SIGNAL COORDINATION FOR A TWO-WAY STREET NETWORK WITH
OVERSATURATED INTERSECTIONS

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SIGNAL COORDINATION FOR A TWO-WAY STREET NETWORK WITH OVERSATURATED INTERSECTIONS

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Abstract

This paper presents an algorithm to solve signal coordination problem on two-way arterial networks with oversaturated intersections. A discrete-time signal coordination model is formulated as a dynamic optimization problem and solved using Genetic Algorithms (GA). The concept of ideal offsets to dissipate queue for the primary and opposing directions and the relationship between the two offsets are developed. When queue in the primary direction is dissipated and, thus offsets can be positive and can potentially provide forward traffic progression, the processes of queue dissipation can be made for the opposing traffic. Thus, releasing queue in the opposing direction is made provided that the process of queue dissipation in the primary direction has been made. A hypothetical arterial network with 10 signals is used for model validation and to demonstrate the implementation of signal coordination with various queue dissipation schemes. The microscopic simulation software, CORSIM, is used to validate the signal coordination model. Some features of the model must be relaxed for the validation since CORSIM cannot simulate traffic-responsive signal timings. The outcome of validation is desirable. Depending on the scheme of queue dissipation process (one or two ways) and the position of critical signals, the algorithm intelligently generates optimal signal timing. The critical signals are those serving two or more competing coordinated movements. For a scheme with one-way directional traffic progression and with balanced flows, the algorithm confirms the notion that traffic progression should start from the critical intersection and move in the direction of coordinated movements. For a scheme with two-way directional progression and with unbalanced flows, the algorithm also confirms that queue can be dissipated in both directions with ideal offsets attained earlier in the primary direction and later in the opposing direction.
INTRODUCTION

During the past 20 years, many researchers have developed prototypes of signal coordination. Two notable ones have been successfully developed and deployed for undersaturated conditions. These are the Split, Cycle, and Offset Optimization (SCOOT) and the Sydney Coordinated Adapted Traffic System (SCATS). SCOOT has performed well in moderate traffic conditions but has shown major deficiencies in oversaturated and highly fluctuating conditions (Yagar, 1996). In addition, SCATS proved more effective at reducing delay during low volume periods than high (Wolshon, 1999). As the existing algorithms for signal coordination do not handle the temporal and spatial propagation of queue, their application to oversaturated conditions leads to sub-optimal results. Little information is available on methodologies that deal with oversaturated networks. Research on oversaturated networks can be distinguished according to the choice of signal schemes (fixed or real time signal timings), objective functions (minimum delays or queue management), and networks (isolated signals or any number of interdependent signals). For fixed time signal controls, Gazis (1964) and Gazis and Potts (1965) invented a method to optimize signal settings for an isolated intersection and two oversaturated intersections situated on one-way streets. Rathi (1986) and Gal-Tzur (1993) used fixed signal timing, but pursued different objectives deviating from the traditional delay minimization concept. Their methods obtained the optimal signal timings that manage or distribute queues over signal networks to avoid spillback. Several real-time algorithms based on the management of queue growth concept have also been proposed (Miller, 1965; Lee et al., 1975), but none of them have been applied in a real system. Michalopoulos and Stephanopoulos (1978) developed a real-time control strategy and concluded that the strategy using real-time timing scheme is superior relative to the fixed time control at a high volume intersection. The works by Abu-lebdeh and Benekohal (1997), and Lieberman (2000) provided an outstanding framework for developing a signal coordination model on oversaturated systems (single arterials). Girianna and Benekohal (2002) extended the concept of signal coordination developed by Abu-lebdeh for a one-way arterial network.

The purpose of this paper is to present a procedure for designing signal coordination for a two-way system with oversaturated signalized intersections. There are at least four aspects that make signal coordination in two-way street networks more complicated than in one-way street networks (Newell, 1989). First, any queue dissipation or traffic progression scheme designed to benefit traffic movement in one direction (primary) is incompatible with a scheme designed to benefit the opposing traffic movement. Second, offsets must be selected so as to compromise between benefiting the primary and opposing directions. Third, a dilemma exists between conflicting objectives: full utilization of a two-way system and keeping traffic moving smoothly. Finally, signal timings are severely constrained because the signal permits only certain combinations of traffic movements simultaneously. These facts limit the domain of signal coordination solutions.

The following section presents the development of ideal offsets for dissipating queue in a two-way street system, followed by the formulation of a signal coordination problem. Next, a brief explanation of a validation procedure using CORSIM and its
results are presented. A case of a 10-signal network is demonstrated with various queue dissipation schemes. After the results are examined, the paper concludes with findings and recommendations for future works.

OFFSET FOR PRIMARY AND OPPOSING DIRECTIONS

The relationship between offsets for the primary, $\phi_{i,j}(k)$, and opposing directions, $\phi_{j,i}(k)$, is defined by equation (1), where $k$ is the index for a cycle number, $C_i(m)$ is the cycle length for signal $i$ at cycle $m$, and $n$ is the number of cycles of signal $i$, reflecting the traffic regimes of the two intersections. When offsets are set to clear heavy queue for the primary directions, $q_{i,j}(k)$, then the green interval for signal $j$ may be set earlier relative to signal $i$, and the opposing traffic tends to arrive at the same cycle as it is released from signal $j$. Thus, $n=0$. This oversaturated condition is shown in Figure 1 (a). With $n=0$, the relationship between offsets for the primary and opposing directions becomes $\phi_{j,i}(k) = -\phi_{i,j}(k)$.

$$\phi_{i,j}(k) + \phi_{j,i}(k + n) = \begin{cases} 0 & \text{for } n = 0 \\ \sum_{m=0}^{k+n-1} C_i(m) & \text{for } n \geq 1 \end{cases} \tag{1}$$

When queue in the primary directions is lighter and, thus positive offsets along the primary directions are attained, the relationship between offsets for the primary and opposing directions is as shown in Figure 1 (b) for $n=1$, and equation (1) simply becomes $C_i(k) = \phi_{i,j}(k) + \phi_{j,i}(k+1)$. With this formulation, one can observe that the relationship of the two offsets depends on the magnitude of queue along the primary directions. As queue is cleared, the relationship shifts from $n=0$ to $n \geq 1$. Since signal coordination developed in this paper is to dissipate queue, the shift of network operation from oversaturated to undersaturated conditions must reflect the shift of the offsets’ relationship defined in equation (1), from $n=0$ to $n \geq 1$. Based on this offset relationship, the next sections describe the formulation of ideal offsets for one-way (primary direction) and two-way (primary and the opposing directions) queue dissipation schemes.

Ideal one-way queue dissipation processes

When the queue dissipation process is made for the primary direction (see Figures 1 (a) and 1 (b)), the ideal offsets between two signals (from signal $i$ to $j$) can be formulated in equation (2), where $\tau_{i,j}(k)$ is the time required for the first vehicle in the released platoon from signal $i$ to join the tail of the downstream platoon (as the tail has reached its desired speed). $\tau_{i,j}(k)$ is calculated by dividing the unoccupied space, $l_{i,j}(k)$, by desired speeds, $v_{i,j}$. The time required for the tail to start moving, $\alpha_{i,j}(k)$, is calculated by dividing the queue length at the approach of signal $j$ at the beginning of green time, $q_{i,j}(k)$, by the starting shock-wave speed, $\lambda$. The final formulation shows that the ideal offsets depend on the distance between the two signals, $l$, the number of vehicles stored in queue at the beginning of green time, $q_{i,j}(k)$, the length of vehicles, $l_{veh}$, starting shock-wave speed, $\lambda$, and desired speeds, $v_{i,j}$. 

$$\phi_{i,j}(k) + \phi_{j,i}(k + n) = \begin{cases} 0 & \text{for } n = 0 \\ \sum_{m=0}^{k+n-1} C_i(m) & \text{for } n \geq 1 \end{cases} \tag{1}$$
Substituting Equation 2 for the ideal offsets for the primary directions defined in equation (1), offsets for the opposing direction (from signal j to i) are formulated as follows:

\[
\phi_{j,i}(k) = \tau_{i,j}(k) - \alpha_{i,j}(k)
\]

\[
= \frac{l_{i,j}(k)}{v_{i,j}} - \frac{q_{i,j}(k)l_{veh}}{\lambda}
\]

\[
= \left(\frac{l - q_{i,j}(k)l_{veh}}{v_{i,j}} - \frac{q_{i,j}(k)l_{veh}}{\lambda}\right)q_{i,j}(k)
\]

Substituting Equation 2 for the ideal offsets for the primary directions defined in equation (1), offsets for the opposing direction (from signal j to i) are formulated as follows:

\[
\phi_{j,i}(k+n) = \begin{cases} 
0 & \text{for } n = 0 \\
\sum_{m=k}^{k+n-1} C_i(m) & \text{for } n \geq 1
\end{cases} - \frac{l}{v_{i,j}}\left(\frac{(v_{i,j} + \lambda)l_{veh}}{v_{i,j} \lambda}\right)q_{i,j}(k)
\]  

(3)

The offsets, \(\phi_{j,i}(k+n)\), do not guarantee clearing queue along the opposing direction, and their magnitude is determined by the offsets in the primary directions. To obtain the effect the queue dissipation process (the change in queue) in the primary direction has on the offsets faced by of the opposing traffic, one can take the first derivative of equation (3) with respect \(q_{i,j}(k)\).

\[
\frac{\partial \phi_{j,i}(k+n)}{\partial q_{i,j}(k)} = \begin{cases} 
0 & \text{for } n = 0 \\
\sum_{m=k}^{k+n-1} C_i(m) & \text{for } n \geq 1
\end{cases} + \left(\frac{(v_{i,j} + \lambda)l_{veh}}{v_{i,j} \lambda}\right)q_{i,j}(k)
\]

(4)

As described in the previous section, when a system of two intersections is severely oversaturated and the ideal offsets are applied in the primary direction, platoons of the opposing directions tend to join the tail of queue at the downstream signals (signal i) at the same cycle as they are released from upstream intersections (signal j). Thus, \(n=0\), as shown in Figure 1 (a). The relationship between the change in offsets in the opposing direction, \(\partial \phi_{j,i}(k)\), and the change in queue in the primary direction, \(\partial q_{i,j}(k)\), becomes
Equation (5) dictates that only the process of queue dissipation determines the opposing offsets. The change in cycle length, \( \partial C_i(k) \), does not affect the change in the offsets. As queue dissipates, \( \partial q_{i,j}(k) < 0 \), the offsets for opposing traffic, \( \phi_{j,i}(k) \), become smaller (if \( \phi_{j,i}(k) > 0 \)) or larger (if \( \phi_{j,i}(k) < 0 \)).

When queue in the primary direction reduces or clears (undersaturated conditions), positive offsets in this direction force the platoons of opposing traffic to arrive at the stop bars during the next cycles and, thus, \( n \geq 1 \). For \( n=1 \), the relationship between offsets and cycle time becomes as described before, i.e., \( C_i(k) = \phi_{j,i}(k) + \phi_{i,j}(k+1) \), and offsets for the opposing direction are formulated in equation (6).

\[
\phi_{j,i}(k+1) = C_i(k) - \frac{l}{v_{i,j}} + \left( \frac{(v_{i,j} + \lambda)l_{veh}}{v_{i,j} \lambda} \right) q_{i,j}(k)
\]

To obtain the effect of cycle length and queue on the offsets for the opposing direction, take the first derivative of equation (6) with respect to queue and solve for the offsets. Equation (7) formulates the result. Clearly, both the change of cycle length and the process of queue dissipation in the primary direction determine the change of the offsets, \( \phi_{j,i}(k+1) \).

\[
\partial \phi_{j,i}(k+1) = \left( \frac{\partial C_i(k)}{\partial q_{i,j}(k)} \right) \partial q_{i,j}(k) + \left( \frac{(v_{i,j} + \lambda)l_{veh}}{v_{i,j} \lambda} \right) \partial q_{i,j}(k)
\]

**Ideal two-way queue dissipation processes**

When one needs to clear accumulated queue in the opposing direction on top of the primary directions, and with the use of the definition of ideal offsets as formulated in equation (2), the relationship between queue and cycle lengths is formulated as follows.
The first derivative of equation (8) with respect to the queue in the opposing direction can be used to obtain a relationship between the changes in queue for both directions.

\[
\phi_{i,j}(k) + \phi_{j,i}(k+n) = \\
\frac{l}{v_{i,j}} - \left(\frac{v_{i,j} + \lambda}{v_{i,j} \hat{\lambda}}\right) q_{i,j}(k) + \frac{l}{v_{j,i}} - \left(\frac{v_{j,i} + \lambda}{v_{j,i} \hat{\lambda}}\right) q_{j,i}(k+n) \\
= \left(\frac{v_{i,j} + v_{j,i}}{v_{ij} v_{ji}}\right) l - \left(\frac{v_{i,j} + \lambda}{v_{i,j} \hat{\lambda}}\right) q_{i,j}(k) - \left(\frac{v_{j,i} + \lambda}{v_{j,i} \hat{\lambda}}\right) q_{j,i}(k+n) \\
= \sum_{m=k}^{k+n-1} C_i(m) \\
\] (8)

The first derivative of equation (8) with respect to the queue in the opposing direction can be used to obtain a relationship between the changes in queue for both directions.

\[
\frac{\partial}{\partial q_{j,i}(k+n)} \sum_{m=k}^{k+n-1} C_i(m) = -\left(\frac{v_{i,j} + \lambda}{v_{i,j} \hat{\lambda}}\right) \frac{\partial q_{i,j}(k)}{\partial q_{j,i}(k+n)} - \left(\frac{v_{j,i} + \lambda}{v_{j,i} \hat{\lambda}}\right) \frac{\partial q_{j,i}(k)}{\partial q_{j,i}(k+n)} \\
\] (9)

Reformulate equation (9) to find \( \frac{\partial q_{j,i}(k+n)}{\partial q_{i,j}(k)} \).

\[
\frac{\partial q_{j,i}(k+n)}{\partial q_{i,j}(k)} = -\left(\frac{v_{j,i}}{v_{j,i} + \lambda} l_{veh}\right) - \left(\frac{\lambda}{v_{j,i} + \lambda v_{j,i} \hat{\lambda}}\right) - \left(\frac{v_{j,i} + \lambda}{v_{j,i} \hat{\lambda}}\right) \frac{\partial q_{j,i}(k+n)}{\partial q_{i,j}(k)} \\
\] (10)

When the desired speeds for both directions are the same, \( v = v_{i,j} = v_{j,i} \), the above equation becomes
For \( n=0 \), the change in queue in the opposing traffic is negatively proportional to the change in the primary direction. Thus, \( \partial q_{i,j}(k) = - \partial q_{j,i}(k) \). For a given cycle, releasing queue in one direction corresponds to an increasing queue for the same cycle in the other direction. Therefore, assigning ideal offsets in both direction when \( n=0 \) is undesirable since it shifts the magnitude of queue from one direction to the other and does not clear queue for the two directions as a cycle rolls. For \( n=1 \),

\[
\frac{\partial q_{i,j}(k+n)}{\partial q_{i,j}(k)} = -\left( \frac{\nu \lambda}{(v + \lambda) l_{veh}} \right) + \frac{\partial \left[ 0 \right]}{\partial q_{i,j}(k)} + 1 \right) \right) \right) (11)
\]

The above equation can be substituted into equation (11) to obtain the effect of \( \partial q_{i,j}(k) \) on \( \partial q_{i,j}(k+n) \).

\[
\frac{\partial q_{j,i}(k+n)}{\partial q_{i,j}(k)} = -\left( \frac{\nu \lambda}{(v + \lambda) l_{veh}} \right) + \frac{\partial \left[ 0 \right]}{\partial q_{i,j}(k)} + 1 \right) \right) = 0 \right) \right) (13)
\]

As seen in Figure 1(b), equation (13) verifies that for \( n=1 \), the change in queue in the primary direction, \( \partial q_{i,j}(k) \), does not affect the change in queue in the opposing direction, \( \partial q_{j,i}(k+n) \). In other words, releasing queue in the primary direction does not cause the accumulation of queue in the opposing direction, and vice versa. With this finding, one can conclude that when oversaturated conditions occur on a two-way street system, signal coordination should be designed to initially clear queue in the primary direction (large negative offsets), as shown in Figure 1 (a). When the queue is dissipated and, thus offsets can be positive and can potentially provide forward traffic progression in the primary direction, the processes of queue dissipation can then be made for the opposing traffic. Thus, one can start releasing queue in the opposing direction provided that the process of queue dissipation in the primary direction has been made.
DYNAMIC SIGNAL COORDINATION MODEL (DSCM)

Let $G=(N,L)$ denote a signalized intersection network consisting of a set of signals $N$ and a set of directional streets $L$. Also let $L_p$ be a set of streets along coordinated paths, and $L_s$ be that along non-coordinated paths. Equation (14) shows the formulation of the objective function. The first term of the equation is the number of vehicles released at signalized intersections weighted by the ratio of the distance traveled to the maximum length of a street in a network. The second term represents a disutility function that penalizes the occurrence of queue at the end of green time along coordinated arterials. The objective function maximizes the net effect of released vehicles and the disutility function.

$$
Max \quad Z = \sum_{i}^{T} \sum_{L}^{H} \frac{d_{i,j}}{d_{max}} D_{i,j}^{h} (t) - \sum_{k}^{K} \sum_{(i,j) \in L_p} \delta_{i,j} (k) q_{i,j}^{h} (k) \\
\delta_{i,j} (k), d_{i,j}, d_{max} > 0 \quad (14)
$$

$D_{i,j}^{h}(t)$ symbolizes departure flows (veh/sec) of phase $h \in H$ at signal $j$ serving flows from signal $i$ over a period of $[t\Delta T, (t+1)\Delta T]$. $H$ is the total phase number, $\Delta T$ is a sample time interval (say 2, 3, 4, or 5 or more seconds), and $t=1,2, \ldots, T$ is a discrete time index. $d_{i,j}$ is the distance from signal $i$ to signal $j$, and $d_{max}$ is the maximum length of streets in the network. $q_{i,j}^{h}(k)$ is the number of vehicles in queue approaching signal $j$ coming from signal $i$ at the beginning of the downstream coordinated green phase, $h^*$, in cycle $k$. Depending on the signal plan and traffic movements served by coordinated phase, $q_{i,j}^{h^*}(k)$ may refer to the left-turning or right-turning plus through movements, or total. $\delta_{i,j}(k)$ is a non-negative disutility factor whose value is determined based on a queue management strategy. In this paper, $\delta_{i,j}(k)=1$ for all $k$ and $(i,j) \in L_p$. $K$ is the period of oversaturation in a cycle number, and $T$ is the period of saturation in a sample time. Note that the disutility function is only for coordinated arterials, $(i,j) \in L_p$. The disutility function ensures that queue is less than storage capacity along coordinated arterials. For non-coordinated arterials, the length of streets bound the length of queue, as formulated later in equation (21).

A set of constraints defined by equations (15) to (18) needs to be satisfied for signal coordination. Offsets in the primary direction from signal $i$ to signal $j$, $\phi_{i,j}^{h^*}(k)$, must satisfy equation (15), where $h^*$ is coordinated phase. $\tau_{i,j}(k)$ is the time required for the first vehicle in the released platoon from signal $i$ to join the tail of the downstream platoon (as the tail has reached its desired speed), and $\alpha_{i,j}(k)$ is the time required for the tail of queue to be released from signal $j$ to start moving. When signals serving the opposing traffic are coordinated, offsets are determined by equation (16a). When signals for the opposing direction are coordinated, the offsets are determined by equation (16b).
De facto red due to backed-up traffic on a receiving street must be avoided. This is defined by equation (17), where $g_i(k)$ is the effective green time for the upstream signal, $g_j(k)$ is that for the downstream signal, and $\beta_{i,j}(k)$ is the time it takes for a stopping shock wave to propagate upstream. The sum of offsets and green times around any loop of the network is equal to an integer multiple of the cycle time (Gartner, 1972). This lock-in constraint is formulated by equation (18).

$$
\sum_{(i,j) \in F(o)} \phi_{i,j}^h(k) + \sum_{(i,j) \in R(o)} \phi_{i,j}^h(k) + \sum_{j \in N(o)} g_j(k) = \sum_{m \in k, j \in N(o)} C_j(m) \\
\forall o \in O
$$

For a given sample time $\Delta T$, the number of vehicles departing intersection $j$ originated from intersection $i$, $D_{i,j}^h(t)$, during the effective green for phase $h$ is expressed in equation (19). $A_{i,j}^h(k)$ is the arrival flow and depends on the departure flows of upstream intersections feeding street $(i,j)$. The capacity during the effective green interval, $c^h(t)$, equals the saturation flow $s^h$ (veh/sec) if the phase $h$ has a right of way. Otherwise, the capacity equals zero. Queue cannot be negative, so equation (20) also governs. In addition, to avoid blockages on coordinated arterials, queue along non-coordinated arterials must be less than the storage capacity of approach links. Equation (21) formulates the blockage avoidance along non-coordinated arterials, that is, $(i,j) \in L_o$.

$$
D_{i,j}^h(t) = \min \left\{ \frac{c^h(t) \Delta T}{A_{i,j}^h(t) \Delta T + q_{i,j}^h(t-1)} \right\} \quad \forall i, j \in L
$$

$$
q_{i,j}^h(t) = \max \left\{ 0, q_{i,j}^h(t-1) + \left( A_{i,j}^h(t) - D_{i,j}^h(t) \right) \right\}
$$

$$
q_{i,j}^h(t) \leq \max q_{i,j}^h \quad (i, j) \in L_o, t = 1, ..., T
$$
Additionally, all control parameters in the two network departure models should be within reasonable ranges. Green time must be within a specified lower bound, \( g_{\text{min}} \), and upper bound, \( g_{\text{max}} \). The number of vehicles stored in queue at \( k=0 \) or at \( t=0 \) is defined by users, that is, representing an oversaturated condition. Two conditions can occur along non-coordinated arterials, i.e., when non-ideal offsets are applied: wasted green and blockages. The duration of wasted green is a period of unused green time after the last vehicle in a queue is cleared until new arrivals pass intersections. Blockages can occur if traffic is prevented from leaving upstream intersections due to the presence of queue on the downstream intersections. Blockages form when the stopping shock wave, caused by the mid-block traffic, reaches upstream intersections and ends when the blockage is cleared. During this time, no vehicles will be processed. A combination of the occurrence of wasted green time and blockages determines the departure flows along non-coordinated traffic movements for both cycle-based and discrete-based models.

Throughput, the first term of equation (14), and queue are evaluated for every \( \Delta T \) sample-time. Genetic algorithms search for the set of optimum effective green times by maximizing equation (14) subject to a set of constraints defined in equations (15) to (21). Genetic algorithms transform the constrained signal coordination problem into an unconstrained problem by associating penalty with all constraint violations. GA’s fitness functions equal the objective function and are degraded in relation to the degree of constraint violations. GA procedures to solve signal coordination problems are described elsewhere (Girianna and Benekohal, 2002).

VALIDATION AND IMPLEMENTATION OF DSCM

Model validation

The objective of model validation is twofold. The first is to test and assess whether DSCM developed in this paper can be implemented in a real situation. The second is whether the traffic volume and relationship of variables developed for the model are realistic to describe the operational performance of a real signal system. CORSIM is a tested microscopic simulation model that can help carrying out validation. Features in DSCM such as demand-responsive green interval and offsets are “turned off,” and the validation is made with fixed-signal timing schemes due to limitations of CORSIM. ITRAf of the FHWA software is used to create the network and to input the necessary parameters.

A two-way street network with 10 signalized intersections, shown in Figure 2, is used for model validation and to demonstrate the implementation of signal coordination algorithms. All signals are oversaturated and each signal works with a two-phase plan. No turning movements are allowed in this network. For each direction, the number of arterial lanes is two. Traffic demand per lane for east/westbound arterials is 1,800 vehicles per hour per lane (vph), which is close the capacity of arterial streets. The northbound arterial is from signal 10 to signal 5, and its opposing direction serves the same traffic demand per lane, 1,800 vph. The remaining north/southbound traffic enters the entry signals with flow rates per lane of 900 vph. These traffic demands are also shown in the figure. The maximum effective green time is \( g_{\text{max}}=40 \). The minimum effective green time is \( g_{\text{min}}=10 \) seconds. The speed limit, or desired speed, equals 30
miles per hour (mph), while vehicle acceleration is 5.5 mph per second. Effective vehicle length is 16.5 ft. Starting and stopping shock wave speeds are 16 ft/sec and 14 ft/sec, respectively. For validation purposes, flows and queues are evaluated at sample time $\Delta T=5$ seconds and the duration of oversaturated period is $T=15$ minutes. For north/southbound arterials, only one northbound arterial is coordinated, i.e., from signal 10 to 5. Signal coordination is made for all eastbound traffic, that is, from signals 1 to 5, and from 6 to 10. Streets that are shown as thick lines in Figure 2 serve coordinated (primary) movements and the thin lines serve the opposing (secondary) movements.

Validation procedures

CORSIM simulation run time is for 25 minutes: TP-1 for 10 minutes and TP-2 for 15 minutes. During TP-1, non-optimal signal timings are set, flows with moderately high volumes are loaded onto the network, and thus, oversaturation is expected to occur. At the end of TP-1, queues are accumulated on signal approaches. The purpose of simulation during TP-1 is to generate the initial oversaturated conditions. At the end of this generation period, the number of vehicles stored in queue, vehicles discharged, and speed are recorded for use in the next step. The next step is to execute DSCM with the initial conditions created by CORSIM using non-optimal signal timings during TP-1. DSCM finds the optimal signal timings for a number of cycles, which are then used by CORSIM for the final simulation during TP-2. In summary, the simulation consists of the following steps:

a) During TP-1, CORSIM is executed with non-optimal signal timings

b) Using the output of CORSIM evaluated at the end of TP-1, DSCM is executed to generate optimal signal timings for a number of cycles, i.e., at least for the duration of TP-2 of CORSIM

c) CORSIM is run with the optimal signal timings obtained in the step b), and the same input data as DSCM are used for CORSIM for the duration of TP-2

For DSCM to find optimal signal timings, queue and traffic content obtained from CORSIM at the end of TP-1 are used as the initial conditions. Traffic content of a street consists of the number of vehicles stored in queue and those traveling along available space of the street between the upstream intersections and the tail of queue at the approach of downstream intersections, i.e., the arrival volume. For the purpose of model validation, the arrival volume approaching queue is obtained by subtracting the number of queue from traffic content. These arrivals are treated as additional inflows on the link approaching the tail of queue at the beginning of signal cycle. Model validation is performed for $r=10$ runs, each with a different random seed number. The number of runs would depend on the variability of the response. For this study, $r=10$ provides good results for validation purposes. Note that optimal signal timings generated by the signal coordination model are unique for certain initial conditions and, thus, for certain seed numbers. For each run, at the end of TP-1, CORSIM generates information on the number of vehicles stored in queue for all approaches. This information is used as initial conditions by the model to generate a set of optimal signal timings. With different queue initial conditions, the model results in different outcomes and provides a different set of
optimal signal timings to be used by CORSIM during TP-2. Therefore, a set of paired \( t \)-tests is used to compare the results of the model and the outcomes of CORSIM at the end of TP-2.

**Validation results**

Validation covers measure of evaluation (MOE) at the network and link levels. At the network level, the total vehicles discharged obtained from CORSIM and DSCM are compared. The average link speed weighted by the vehicles discharged is used to compare the speed parameter at the network level. Table 2 shows the results of a paired \( t \)-test for the total link vehicles discharged and the weighted-average speed that resulted from CORSIM and DSCM. The paired \( t \)-test considers the null hypothesis (NH) against the alternative hypothesis (AH). For vehicles discharged, NH claims that there is no significant difference between the total number of vehicles discharged that resulted from CORSIM, \( T^c \) (shown in column 2 of the table), and those that resulted from DSCM, \( T^m \) (shown in column 3 of the table).

\[
\begin{align*}
\text{NH:} & \quad T^c = T^m \\
\text{AH:} & \quad T^c \neq T^m
\end{align*}
\]

For the first run, \( T^c = 14,579 \) trips and \( T^m = 14,314 \), and the difference is 265 trips (see column 3), or 1.82% (see column 4). For the second run, the difference is 476 trips, etc. Results of the significance test are given at the lower part of the table. With the degree of freedom \( n-1=9 \), the \( t \)-value is -0.1879, which is not significant at the 5% level (the two-tail test \( t_{0.05,95\%} = 2.2622 \)), and NH is accepted. The \( p \)-value is 0.8551, which is high and confirms that the NH is accepted. In other words, the total number of vehicles discharged that resulted from DSCM is not significantly different than those that resulted from CORSIM. Similarly, for the average speed, \( t = -1.4569 \) and is less than \( t_{0.05,95\%} \), i.e., 2.2622 (two-tailed test). The average link speed calculated using DSCM equals the average link speed that resulted from CORSIM.

In the second test, we compare the MOEs from a different set of runs for a given link. The test considers the null hypothesis, NH: \( T^c_i = T^m_i \), and the alternative hypothesis, AH: \( T^c_i \neq T^m_i \), where \( i \) is the link index and \( i=1,\ldots,L \), and \( L=54 \) is the number of links in the network in which the vehicles discharged are compared. The null hypothesis claims that for a given link there is no significant difference between MOEs that resulted from CORSIM and DSCM. The test is based on the 5% two-tail confidence level. In the network, there are 54 links on which MOEs are calculated. From these links, it was found that \( t \)-values for the majority of links (45 out of 54 links or 83%) are smaller than the critical value (2.2622). Therefore, at the link level, NH is accepted for the majority of the links. Similarly, for speed, \( t \)-values for the majority of links (42 out of 54 links or 78%) are smaller than the critical value (2.2622). Accordingly, link average speeds calculated by DSCM are statistically the same as those that resulted from CORSIM.
DSCM implementation

Balanced and unbalanced flows

For a network with balanced flows in east/west directions, four cases are made to show the merits of different strategies for signal coordination along east/westbound traffic. Case 1 assigns all eastbound traffic (from signals 1 to 5, and from 6 to 10) to be the primary movements and signal coordination is made to serve these movements. Case 1 is similar to a case for validation purposes. Unlike the first case, Case 2 assumes all westbound traffic is the primary movement. The difference between the first and the second case is that, as seen Figure 2 for Case 1, two coordinated arterials (eastbound and the coordinated northbound) intersect at the downstream section of the primary direction, whereas for Case 2, they intersect in the upstream section of the primary direction. A comparison between the two cases demonstrates the effect of coordinated network topology on the performance of network traffic operation. Cases 3 and 4 demonstrate two-way signal coordination when the primary direction is not the same for east/westbound arterials. Case 3 assigns the path from signal 1 to 5 (eastbound) and from signal 10 to 6 (westbound) as the primary movements. The opposite is true for Case 4. All signal control parameters and traffic demands are similar to that used for validation purposes except that flows and queues are evaluated at every $\Delta T=10$ seconds and initial queues at all coordinated approaches are 20 vehicles per lane.

For a network with unbalanced flows, traffic demands are similar as previously defined except that traffic demands per lane for all westbound movements are 1,500 vph. Thus eastbound traffic is the primary movement and westbound traffic is the secondary movement. A set of signal coordination schemes defined for a network with balanced flows as Cases 1 to 4 is also applied. For each case, however, the secondary movements or the opposing traffics are also coordinated. The merits of having two-way over one-way queue dissipation schemes are also examined.

For each case, three different arterial MOEs are used to examine the traffic performance: vehicles discharged, queue at the end of green interval, and average speed. Before we investigate the MOEs for each case, the examination on how soon the signal coordination schemes attain ideal offsets is presented.

Results of DSCM implementation

The attainment of ideal offsets (balanced flows)

Recall that for a given street, ideal offsets depend on the number of vehicles in queue (to be released) at the beginning of green intervals. When actual offsets deviate from the ideal offsets, then queue cannot be properly released. For Case 1, the fluctuation of ideal offsets, actual offsets, and queue (as cycles rolls) for the coordinated eastbound arterial, EB [1-5], and the opposing non-coordinated arterial, WB [5-1], are shown in Figures 3 (a) and (b), respectively. The dotted line with circles show queue, the thin solid line with triangles displays the ideal offsets, the thick solid line with circles denotes the actual offsets for the primary movements, and the dotted lines with crosses are for the actual offsets for the opposing movements. Along EB [1-5], negative (actual) offsets are set for
the first few cycles as queue is still accumulated. As queue is cleared after several cycles, the offsets become positive. Note that the deviation of offsets from the ideal offsets is large for the first few cycles and becomes very small as queue is dissipated. Positive offsets are attained a few cycles later for the downstream intersection after all upstream intersections operate in undersaturated conditions. Since no signal coordination is imposed along the opposing direction, queue is not dissipated. Signals operate in oversaturated conditions for almost all cycles. Actual offsets deviate from the ideal offsets.

The attainment of ideal offsets (unbalanced flows)

Figures 4 (a) and (b) show the fluctuation of offsets and queues when the primary, EB [5-1], and the opposing directions, WB [5-1], are coordinated (Case 1 with unbalanced flows). Notice that the queues for the two directions are dissipated as the traffic signal cycle rolls. Offsets for both directions converge to ideal offsets. For the primary direction, a marginal deviation from the ideal offsets occurs because, unlike in the one-way signal coordination, both ideal offsets for the primary and opposing traffics conflict and demand for an equivalent early advancement of green times. Offsets for the opposing directions converge to the positive ideal offsets after a few cycles. Similar patterns of offset convergence to the ideal offsets are observed for the other three cases with two-way signal coordination. In the primary direction, ideal offsets are attained at earlier cycles. In the opposing direction, ideal offsets are attained at later cycles. As the offsets converge, queues in both directions dissipate.

MOEs at network level

Table 2 (a) reveals the MOEs at the network level for all the different schemes of signal coordination. For one-way traffic progression with balanced flows, Case 2 provides the best results in terms of the smallest queue (6002 vehicles in 15 minutes) and the largest average speed (8.05 mph). Although the vehicle discharged is the smallest among all the cases, the range of the vehicle discharged is very narrow. Thus, for balanced flows, the importance of the vehicle discharged criterion for all cases with one-way traffic progression scheme is greatly diminished. Case 2 assigns one-way traffic progression for traffic in the westbound direction. As seen in Figure 3, the exit signals of the westbound arterials are not the critical ones, i.e., they do not intersect with other coordinated arterials and they are not as restricted as the exit signals on eastbound arterials. The exit signals of eastbound arterials intersect with northbound coordinated arterials and are critical because two different conflicting movements demand for traffic progression. With Case 2 being the best signal scheme for cases of balanced flows, DSCM confirms the notion that traffic progression should start from the critical intersection and move in the direction of coordinated movements. The MOEs at the network level for cases 3 and 4 are identical. This is expected because the critical intersections are at the exit signal on one arterial and at the entry signal on the other arterial for both cases.

MOEs for cases with unbalanced flows and when one-way progression is imposed are shown in Columns (5), (6), and (7) of Table 2 (a). Similar to cases with balanced flows, Case 2 provides the best progression scheme (smallest queue and largest speed). The number of vehicles discharged is the smallest, but this is expected because traffic
progression is assigned along traffic movement with less demand. Columns (8), (9), and (10) of the table show the MOEs for two-way progression, and columns (11), (12), and (13) of the table reveal the difference between MOEs for one-way and two-way progressions, which shows the merit of assigning traffic progression to the opposing directions. For all cases, the number of vehicles discharged becomes smaller as traffic progression is imposed along the opposing directions. In Case 1, for example, the number of vehicles discharged reduces by 22.1% when the opposing (westbound) movements are coordinated. In Case 2, the number of vehicles discharged reduces by 9.2% when the opposing (eastbound) movements are coordinated. Similarly, queue is reduced by a significant percentage ranging from 19% (Case 4) to 25% (Cases 1 and 3). The average speed increases noticeably from 39.8% (Case 1) to 53.5% (Case 4). The number of vehicles released by arterials systems also reduces as the opposing traffic progression is imposed. This is expected because coordinated signals control the number of vehicles entering the signal system from all entries (eastbound and westbound) such that queue within the system does not accumulate to block upstream intersections. As a result, the number of vehicles processed by the signal network with a two-way traffic progression is less.

**MOEs at arterial level**

This section discusses unbalanced flows for only Case 1. The MOEs are shown in Table 2 (b). However, the findings can be applied to all four cases. Column (1) of the table shows the signal path. SB [2-7] corresponds to a southbound arterial path from signal 2 to signal 7, EB [1-5] is an eastbound arterial path from signal 1 to 5, etc. There are 15 arterial paths in the network. The signal paths with one star denote coordinated arterials carrying movements with primary traffic progression. Those with two stars denote signal paths carrying movements with opposing traffic progression. For a one-way progression scheme, signals serving the opposing traffic progression are not coordinated, whereas for two-way progression, they are coordinated. No signal coordination is imposed on signal timings along signal paths without a star.

Columns (2), (3), and (4) show the MOEs only when the eastbound arterials, EB [1-5] and EB [6-10], are coordinated. With this one-way progression scheme, the number of vehicles discharged by EB [1-5] is 1,850 vehicles, the total number of queue is 665 vehicles, and the average speed is 13.8 mph. Since no coordination is imposed in the opposing direction, queue is accumulated along the opposing direction, WB [5-1], i.e., 1,520 vehicles during a 15 minute period with an average speed of only 5.2 mph. When signal coordination is also imposed to the opposing direction, WB [5-1], the queue considerably reduces and the average speed along WB [5-1] improves. As shown in Columns (7) of the table, the queue reduces to 984 vehicles (35.3% reduction) and the average speed increases to 7.1 mph (36.8% improvement). The average speed for the primary movements (eastbound) decreases. For EB [1-5], the speed decreases from 13.8 mph to 10.0 mph (27.5% reduction). Similarly, for EB [6-10] and WB [10-6], imposing signal coordination along the opposing directions improved the MOEs for the opposing arterials in terms of reduced queue and higher average speed.
The improvement of traffic performance along the opposing coordinated arterials is at the cost of the worst traffic performance for the rest of the system, specifically along the primary movements. Examining the table, one can notice that the average speed for all paths, except for the opposing coordinated arterials, decreases. The number of vehicles discharged for the majority of non-coordinated arterials (north and southbound) decreases as signal coordination is imposed on the opposing (westbound) directions. This is expected since more restrictive green intervals can be allocated to the non-coordinated arterials. A larger number of queues accumulate along eastbound arterials, EB [1-5] and EB [6-10]. The queue accumulation and the average of speed for a one-way and two-way progression schemes are graphically shown in Figures 5 (a) and (b). Bars indicate the change of queue accumulation (or the average speed) in percentages when a two-way progression scheme is imposed. Clearly, imposing signal coordination along the opposing movements decreases the average speed along the primary and crossing movements. Overall, however, assigning the two-way directional signal coordination along east/westbound arterials improved the MOEs.

CONCLUSIONS AND RECOMMENDATIONS

Our research presented the development of an algorithm for signal coordination on a two-way oversaturated arterial network. The algorithm used the notion of ideal offsets that dissipate queue as the traffic signal cycle rolls. In the primary direction, the ideal offsets must be attained earlier relative to that in the opposing (secondary) direction so that traffic progression can be promoted in both directions. The algorithm was validated using CORSIM and the results were satisfied. The algorithm was implemented to an arterial grid network with ten signals, balanced and unbalanced flows, and without turning movements. The outcomes were desirable. Depending on the scheme of queue dissipation processes (one or two ways) and the topology of coordinated arterial networks, the algorithm intelligently generated optimal signal timing. For a scheme with one-way directional traffic progression and balanced flows, the algorithm confirmed the notion that traffic progression should start from the critical intersection and move in the direction of coordinated movements. For a scheme with two-way directional progression with unbalanced flows, the algorithm was capable of dissipating queue in both directions with ideal offsets attained earlier in the primary direction and later in the opposing direction.

In our research, the effect of turning movements on the quality of traffic progression is not accounted for. Further research on ideal offsets with the existence of turning movements is needed. Extending the concept of queue dissipation process presented in this paper to oversaturated networks with closed loops is another area for future works. Moreover, all traffic characteristics modeled in this paper were deterministic, and the development of stochastic models needs to be explored. Finally, a larger fraction of computation time to solve DSCM using GA is on the evaluation of fitness functions. Ways to speed-up computation using new techniques, such as parallel GA or hybrid GA, need to be explored.
REFERENCES


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1. TABLE 1 Paired t-test for MOEs at aggregate link level
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2. FIGURE 2 A two-way street network with 10 signalized intersections
3. FIGURE 3 Dynamic offsets and queues for a one-way queue dissipation scheme, Case 1. (a) The eastbound, EB [1-5], coordinated arterial (primary direction). (b) The westbound, WB [5-1], non-coordinated arterial (opposing direction).
4. FIGURE 4 Dynamic offsets and queues for a two-way queue dissipation scheme, Case 1. (a) The eastbound, EB [1-5], coordinated arterial (primary direction). (b) The westbound WB [5-1], coordinated arterial (opposing direction).
5. FIGURE 5 Queue accumulation (a) and average speed (b) for arterial paths with one-way and two-way progression schemes (Case 1).
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Paired t-test

- Average: CORSIM = 14,098, DSCM = 14,124, mean difference = 27
- t-stat: -0.1879
- p-value (2-tail): 0.8551
- t-critical (2-tail) at 5%: 2.2622

**TABLE 1** Paired t-test for MOEs at aggregate link level
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**TABLE 2 (a) MOEs at network level for different schemes of signal coordination**

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<td>9.46</td>
<td></td>
<td>-11.1</td>
<td>-25.0</td>
<td>29.8</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**TABLE 2 (b) Link-based MOEs for Case 1 (unbalanced flows) during 15 minute oversaturated periods**
FIGURE 1 (a) Relationship between offsets for primary and opposing traffic with $n=0$

FIGURE 1 (b) Relationship between offsets for primary and opposing traffic with $n=1$
FIGURE 2 A two-way street network with 10 signalized intersections
FIGURE 3 Dynamic offsets and queues for a one-way queue dissipation scheme, Case 1. (a) The eastbound, EB [1-5], coordinated arterial (primary direction). (b) The westbound, WB [5-1], non-coordinated arterial (opposing direction).
FIGURE 4 Dynamic offsets and queues for a two-way queue dissipation scheme, Case 1. (a) The eastbound, EB [1-5], coordinated arterial (primary direction). (b) The westbound WB [5-1], coordinated arterial (opposing direction).
FIGURE 5 Queue accumulation (a) and average speed (b) for arterial paths with one-way and two-way progression schemes (Case 1).