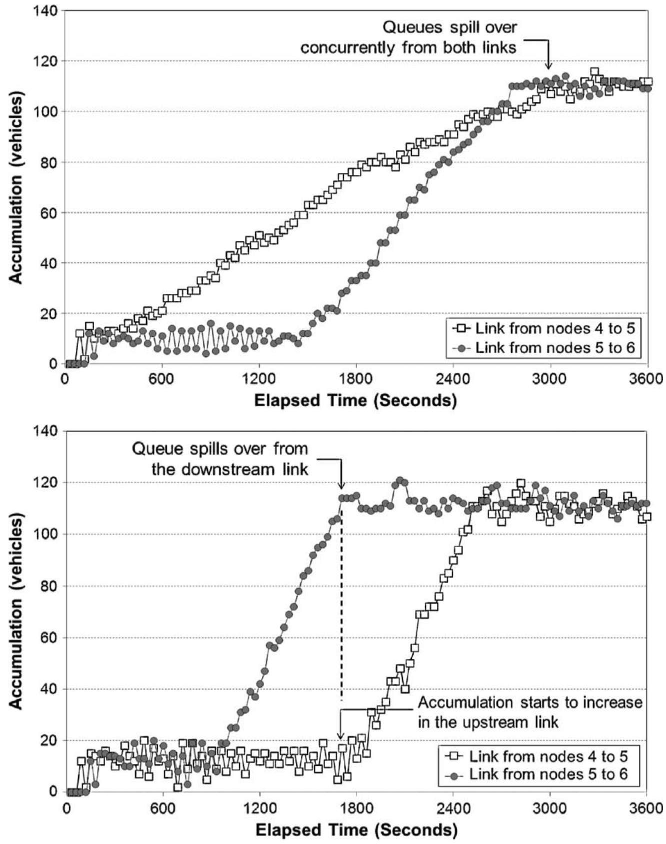


Fig. 5. Accumulations over time in link from nodes 4 to 5, and link from nodes 5 to 6 in Scenario 2 (a) QGE; and (b) T-7F.

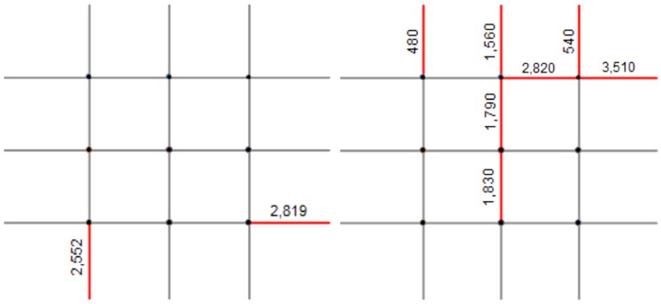
over. As a result, the total outflow from the network remained high for a longer duration.

C. Scenario 3: Uniform Demand With Multiple Bottlenecks and Multi-Directional Flow

Another bottleneck was added to the network, as depicted in Fig. 2; the capacity of the vertically outward-bound link from node 9 was reduced by half to create an additional bottleneck. Different bottleneck locations were also tested but the outcomes were comparable across scenarios. Hence, the scenario with bottlenecks at outward-bound links was presented for observation of queue growth patterns over the entire network.

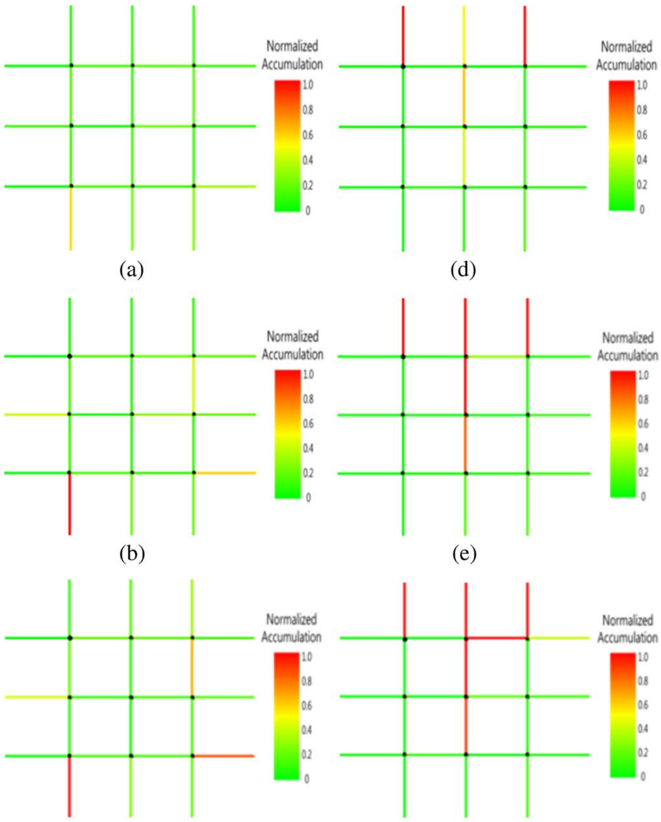
To replicate a real-world case in which demand patterns are more complicated, split ratios at each link were randomly assigned (i.e., multi-directional flow) while holding the inflow constant at 1,000 vph, as in Scenario 2. In this scenario, the unbalanced demand is loaded to the links and thus forms queues sporadically over the network unless proper signal settings are installed.

Again, for Scenario 3, signal timings were optimized using both QGE and T-7F. Computation time for QGE was 6.73 minutes while that for T-7F was 21.85 minutes. The model was then simulated in order to evaluate the performance. During one hour in simulation, average total outflows from networks for QGE and T-7F were 4,972 vph and 2,749 vph, respectively. Considering that the total network inflow was set at 6,000 vph, it was possible to compute the average total delay using queuing



(a) (b)

Fig. 6. Occurrence time of queue spill-over at each link in Scenario 3. (a) QGE; (b) T-7F.



(a) (d)

(b) (e)

(c) (f)

Fig. 7. Accumulations over the network at elapsed times of 1,000 seconds, 2,000 seconds, and 3,000 seconds for QGE and T-7F in Scenario 3. (a) QGE at 1,000 seconds; (b) QGE at 2,000 seconds; (c) QGE at 3,000 seconds; (d) T-7F at 1,000 seconds; (e) T-7F at 2,000 seconds; (f) T-7F at 3,000 seconds.

analysis; average total delay was thus 514 vehicle·hrs for QGE and 1625.5 vehicle·hrs for T-7F. The higher network discharge flow (i.e., 4,972 vph versus 2,749 vph) and lower delay (i.e., 514 vehicle·hrs versus 1,625.5 vehicle·hrs) clearly indicate that the signal settings of QGE outperform those of T-7F.

Fig. 6 shows the spill-over times for the two different signal settings of QGE and T-7F. It can be clearly seen that more links become saturated earlier with the signal settings of T-7F. This implies that the signal settings of T-7F reduce total network outflows.

TABLE I
COMPARISON OF PERFORMANCE MEASURES

		Network outflow (vph)	VMT	Delay (Vehicle-hours traveled)	Computation Time (Minutes)
Scenario 1	QGE	5568	14696.2	216	10.70
	T-7F	5568	14696.2	216	16.63
Scenario 2	QGE	4610	12043.3	675	7.92
	T-7F	3790	9917.7	1105	22.42
Scenario 3	QGE	4972	13400.3	514	6.73
	T-7F	2749	7442.4	1625.5	21.85

Fig. 7 illustrates queue growth patterns for each link at the elapsed times of 1,000 seconds, 2,000 seconds, and 3,000 seconds. Fig. 7(a) to (c) show that the queues in the network grow at comparable rates and that only a few links become saturated when using the signal settings of QGE. On the other hand, several links in the network become rapidly saturated when using the signal settings of T-7F, as shown in Fig. 7 (d) to (f). However, the link with reduced capacity remains undersaturated throughout the one-hour simulation duration, meaning that the capacity of the network is not fully utilized due to the constrained flows in the upstream spill-over links.

D. Summary From Simulation-Based Experiments

This section compares performance outcomes of QGE and T-7F from Scenarios 1, 2, and 3. The performance measures are outflow, VMT, delay, and computation time.[2] These measures computed for each scenario are summarized in Table I. The first scenario was designed to validate that both QGE and T-7F return the correct signal settings. Compared with T-7F, QGE have the same outflow, VMT, and delay with faster computation time, resulting in no delay except for a control delay that arose as vehicles stop at the signal and pass within a signal cycle (See the first and second rows in Table I).

In the second scenario, a single bottleneck was created by reducing the capacity of one link; this induced oversaturated traffic conditions. The simulation results demonstrate that QGE outperforms T-7F in terms of four performance measures: outflow, VMT, delay, and computation time (See the third and fourth rows in Table I). As expected, QGE successfully held demand upstream of the bottleneck and thereby mitigated congestion at the bottleneck links throughout the network. This eventually postponed the gridlock mechanism so as to maintain higher total outflows from the entire network. It should also be noted that the value of VMT is also higher for QGE because T-7F results in constrained inflows and outflows in the network due to spill-overs.

The third scenario assigned multiple bottlenecks and multi-directional flows to replicate the realistic, oversaturated situation in urban networks. Again, QGE performed better than

[2]The computation was performed using the Intel Core i7 that has a clock frequency of 3.7 GHz and a memory of 8.0 GB.

T-7F in all four measures (See the fifth and sixth rows in Table I). It is noticeable that the signal settings of QGE result in an outcome comparable to that in Scenario 2, implying that the performance of QGE is less sensitive to demand patterns than is the performance of T-7F. Therefore, QGE can provide an acceptable and reliable level of service to drivers under various demand situations.

IV. Conclusion

The present study has proposed a novel method, queue growth equalization (QGE), for traffic signal control under oversaturated demand. This method employs the degree of QGE in a given network as a new measure of effectiveness (MOE) and minimizes the degree of QGE to balance queue growth rates over the network, while requiring the same set of input data–traffic volumes and turning ratios at intersections–as in conventional methods. Using the new MOE, traffic signal optimization for oversaturated networks was formulated and conducted by deriving the sensitivities of the objective and constraint functions with respect to the design variables (i.e., the signal phase ratios at the nodes). Simulation-based experiments showed that the traffic signal settings of QGE successfully distributed queues over the upstream links, which queues otherwise would have been concentrated at one link and would have spilled over into the network. Thus, the proposed method can postpone gridlock activation by holding up queue spill-overs, therefore maintaining high network outflows for a prolonged duration. Comparative analysis with T-7F demonstrates that QGE outperforms T-7F in terms of four performance measures (i.e., higher network outflow, higher VMT, smaller delay, and faster computation time) and also provides consistent performance in three different demand scenarios. These findings indicate that the proposed method can enhance the state of the art in the field of traffic signal control. However, the limitations of this study should be addressed for future work. The simulated experiments were idealized for a 3×3 roadway network with simplified signal phases. It will be necessary to thoroughly examine the applicability of the proposed method under more realistic conditions (e.g., complicated network, varied link length and lanes, varied cycle time, pedestrian crossing, etc.). Additionally, because realistic demand patterns are more dynamic and stochastic, it is also necessary to evaluate how the proposed algorithm responds to the realistic demand. Related work is currently underway. Furthermore, although a 3×3 network was considered in this paper, the QGE-based signal optimization is easy to use for modularizing a network into smaller units and can efficiently search for optimal signal settings with analytical sensitivities. Thus, this new method will open the door to new ways of controlling oversaturated conditions in complicated, large-scale urban networks.

References

[1] A. Gal-Tzur, D. Mahalel, and J. N. Prashker, "Signal design for congested networks based on metering," *Transp. Res. Rec.*, vol. 111, pp. 118– 1584, 1993.

[2] "Global urbanization in Asia," Asian Development Bank, Mandaluyong City, Philippines, 2012.

[3] B. Park, N. M. Rouphail, J. P. Hochanadel, and J. Sacks, "Evaluating reliability of TRANSYT-7F optimization schemes," *J. Transp. Eng.*, vol. 127, no. 4, pp. 319–326, Jul./Aug. 2001.

[4] B. Park, C. J. Messer, and T. Urbanik II, "Enhanced genetic algorithm for signal-timing optimization of oversaturated intersections," *Transp. Res. Rec.*, vol. 1727, pp. 32–41, 2000.

[5] C. F. Daganzo, "The nature of freeway gridlock and how to prevent it," in *Proc. 13th Int. Symp. Transp. Traffic Theory*, Amsterdam, The Netherlands, pp. 629–646, 1996.

[6] C. F. Daganzo, "Urban gridlock: Macroscopic modeling and mitigation approaches," *Transp. Res. B*, vol. 41, no. 1, pp. 49–62, Jan. 2007.

[7] C.-J. Lan, C. J. Messer, N. A. Chaudhary, and E. C.-P. Chang, "Compromise approach to optimize traffic signal coordination problems during unsaturated conditions," *Transp. Res. Rec.*, vol. 1360, pp. 112–120, 1992.

[8] C. Bielefeldt, "SIGMA-A new program for optimising signal timings," Heusch Boesefeldt GmbH, Aachen, Germany, 1987.

[9] C. E. Wallace, K. G. Courage, D. P. Reaves, and G. W. Schoene, G. W. Euler, *TRANSYT-7F User's Manual*. Washington, DC, USA: U.S. Dept. Transp. (USDOT), Federal Highway Admin. (FHWA), 1984.

[10] C. C. Liu, "Bandwidth-constrained delay optimization for signal systems," *Int. Transp. Eng. J.*, vol. 58, no. 12, pp. 21–26, Dec. 1988.

[11] D. Schrank, B. Eisele, and T. Lomax, "Urban mobility report," Texas A&M Transp. Inst., Texas A&M Univ., College Station, TX, USA, Jan. 2012.

[12] D. C. Gazis, "Optimum control of a system of oversaturated intersections," *Oper. Res.*, vol. 12, no. 6, pp. 815–831, 1964.

[13] D. C. Gazis and R. B. Potts, "The oversaturated intersections," *Proc. 2th Int. Symp. Theory Road Traffic Flow*, Paris, France, 1965, pp. 221– 237.

[14] D. G. Green, "Control of oversaturated intersections," *Oper. Res.*, vol. 18, no. 2, pp. 161–173, Jun. 1967.

[15] E. Christofa, J. Argote, and A. Skabardonis, "Arterial queue spillback detection and signal control based on connected vehicle technology," *Transp. Res. Rec.*, vol. 2356, pp. 61–70, 2013.

[16] "Managing urban traffic congestion," Eur. Conf. Ministers Transp. (ECMT), Paris, France, 2007.

[17] F. V. Webster, "Traffic signal settings," Her Majesty's Stationary Office, London, U.K., Road Res. Tech. Paper No. 39, 1958.

[18] G. Abu-Lebdeh and R. F. Benekohal, "Development of traffic control and queue management procedures for oversaturated arterials," *Transp. Res. Rec.*, vol. 1603, pp. 119–127, 1997.

[19] G. Abu-Lebdeh and R. F. Benekohal, "Genetic algorithms for traffic signal control and queue management of oversaturated two-way arterials," *Transp. Res. Rec.*, vol. 1727, pp. 61–67, 2000.

[20] H. K. Lo, "A novel traffic signal control formulation," *Transp. Res. A*, vol. 33, no. 6, pp. 433–448, Aug. 1999.

[21] H. K. Lo, "A cell-based traffic control formulation: Strategies and benefits of dynamic timing plans," *Transp. Sci.*, vol. 35, no. 2, pp. 148–164, May 2001.

[22] H. S. Mahmassani, M. Saberi, and A. Zockaie, "Urban network gridlock: Theory, characteristics, and dynamics," *Procedia—Social Behav. Sci.*, vol. 80, pp. 79–98, Jun. 2013.

[23] J. Schmocker, S. Ahuja, and M. Bell, "Multi-objective signal control of urban junctions–Framework and a London case study," *Transp. Res. C*, vol. 16, no. 4, pp. 454–470, Aug. 2008.

[24] J. Sacks, N. M. Rouphail, B. Park, P. Thakuriah, "Statistically-based validation of computer simulation models in traffic operations and management," *J. Transp. Statist.*, vol. 5, no. 1, pp. 1–15, 2002.

[25] J. Chang, B. Bertoli, and W. Xin, "New signal control optimization policy for oversaturated arterial systems," in *Proc. 89th Transp. Res. Board Annu. Meet.*, Washington, DC, USA, 2010, pp. 1– 20, .

[26] J. D. C. Little, M. D. Kelman, and N. H. Gartner, "MAXBAND: A program for setting signals on arterials and triangular networks," *Transp. Res. Rec.*, vol. 795, pp. 40–46, 1981.

[27] L. Laval, "The effect of signal timing and network irregularities in the macroscopic fundamental diagram," in *Proc. Traffic Flow Theory Summer Meet.*, Annecy, France, 2010, pp. 1– 5.

[28] L. E. Owen, Y. Zhang, L. Rao, and G. McHale, "Traffic flow simulation using CORSIM," in *Proc. Winter Simul. Conf.*, Orlando, FL, USA, 2000, pp. 1143– 1147.

[29] M. R. Crabtree, TRANSYT/9 Users' Manual. TRL, Crowthorne, U.K., Transp. Road Res. Lab. Report AG8, 1988.

[30] M. M. Abbas, Z. M. Adam, and D. Getteman, "Development and evaluation of optimal arterial control strategies for oversaturated conditions," *Transp. Res. Rec.*, vol. 2259, pp. 242–252, 2011.

[31] M. Girianna and R. F. Benekohal, "Using genetic algorithms to design signal coordination for oversaturated networks," *J. Intell. Transp. Syst.*, vol. 8, no. 2, pp. 117–129, 2004.

[32] N. H. Gartner, J. D. C. Little, and H. Gabbay, "Optimization of traffic signal settings by mixed-integer linear programming. Part I: The network coordination problem," *Transp. Sci.*, vol. 9, no. 4, pp. 321–343, Nov. 1975.

[33] N. H. Gartner, J. D. C. Little, and H. Gabbay, "Optimization of traffic signal settings by mixed-integer linear programming: Part II: The network synchronization problem," *Transp. Sci.*, vol. 9, no. 4, pp. 344–363, Nov. 1975.

[34] N. de Lamberterie, M. Ramezani, A. Skabardonis, and N. Geroliminis, "A clustering approach for real-time control of queue spillbacks on signalized arterials," in *Proc. 93th Transp. Res. Board Annu. Meet.*, Washington, DC, USA, 2014, pp. 1– 16.

[35] P. Lertworawanich, M. Kuwahara, and M. Miska, "A new multiobjective signal optimization for oversaturated networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 967–976, Dec. 2011.

[36] P. G. Michalopoulos and G. Stephanopoulos, "Oversaturated signal system With queue length constraints–I: Single intersection," *Transp. Res.*, vol. 11, no. 6, pp. 413–421, Dec. 1977.

[37] P. G. Michalopoulos and G. Stephanopoulos, "Oversaturated signal system With queue length constraints–II: Systems of intersections," *Transp. Res.*, vol. 11, no. 6, pp. 423–428, Dec. 1977.

[38] L. A. Prashanth and S. Bhatnagar, "Reinforcement learning with function approximation for traffic signal control," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 2, pp. 412–421, Jun. 2011.

[39] R. A. Vincent, A. I. Mitchell, and D. I. Robertson, "User guide to TRANSYT version 8", TRL, Crowthorne, U.K., Transp. Road Res. Lab. Rep. LR888, Jan. 1980.

[40] R. L. Gordon, "A technique for control of traffic at critical intersections," *Transp. Sci.*, vol. 3, no. 4, pp. 279–288, 1969.

[41] J. J. Sánchez-Medina, M. J. Galán-Moreno, and E. Rubio-Royo, "Traffic signal optimization in 'La Almozara' district in saragossa under congestion conditions, using genetic algorithms, traffic microsimulation, and cluster computing," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 1, pp. 132–141, Mar. 2010.

[42] J. Sánchez, M. Galán, and E. Rubio, "Applying a traffic lights evolutionary optimization technique to a real case: 'las ramblas' area in santa cruz de Tenerife," *IEEE Trans. Evol. Comput.*, vol. 12, no. 1, pp. 25–40, Feb. 2008.

[43] T.-H. Chang and G.-Y. Sun, "Modeling and optimization of an oversaturated signalized network," *Transp. Res. B*, vol. 38, no. 8, pp. 687–707, Sep. 2005.

[44] T.-H. Chang and J.-T. Lin, "Optimal signal timing for an oversaturated intersection," *Transp. Res. B*, vol. 34, no. 6, pp. 471–491, Aug. 2000.

[45] CORSIM user manual, U.S. Dept. Transp. (USDOT), Federal Highway Admin. (FHWA), Washington, DC, USA, 1996.

[46] S. B. Lee, S. Ahn, and I. G. Jang, "Development of the optimization framework for low-power wireless power transfer systems," *IEEE Trans. Microw. Theory Tech.*, DOI: 10.1109/TMTT.2015.2398414, to be published.

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