TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Article

Transportation Research Record
1–13

DOI: 10.1177/0361198118793007
journals.sagepub.com/home/trr
SAGE

OD-NETBAND: An Approach for Origin–Destination Based Network Progression Band Optimization

Tugba Arsava[1], Yuanchang Xie[2], and Nathan Gartner[2]

Abstract

Traditional progression band optimization methods are focused on providing uninterrupted flow along arterial streets. For arterials with significant traffic streams joining and leaving from side streets, these approaches often generate poor traffic signal control performance. To address this deficiency, an origin–destination (OD) information based progression band optimization model, OD-BAND, was formulated to coordinate signals for arterials with major side-street traffic streams. This paper aims to extend the OD-BAND model further to address the OD based traffic signal coordination problem in multi-arterial grid networks. The extended model is able to create separate progression bands for each major OD stream in the network. In this expanded model, individual arterials are connected with loop constraints to ensure that offsets derived via different paths for a particular intersection are equal. The new OD-NETBAND model is formulated as a mixed integer linear program that maximizes the sum of each major OD stream's progression bandwidth. It can optimize simultaneously cycle length, offsets, and phase sequences for the entire network. Performance of the new model is evaluated with AIMSUN microscopic simulation and is compared with MAXBAND-86 and Synchro results.

Coordinating a group of neighboring traffic signals can result in less delay and fewer stops for drivers, reduced fuel consumption and emissions, uniform and improved travel speed, decreases in accidents and red light violations, and increase in the use of arterials instead of parallel minor streets. Given these potential benefits, many studies have been conducted to continue improving existing traffic signal coordination methods or explore new ideas. These methods can be largely classified into two categories based on their optimization objectives: delay minimization and bandwidth maximization. Delay is typically defined as the difference between expected and actual travel times, whereas bandwidth is the width of a progression band measured in seconds, representing the available green time interval for a traffic stream to travel multiple consecutive intersections without stopping. Although bandwidth maximization methods do not explicitly include delay functions in their objectives, both research and practice have demonstrated that these methods work well due to the intricate connection between progression band and delay (*1*).

Little (*2*) initially introduced a mixed integer linear program that generates progression bands for arterial through traffic. This model was further enhanced by Little et al. (*3*) and is widely known as MAXBAND, which generates uniform inbound and outbound progression bands along an arterial and maximizes them by calculating cycle time, offsets, and phase sequence patterns. MAXBAND was later extended by Gartner et al. (*4*, *5*) as MULTIBAND, which creates symmetrical progression bands along an arterial with varying bandwidths. In MULTIBAND, the objective function of MAXBAND was reformulated to maximize the sum of progression bandwidths along individual arterial segments weighted by the directional link volumes. Recently, Zhang et al. (*6*) formulated an AM-BAND model by relaxing the symmetrical progression band requirement in MULTIBAND. The AM-BAND model allows arterial progression bands to be asymmetrical with respect to the progression line in MULTIBAND, adding more flexibility in the signal control space.

The arterial models mentioned above have also been extended to handle network problems. Little (*2*) has

[1]Department of Civil Engineering and Technology, Wentworth Institute of Technology, Boston, MA
[2]Department of Civil and Environmental Engineering, University of Massachusetts Lowell, Lowell, MA

Corresponding Author:
Address correspondence to Yuanchang Xie: yuanchang_xie@uml.edu

already pointed the way to formulate the network synchronization problem as a mixed integer linear programming problem by considering the network loop constraints. Gartner (*7*) described a scheme to formulate a fundamental set of loop constraints in a given network. These basic formulations were later implemented in computer programs using the MAXBAND model (*8*, *9*) as well as the MULTIBAND model (*10*, *11*). Heuristics were developed to improve the computational efficiency of these models for implementation in large-scale networks (*12*, *13*). Other important issues related to arterial signal coordination problems have also been extensively studied, including lead-lag phasing sequence optimization (*14*), signal coordination under oversaturated conditions (*15*), and formulating bandwidth maximization as an unconstrained nonlinear program considering relative offset and vehicle arrival functions (*16*).

All the aforementioned models use as input the total link volumes, that is, they consider only the turning traffic volumes at the individual intersections without knowing from where they originate and where they are eventually destined to go. These models aim to maximize progression bands along arterial streets and ignore traffic streams coming in from, and going out to, the side streets. Recently, an OD-BAND model (*17*) was proposed that takes OD and side-street traffic information into consideration. Arsava et al. (*18*) further enhanced the OD-BAND model by adopting a revised objective function that considers the number of road segments that a traffic stream or progression band traverses. They also generalized the original model to consider all possible major OD streams and to include left-turn phase sequence optimization as well. In the new OD-BAND model, progression bands are generated based on traffic OD data and for each major OD stream a separate progression band is created. With this approach, major traffic streams flowing in and out of the arterial can also be properly modeled and the network performance improved.

In this paper, the basic OD-BAND model is reformulated and extended for network progression band optimization and the new model is named OD-NETBAND. The new model has the capability of optimizing cycle time, phase sequences, and offsets while creating a separate progression band for each selected major OD stream. OD-NETBAND is also formulated as a mixed integer linear program and solved by the CPLEX Optimization Studio. The effectiveness of this model is evaluated using AIMSUN simulation and is compared with the performances of well-known network progression optimization models/tools such as MAXBAND-86 and Synchro.

Methodology

In this paper, OD-NETBAND is described based on a three-by-three grid network with nine intersections and eight centroids (i.e., origins and destinations) as in Figure 1. Two case studies are conducted and presented. Case I considers seven major OD streams and an additional OD stream is included in Case II. In both case studies, all lane widths are set to 3.5 meters with 200 meters used as the reserved lane visibility distance in AIMSUN. In Figure 1, the eight small circles with blue dots in the center represent centroids, where vehicles enter and exit the network. The centroids are named with two numbers. The first number is for column index and the second one is for row index. Each intersection (i.e., node in Figure 1) is controlled by a pre-timed signal plan. The OD streams and their selected paths considered in this study are presented in Table 1 and Figure 2, respectively. In Figure 2, the colored arrows represent the paths of major OD streams. The paths for OD streams considered in both Cases I and II are represented by orange arrows; and the path for the extra OD stream considered in Case II only is represented by purple arrows.

OD-BAND Model

Similar to OD-BAND, OD-NETBAND is formulated as a mixed integer linear program. Its objective is to maximize the sum of progression bandwidths created for major OD streams in the network. For ease of understanding of OD-NETBAND, OD-BAND is described first. Additional loop constraints are introduced into the basic model to account for the underlying network structure. The following variables are used in OD-BAND:

m_i = loop integer

$b(\bar{b})$ = outbound (inbound) arterial progression through bandwidth (cycles)

$a_i(\bar{a}_i)$ = weight for outbound (inbound) arterial progression band at section i

$y_{N_s,N_e}(\bar{y}_{N_s,N_e})$ = outbound (inbound) progression cross-bandwidth (cycles) for major OD

$a_{(o,d)}(i)(\bar{a}_{(o,d)}(i)\ )$ = weight for $y_{N_s,N_e}(\bar{y}_{N_s,N_e})$ progression cross-bands at section i

C_1, C_2 = lower and upper limits on cycle length

$R_i(\bar{R}_i)$ = outbound (inbound) common red time to allow side street movement at intersection N_i (cycles)

$L_i(\bar{L}_i)$ = time allocated for outbound (inbound) left turn green at intersection N_i (cycles)

$r_i(\bar{r}_i)$ = outbound (inbound) red time for arterial direction at intersection N_i (cycles), $((r_i = R_i + \bar{L}_i)$ $(\bar{r}_i = \bar{R}_i + L_i))$

$w_i(\bar{w}_i)$ = outbound (inbound) interference (cycles), measured from the right (left) end of outbound (inbound) red to the left (right) boundary of outbound (inbound) arterial progression band at intersection N_i (cycles)

$\bar{w}_i$‘ = inbound interference (cycles), measured from right end of inbound red to the left boundary of inbound arterial progression band at intersection N_i (cycles)

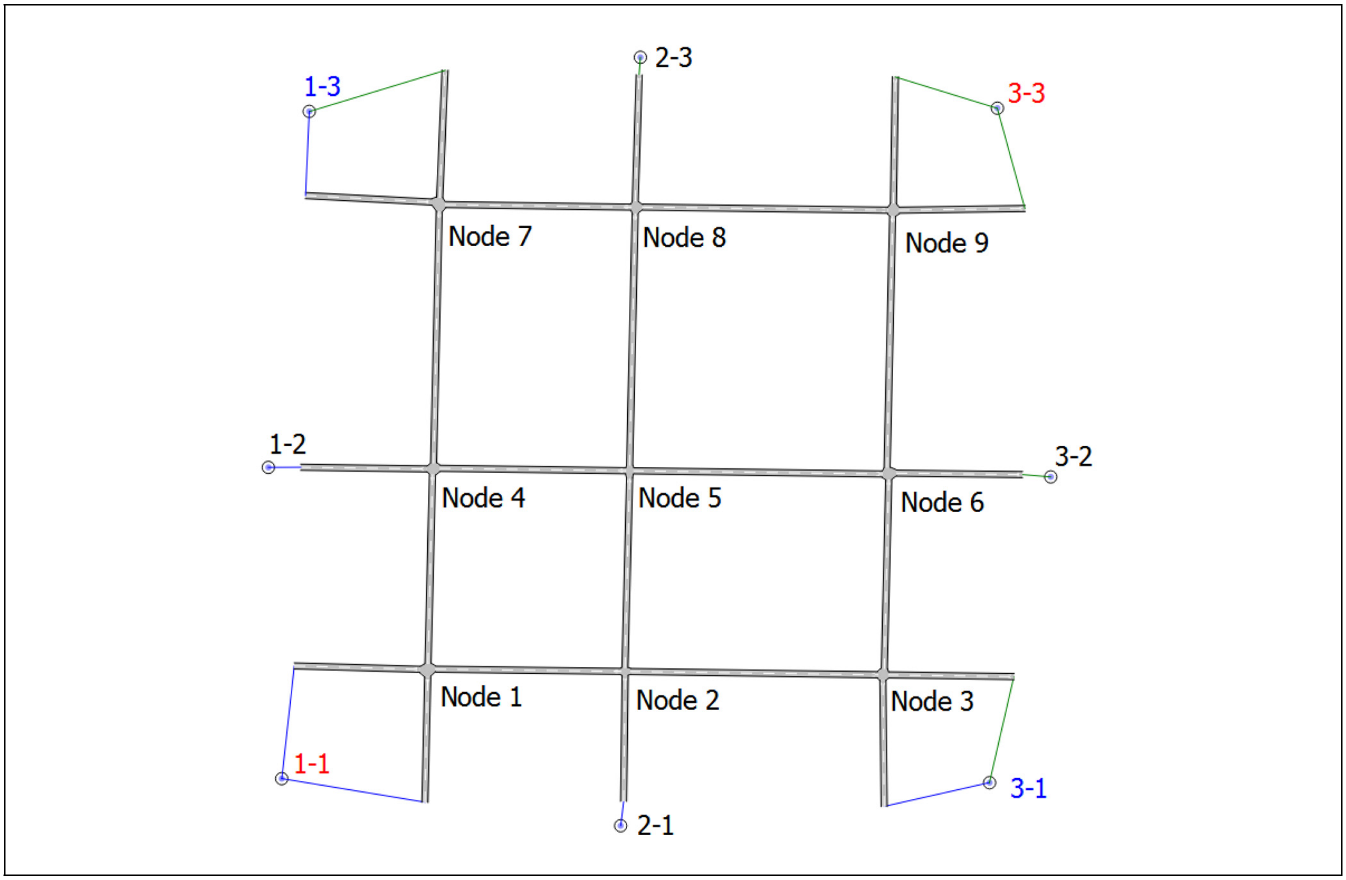


Figure 1. Case study network.

Table 1. OD Streams Considered in Case Studies

Origin	Destination	Case I	Case II
1-1	1-3	500	500
1-1	3-1	500	500
1-1	3-3	800	800
2-1	2-3	500	500
3-1	3-3	500	500
3-1	2-3	–	800
1-2	3-2	500	500
1-3	3-3	500	500
Total demand (vehicles/hour)		3800	4600

$x_{N_s,N_e,i}(\bar{x}_{N_s,N_e,i})=$ interference (cycles) measured from the left end of outbound (inbound) red to the beginning of $y_{o,d}(\bar{y}_{o,d})$ band at intersection N_i (cycles). Subscripts indicate the corresponding progression band information. (origin, destination, current intersection, respectively)

$z = 1/C =$ signal frequency (cycles/second)

$k =$ ratios of inbound volume to outbound volume of arterial progression band

$k_{o,d}(j)\left(\bar{k}_{o,d}(j)\right) =$ ratios of outbound (inbound) traffic volume turned into main street from side street to outbound (inbound) arterial through traffic volume

$\phi_{i,i+1}\left(\bar{\phi}_{i,i+1}\right) =$ internode offsets (cycles) at intersection N_i (cycles)

$\Delta_i =$ internode offset, time difference between center of r_i and nearest center of $\bar{r}_i$ at intersection N_i (cycles)

$\delta_i, \left(\bar{\delta}_i\right) =$ zero/one variables that indicate left turn patterns for outbound (inbound) along the arterial at intersection N_i (cycles)

$t_{i,i+1}(\bar{t}_{i,i+1}) =$ travel time from N_i to N_{i+1} outbound (N_{i+1} to N_i inbound) (cycles)

$d_{i,i+1}\left(\bar{d}_{i,i+1}\right) =$ distance between N_i and N_{i+1} outbound (inbound) (feet)

$G_i(\bar{G}_i) =$ outbound (inbound) green time for through traffic at S_i (cycles)

$e_i, f_i\left(\bar{e}_i, \bar{f}_i\right) =$ lower/upper limits on outbound (inbound) speed (feet/second) at section i

$g_i, h_i\left(\bar{g}_i, \bar{h}_i\right) =$ lower/upper limits on change in outbound (inbound) speed (feet/second) at section i

$V(\bar{V}) =$ outbound (inbound) arterial through volume

$V_{(o,d)}\left(\bar{V}_{(o,d)}\right) =$ outbound (inbound) traffic volume of specific OD pair

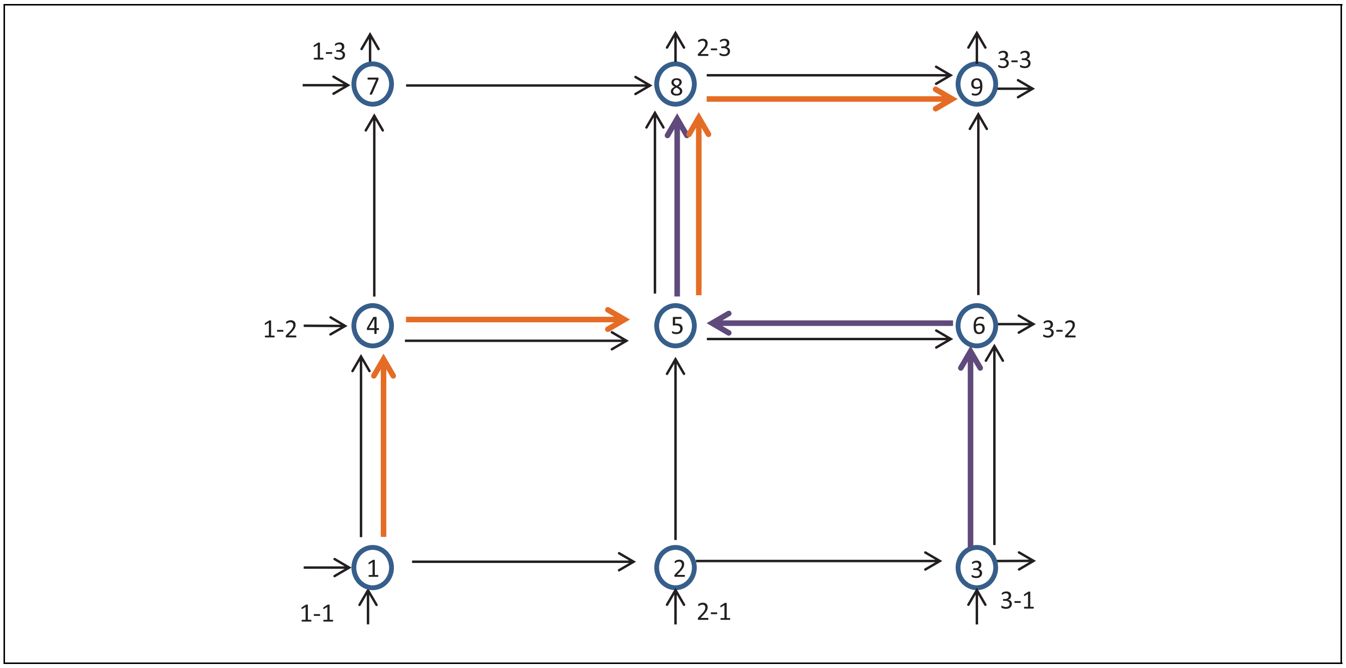


Figure 2. Illustration of paths.

$S(\bar{S})$ = outbound (inbound) saturation flow rate

$S_{(o,d)}(\bar{S}_{(o,d)})$ = outbound (inbound) saturation flow of specific OD pair

n = total number of intersections

$N_s(N_e)$ = Intersection that progression band started (ended)

i = index variable represents intersection number and corresponding downstream (upstream) section for outbound (inbound) traffic

j = index variable represents the note for specific OD pair

p = number of OD pairs for which dedicated bands are sought

$y_{o,d}(\bar{y}_{o,d})$ represent progression bands created for major ODs that join an arterial from side streets. The subscript "o, d" indicates the origin and destination of an OD pair. A lag left turn is considered for side streets with major OD streams. Therefore, the progression bands corresponding to these ODs start in the middle of a red interval for arterial direction. As shown in Equations 1 and 2, the objective function of OD-NETBAND is defined to maximize the sum of progression bandwidths weighted by both the volume to saturation flow ratio and the total number of road segments traveled. $b, \bar{b}, z, w_i, \bar{w}_i, \bar{w}'_i, t_i, \bar{t}_i, x_{o,d,i}, \bar{x}_{o,d,i}, y_{o,d}, \bar{y}_{o,d}, \delta_i, \bar{\delta}_i$ are decision variables that maximize the objective function (Equation 1):

$$MaxB = \underbrace{\sum_{i=1}^{n-1} (a_i * b) + (\bar{a}_i * \bar{b})}_{I} + \underbrace{\sum_{j=1}^{p} \left[\underbrace{\sum_{i=1}^{N_e - N_s} a_{(o,d)}(i) * y_{N_s, N_e}}_{a^*} + \underbrace{\sum_{i=1}^{N_s - N_e} \bar{a}_{(o,d)}(i) * \bar{y}_{N_s, N_e}}_{b} \right]}_{II} \quad (1)$$

(Part a^* is for OD pairs that travel along outbound direction, part b^* is for OD pairs that travel along inbound direction.)
where

$$a_i = \frac{V_i}{S_i} \quad \bar{a}_i = \frac{\bar{V}_i}{\bar{S}_i} \quad a_{od}(i) = \frac{V_{o,d}}{S_{o,d}} \quad \bar{a}_{od}(i) = \frac{\bar{V}_{o,d}}{\bar{S}_{o,d}} \quad (2)$$

subject to

$$1/C_2 \le z \le 1/C_1 \quad (3)$$

$$(1 - k) * \bar{b} \ge (1 - k) * k * b \quad (4)$$

$$(1 - k_{od}(j)) * y_{N_s, N_e} \ge (1 - k_{od}(j)) * k_{od}(j) * b \ where\ j = \begin{cases} 1 & (for\ OD_1) \\ \cdots & \cdots \\ n & (for OD_n) \end{cases} \quad (5)$$

$$(1-\bar{k}_{od}(j))*\bar{y}_{N_s,N_e} \geq (1-\bar{k}_{od}(j))*\bar{k}_{od}(j)*\bar{b} \text{ where } j = \begin{cases} 1 & (for\ OD_1) \\ \dots & \dots \\ n & (forOD_n) \end{cases} \tag{6}$$

$$\begin{cases} w_i + b_i \leq 1 - r_i \\ \bar{w}_i + \bar{b}_i \leq 1 - \bar{r}_i \\ \bar{w}'_i + \bar{b}_i \leq 1 - \bar{r}_i \end{cases} \quad i = 1, \dots, n; \tag{7}$$

$$\begin{cases} (d_i/f_i)z \leq t_i \leq (d_i/e_i)z \\ (\bar{d}_i/\bar{f}_i)z \leq \bar{t}_i \leq (\bar{d}_i/\bar{e}_i)z \end{cases} \quad i = 1, \dots, n-1; \tag{8}$$

$$\begin{cases} (d_i/h_i)z \leq (d_i/d_{i+1})t_{i+1} - t_i \leq (d_i/g_i)z \\ (\bar{d}_i/\bar{h}_i)z \leq (\bar{d}_i/\bar{d}_{i+1})\bar{t}_{i+1} - \bar{t}_i \leq (\bar{d}_i/\bar{g}_i)z \end{cases} i = 1, \dots, n-2; \tag{9}$$

$$\begin{aligned} &(w_i + \bar{w}_i) - (w_{i+1} + \bar{w}_{i+1}) + (t_i + \bar{t}_i) \\ &+ \delta_i L_i - \bar{\delta}_i \bar{L}_i - \delta_{i+1} L_{i+1} + \bar{\delta}_{i+1} \bar{L}_{i+1} - m_i \\ &= (r_{i+1} - r_i) \quad i = 1, \dots, n-1; \end{aligned} \tag{10}$$

$$\bar{w}'_i + \bar{b} + \bar{w}_i = 1 - \bar{r}_i \quad i = 1, \dots, n; \tag{11}$$

$$\bar{r}_i - \bar{r}_{i+1} + \bar{w}'_i - \bar{w}'_{i+1} = w_{i+1} - w_i \quad i = 1, \dots, n-1; \tag{12}$$

$$x_{N_s,N_e,i} \geq r_i \quad i = N_s + 1, \dots, N_e; \tag{13}$$

$$\bar{x}_{N_s,N_e,i} \geq \bar{r}_i \quad i = N_s - 1, \dots, N_e; \tag{14}$$

$$\begin{cases} y_{N_s,N_e} + x_{N_s,N_e,i} \leq r_i \\ \bar{x}_{N_s,N_e,i} + \bar{}_{N_s,N_e} \leq \bar{r}_i \end{cases} \quad i = N_s; \tag{15}$$

$$\begin{aligned} &x_{N_s,N_e,i} - x_{N_s,N_e,i+1} = w_i - w_{i+1} - r_{i+1} + r_i \\ &i = N_s, \dots, N_e - 1; \end{aligned} \tag{16}$$

$$\begin{aligned} &\bar{x}_{N_s,N_e,i+1} - \bar{x}_{N_s,N_e,i} = \bar{w}'_{i+1} - \bar{w}'_i + \bar{r}_{i+1} - \bar{r}_i \\ &i = N_e, \dots, N_s - 1; \end{aligned} \tag{17}$$

$$\sum y_{N_s,N_e} + b \leq 1 - r_i \quad i = max(N_s) + 1, \dots, min(N_e); \tag{18}$$

$$\sum \bar{y}_{N_s,N_e} + \bar{b} \leq 1 - \bar{r}_i \quad i = min(N_s) - 1, \dots, max(N_e); \tag{19}$$

$$\begin{aligned} &b, \bar{b}, z, w_i, \bar{w}_i, \bar{w}'_i, t_i, \bar{t}_i, x_{N_s,N_e,i}, \bar{x}_{N_s,N_e,i}, y_{N_s,N_e}, \\ &\bar{y}_{N_s,N_e}, \delta_i, \bar{\delta}_i \geq 0 \quad i = 1, \dots, n. \end{aligned} \tag{20}$$

Objective function (1) aims to maximize a weighted sum of progression bandwidths. The weights are calculated as the sum of each OD flow divided by its corresponding saturation flow rate at each link. It maximizes the progression bands both along arterials (see Part I) and for specific major OD pairs (see Part II). $a_i(\bar{a}_i), a_{od}(\bar{a}_{od})$ in Equation 2 are the volume to saturation flow ratios of each traffic stream that are defined for individual segments; constraint (3) defines the upper and lower limits for cycle time; constraints (4), (5) and (6) are to provide a wider band to one of the two arterial directions and to the OD pair with a higher traffic volume; constraints (7) and (11) ensure that all through bands along arterial direction are within the available green time; constraint (8) defines upper and lower travel speeds; constraint (9) controls the speed changes and ensures that these changes are not too drastic; constraints (10) and (12) are the loop integer constraints that provide synchronization of traffic signals along the arterial direction; constraints (13), (14), (18) and (19) assure that any one of the OD bands does not infringe upon the red intervals along arterial directions; constraint (15) makes sure that vehicles join the arterial from a side street only when the arterial direction is subject to a red signal; constraints (16) and (17) provide synchronization between intersections for major ODs; and constraint (20) ensures all decision variables are non-negative.

The OD-BAND model is formulated for a sample arterial shown in Figure 3. As an example, progression

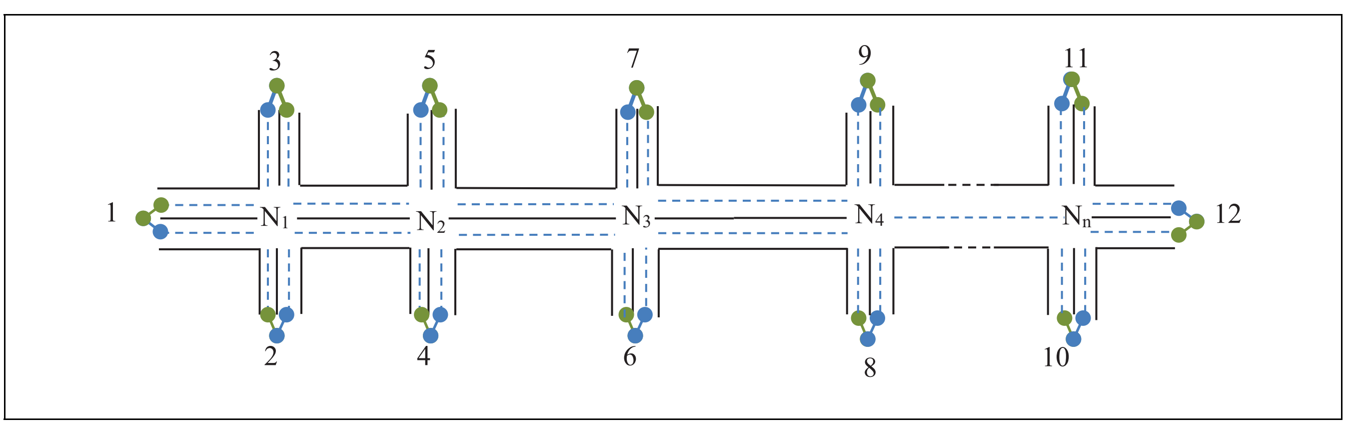


Figure 3. Sample arterial scheme for OD-BAND model formulation.

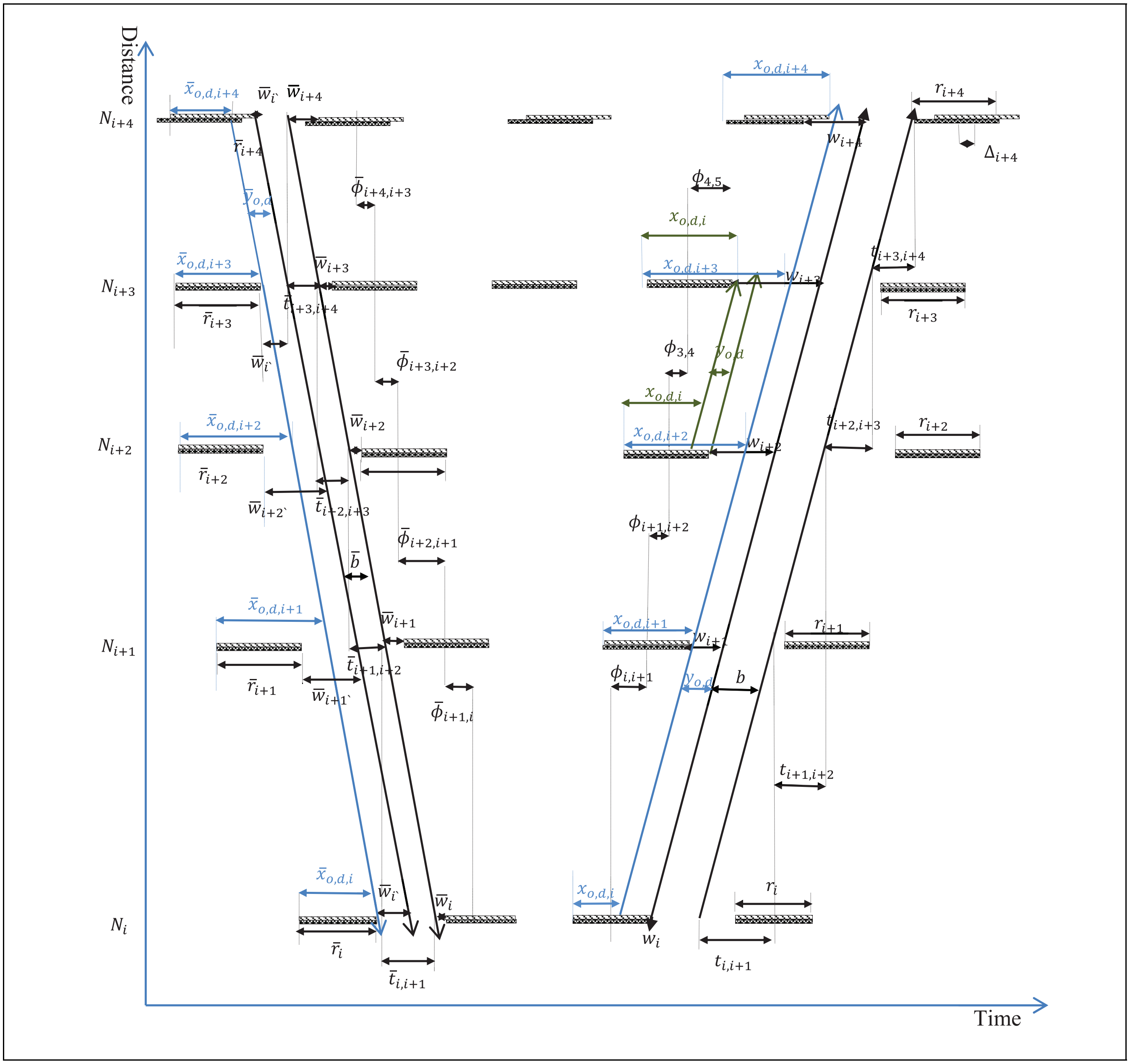


Figure 4. Time–space diagram for OD-BAND model.

bands are generated for additional major OD pairs 3→12, 6→9 (for outbound direction) and 10→1 (for inbound direction). Figure 4 presents a time–space diagram to illustrate formulation of the OD-BAND model.

OD-NETBAND: Network Model

As in the OD-BAND model, separate progression bands for major OD pairs are dedicated in the network model. Different from OD-BAND, network loop constraints are included to ensure all signals in the network are synchronized and operate with a common cycle time. The loop constraints are formulated separately based on the time–space diagrams for traffic movements from east to west and north to south. Previously defined variables are modified and converted into a matrix version for ease of formulation of the network model. As an example, the red times of outbound and inbound through traffic are represented by $r_i(\bar{r}_i)$ in OD-BAND. In OD-NETBAND, these red times are denoted by $r_m[n](\bar{r}_m[n])$, where m indicates column number and n indicates the row number. For instance, $r_2[3]$ is the outbound (N–S) red time for intersection 8 in Figure 3, since it is located

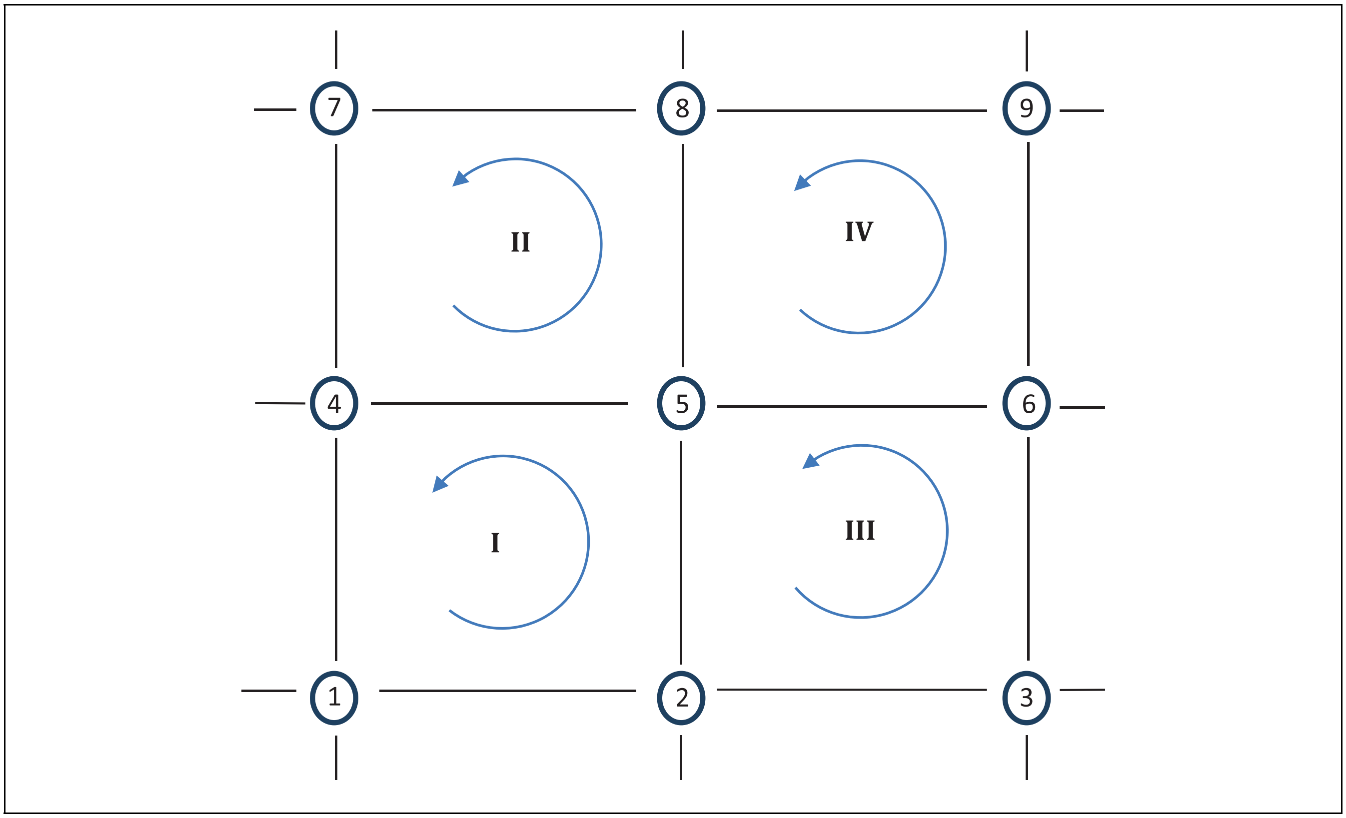


Figure 5. Possible loop constraints for three-by-three grid network.

at the intersection point of the second column and the third row. Similarly, other variables defined in OD-BAND are adopted by adding a notation that indicates column and row numbers with an exception for travel time. In OD-NETBAND, travel times between intersections are represented by $t_{ns}[m, n]$ and $t_{ew}[n, m]$, where "ns" and "ew" indicate north to south and east to west directions, respectively. Additionally, "m" and "n" indicate the column and row numbers, respectively.

Four loop constraints are defined for the three-by-three case study network. Each loop constraint is formulated to connect four intersecting arterials. As shown in Figure 5, Loop constraint I connects intersections 1, 2, 5, and 4; loop constraint II connects intersections 4, 5, 8, and 7; loop constraint III connects 2, 3, 6, and 5, and the last loop constraint (IV) connects intersections 5, 6, 9, and 8. Since any two loop constraints have at least one intersection in common and collectively they cover all intersections, there is no need to define additional loop constraints.

In Figure 6, the movements of traffic flows for both north to south and east to west directions are presented. These time–space diagrams are used to derive the loop constraints for OD-NETBAND. The two sets of time–space diagrams share some common points and they are marked as green stars. These common points provide the continuity needed in developing the loop constraints. Using the beginning of the red time of northbound through traffic as the start point, Loop Constraint I is formulated as follows:

$$\begin{aligned} &R_1[1] + \bar{L}_1[1] + w_1[1] + t_{ns}[1,1] - w_1[2] - \bar{L}_1[2] - R_1[2] \\ &= \bar{L}_{1,1}[1] + w_{1,1}[1] + t_{ew}[1,1] \\ &- w_{2,2}[1] - \bar{L}_{2,2}[1] + R_2[1] + \bar{L}_2[1] + w_2[1] \\ &+ t_{ns}[2,1] - w_2[2] - \bar{L}_2[2] - R_2[2] \\ &+ \bar{L}_{2,2}[2] + w_{2,2}[i+1] - t_{ew}[2,1] - w_{1,1}[2] - \bar{L}_{1,1}[2] \end{aligned} \tag{21}$$

$$r_m[n] = R_m[n] + \bar{L}_m[n] \quad m = 1,2,3; n = 1,2,3 \tag{22}$$

In Figure 6, $r_m[n]$ is calculated using Equation 22. The left side of Equation 21 connects intersections 1 and 4, whereas the right side of the equation connects intersections 1, 2, 5, and 4. Both sides of Equation 21 end at the beginning of through traffic red interval of intersection 4. By making the two sides equal, the four intersections (i.e., 1, 2, 4, and 5) are synchronized. Similarly, other loop constraints (II, III, and IV) are formulated.

Properly setting offsets can significantly improve the network traffic control performance and provide efficient platoon movements through several intersections.

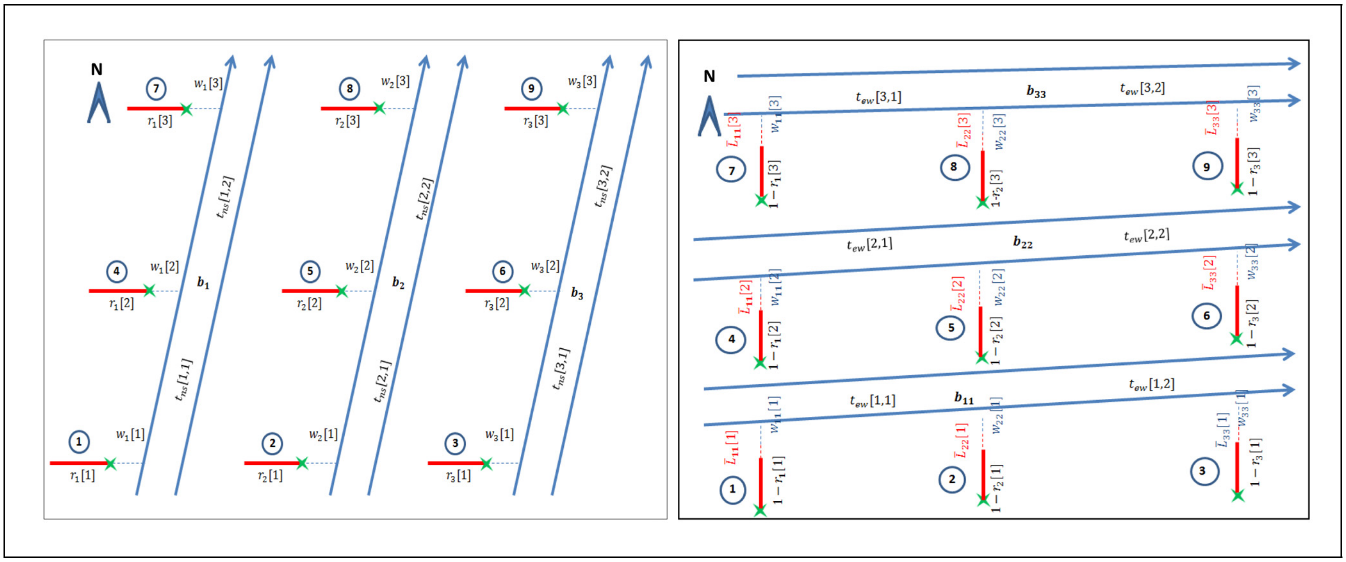


Figure 6. Time–space diagrams of traffic flows along north to south and east to west directions.

Table 2. Summary of Optimal Cycle Lengths and Offsets

Case	Model	Cycle length	Offsets for all nodes								
			1	2	3	4	5	6	7	8	9
I	MAXBAND-86	76	0.0	9.7	30.5	9.7	16.8	55.2	15.2	66.0	57.4
	Synchro	65	0.0	5.0	22.0	10.0	22.0	34.0	38.0	36.0	50.0
	OD-NETBAND	60	0.0	2.1	18.7	15.0	1.5	35.8	18.0	46.0	36.9
II	MAXBAND-86	61	0.0	1.3	30.3	2.3	18.6	32.6	18.6	31.6	39.6
	Synchro	65	0.0	10.0	27.0	21.0	21.0	38.0	38.0	33.0	3.0
	OD-NETBAND	60	0.0	1.3	33.3	13.0	16.3	43.3	24.3	38.3	50.0

The determination of offsets for a closed network is different from those for a single arterial. In a network, the existence of loops requires that adding all offsets along any loop should give the same offset at the beginning intersection. The offsets in OD-NETBAND are derived based on the time–space diagrams shown in Figure 6. The beginning of northbound through red interval of the first intersection is selected as the reference point. Since there are no left turns from any approaches at this intersection, this reference point is fixed for both inbound and outbound traffic movements. As an example, the offset constraint of intersection 5 is derived as follows:

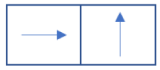
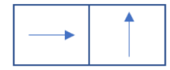
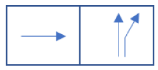
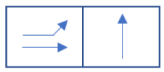
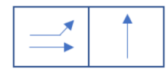
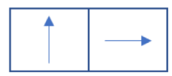
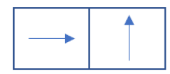
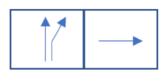
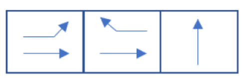
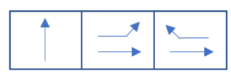
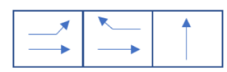
$$\begin{aligned} R_1[1] + \bar{L}_1[1] + w_1[1] + t_{ns}[1,1] - w_1[2] - \bar{L}_1[2] - R_1[2] \\ + \bar{L}_{1,1}[2] + w_{1,1}[2] + t_{e,w}[2,1] \\ - w_{2,2}[2] - \bar{L}_{2,2}[2] = \bar{L}_{1,1}[1] + w_{1,1}[1] + t_{e,w}[1,1] \\ - w_{2,2}[1] - \bar{L}_{2,2}[1] + R_2[1] \\ + \bar{L}_2[1] + w_2[1] + t_{ns}[2,1] - w_2[2] - \bar{L}_2[2] - R_2[2] \end{aligned} \tag{23}$$

The left side of Equation 23 calculates the offset through intersections 1→4→5, while the right side of the equation calculates the offset through intersections 1→2→5. By ensuring that the two sides are equal to each other, we can be confident that the offset of intersection 5 is correctly specified, which is a key requirement in network-wide traffic signal coordination. Similarly, the offset constraints for the remaining intersections are formulated.

Study Design

OD-NETBAND is formulated as a mixed integer linear program. The IBM CPLEX Optimization Studio (*19*) is used to find the optimal control plan (e.g., cycle length, phase sequence, offsets) for the grid network in Figure 1. Additional control plans for the same network are calculated using MAXBAND-86 (*8*) and Synchro (*20*). These control plans are summarized in Tables 2 and 3 and are evaluated using AIMSUN (*21*). Each of these plans is

Table 3. Phase Sequences for Case I and Case II

Case I			
Nodes	MAXBAND-86	Synchro	OD-NETBAND
1,2,3,6,7, and 9			
4 and 8			
5			
Case II			
Nodes	MAXBAND-86	Synchro	OD-NETBAND
1,2,3,6,7, and 9			
4 and 8			
5			

simulated 20 times based on the same set of random seeds and each simulation run represents 60 minutes of traffic operations.

In addition to the data provided in Figure 1 and Table 1, four seconds of loss time are considered in the AIMSUN simulation, including 3 seconds of yellow and 1 second of all red intervals. Speed limits on all road segments are set to 34 mph (about 55 kilometers per hour) and default turning speeds in AIMSUN are used. The saturation flow rate is set as 1,900 vehicles/hour green time/lane. Two through lanes and additional exclusive lane(s) are coded for each approach.

Evaluation Results

The performance of OD-NETBAND is compared with the performance of Synchro and MAXBAND-86 for the same grid network and traffic demand. Two case studies with different traffic flow patterns and lane configurations are considered. In Case I, in addition to through traffic along arterials, an additional OD stream (OD1) is included with one turning lane. In Case II, two additional OD streams (OD1 and OD2) are considered with two turning lanes (one for each OD). For both cases, fixed paths are assumed for the two major ODs and the paths are selected based on the shortest free flow travel times.

The simulation results are analyzed in terms of overall network performance, through traffic performance and major OD performance. Delay time, speed, stop time, and travel time are selected as measures of effectiveness (MOEs) for model comparison. Delay time is defined as the average delay time in seconds per vehicle mile, which represents the time difference between the expected and the actual travel time; speed is calculated as the average journey speed of each vehicle that has left the system within simulation duration, in miles per hour; stop time is described as the average time that is spent by vehicles at stand still position per vehicle mile, and travel time is represented in hours as the sum of all travel times experienced by vehicles that have exited the network within simulation duration.

Case I Result

Case I considers one major OD (i.e., OD1) with 800 vehicles per hour from node 1-1 to 3-3 (Figure 7), in addition to the through traffic along six arterials (500 vehicles/hour). Table 4 shows the performance of control plans generated by MAXBAND-86, Synchro, and OD-NETBAND. It can be seen that the latter generates the lowest overall network and major path (OD1) delays.

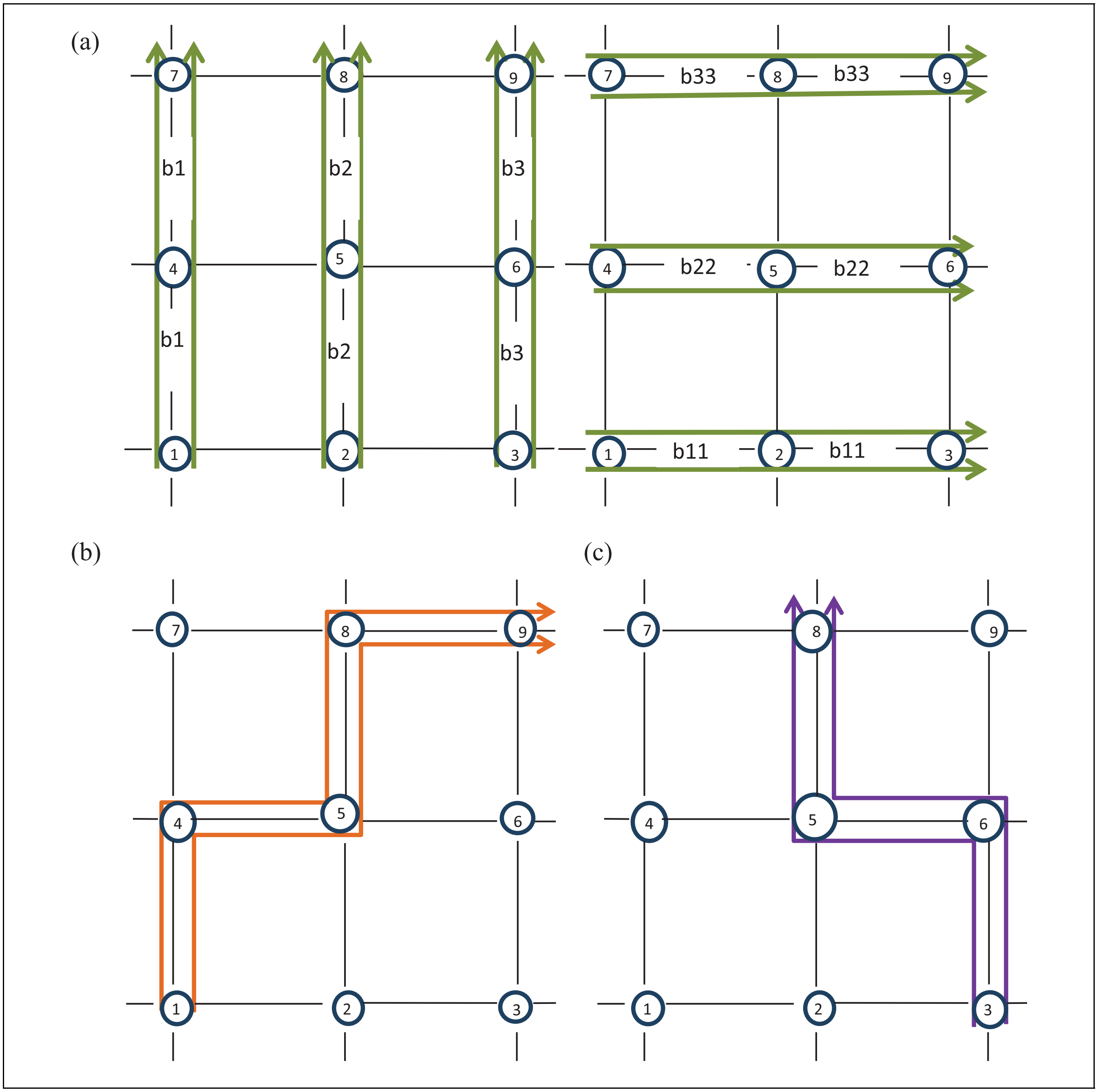


Figure 7. Illustration of continuous uniform progression bands created by OD-NETBAND: (*a*) bands created for through traffic; (*b*) bands for OD1; (*c*) bands for OD2.

Additionally, in terms of almost all remaining MOEs, OD-NETBAND performs the best. Its control plan generates the lowest stop time, travel time, and delay with the highest travel speed.

The three network signal coordination models are also compared in terms of progression bandwidths. Since MAXBAND-86 and Synchro cannot create separate progression bands for specific major ODs, their progression bands for through traffic streams are illustrated in Figure 7*a*. For OD-NETBAND, in addition to through progression bands, a dedicated progression band OD1 is also presented in Figure 7*b*.

In Table 5, progression bandwidths of the three models are compared in terms of bandwidth to cycle ratio. It can be seen that OD-NETBAND generates dedicated progression bands for each traffic stream, while Synchro and MAXBAND-86 generate progression bands just for through traffic along the arterials and fail to create a

Table 4. Performance Results for Cases I and II

	MAXBAND-86		Synchro		OD-NETBAND		
	Mean	SD	Mean	SD	Mean	SD	Units
Case I Results							
Delay							
Overall network	69.92	0.38	53.67	0.17	51.30	0.19	sec/mile
Through traffic	70.15	0.46	48.45	0.22	49.80	0.22	
OD 1	69.06	0.57	73.68	0.40	56.99	0.42	
Speed							
Overall network	21.85	0.06	23.70	0.03	23.81	0.03	mph
Through traffic	22.19	0.07	24.66	0.04	24.30	0.04	
OD 1	20.56	0.07	20.01	0.04	21.95	0.05	
Stop time							
Overall network	53.53	0.33	39.51	0.14	36.02	0.15	sec/mile
Through traffic	56.01	0.40	38.30	0.19	37.89	0.17	
OD 1	44.10	0.46	44.16	0.28	28.89	0.31	
Travel time							
Overall network	176.34	0.44	160.08	0.19	157.71	0.21	hour
Through traffic	175.99	0.50	154.28	0.25	155.63	0.23	
OD 1	177.67	0.58	182.30	0.35	165.60	0.34	
Case II Results							
Delay							
Overall network	68.55	2.77	60.18	0.29	57.00	0.45	sec/mile
Through traffic	55.00	1.29	52.52	0.34	49.40	0.28	
OD 1 + OD 2	94.16	7.07	74.79	0.77	71.48	1.09	
Speed							
Overall network	21.88	0.22	22.65	0.04	23.04	0.06	mph
Through traffic	23.73	0.13	24.03	0.06	24.37	0.05	
OD 1 + OD 2	18.37	0.52	20.01	0.08	20.50	0.14	
Stop time							
Overall network	50.43	2.25	42.73	0.22	39.16	0.40	sec/mile
Through traffic	41.88	1.03	38.97	0.30	36.23	0.25	
OD 1 + OD 2	66.59	5.89	49.89	0.58	44.76	0.99	
Travel time							
Overall network	175.19	2.77	166.78	0.28	163.62	0.49	hour
Through traffic	160.90	1.30	158.40	0.38	155.28	0.33	
OD 1 + OD 2	202.20	7.08	182.77	0.73	179.51	1.16	

Table 5. Progression Bandwidths for Cases I and II (Cycles)

	b1	b11	b2	b22	b3	b33	OD1	OD2	Total band
Case I									
OD-NETBAND	0.25	0.31	0.27	0.27	0.23	0.21	0.44	-	1.98
MAXBAND-86	0.50	0.30	0.22	0.22	0.30	0.00	-	-	1.54
Synchro	0.49	0.26	0.26	0.22	0.31	0.22	-	-	1.76
Case II									
OD-NETBAND	0.47	0.31	0.21	0.40	0.26	0.31	0.13	0.34	2.43
MAXBAND-86	0.50	0.31	0.20	0.34	0.31	0.31	-	-	1.97
Synchro	0.48	0.31	0.22	0.25	0.34	0.22	-	-	1.82

progression band for OD1. Such a failure may contribute to the higher overall network delays for Synchro and MAXBAND-86 in Table 4.

Case II Result

Case II considers two major ODs (OD1 and OD2) with 800 vehicles per hour from node 1-1 to 3-3 and from node 3-1 to 2-3, in addition to the through traffic along arterials (500 vehicles/hour). The performance of the proposed model is compared with the performance of MAXBAND-86 and Synchro in Table 4. Consistent with the Case I results, OD-NETBAND generates the lowest overall network and major path (OD1 + OD2) delays. The new model performs the best in terms of all selected MOEs. The result confirms the advantages of the new model's unique ability to generate separate progression bands for major OD flows. It also suggests the importance of considering vehicular OD data instead of individual intersection turning movement count data as Synchro and MAXBAND-86 do.

To compare the three models further, the progression bandwidths of each traffic stream are presented in Table 5. The result again indicates that OD-NETBAND is able to generate balanced progression bands for each traffic stream compared with MAXBAND-86 and Synchro.

Conclusions and Discussion

This research develops a network-wide progression bandwidth optimization model OD-NETBAND, which utilizes vehicular origin–destination (OD) information as the model input. Previous network-wide progression bandwidth optimization methods are only able to optimize progression bands along single arterials by considering individual intersection traffic counts and ignore the important information contained in major traffic OD flows. Ignoring OD information may lead to unnecessary wait time and increase the overall network delay, especially when there are major OD flows starting from one arterial and traversing to other arterials. This study aims to fill this knowledge gap by developing a network-wise OD based progression bandwidth optimization method that allocates dedicated progression bands for each major OD pair.

The proposed new model is formulated as a mixed integer linear program and solved by IBM CPLEX Optimization Studio. The performance of the proposed model is then compared with optimum control plans generated by MAXBAND-86 and Synchro using AIMSUN microscopic simulation. Two case studies are conducted with different traffic demand patterns and lane configurations. The results of both case studies are analyzed and compared based on delay, stop time, speed, travel time, and progression bandwidth. In terms of all selected MOEs, OD-NETBAND is found to be very effective when the traffic volumes of some cross-street OD streams are significant. This demonstrates the importance of allocating dedicated progression bands to major OD streams within a network.

Note that MAXBAND-86 has the worst overall performance in both cases but Synchro has the smallest bandwidths in Case II. A possible explanation is that there is not a straightforward and linear relationship between progression bandwidth and delay. However, we have seen, in general, that maximizing bandwidth improves MOEs such as delay and travel speed. Also, MAXBAND maximizes progression bandwidths without considering the corresponding traffic demands. Some of the progression bands may not be effectively utilized due to low demand. On the other hand, Synchro takes delay minimization into consideration while maximizing progression bandwidths. This is why in some cases it is difficult for bandwidth maximization models to outperform Synchro in terms of delay, though significantly improving stop time and the smoothness of the OD traffic flows.

This research considers a three-by-three network and represents an initial attempt to develop a formulation for more general networks in the future. General networks would require additional considerations depending on the major OD flows to be modeled and optimized. The loop constraints, specifically, can be derived automatically for a general network using graph-theoretic concepts (see [*7*, *22*]). The proposed OD-NETBAND is well suited to address the forthcoming introduction of connected and autonomous vehicles, which will provide the opportunity of obtaining accurate and detailed OD information for signal coordination and for integrated route guidance and progression band optimization.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Nathan H. Gartner, Tugba Arsava, Yuanchang Xie; data collection: Tugba Arsava; analysis and interpretation of results: Tugba Arsava, Nathan H. Gartner, Yuanchang Xie; draft manuscript preparation: Tugba Arsava, Nathan H. Gartner, Yuanchang Xie. All authors reviewed the results and approved the final version of the manuscript.

References

1. Yang, X. K. Comparison among Computer Packages in Providing Timing Plans for Iowa Arterial in Lawrence. *Journal of Transportation Engineering*, Vol. 127, No. 4, 2001, pp. 311–318.
2. Little, J. D. The Synchronization of Traffic Signals by Mixed-Integer Linear Programming. *Operations Research*, Vol. 14, No. 4, 1966, pp. 568–594.
3. Little, J. D. C., M. D. Kelson, and N. H. Gartner. MAXBAND: A Program for Setting Signals on Arterials and Triangular Networks. *Transportation Research Record: Journal of the Transportation Research Board*, 1981. 795: 40–46.
4. Gartner, N. H., S. F. Assmann, F. Lasaga, and D. L. Hou. MULTIBAND—A Variable-Bandwidth Arterial Progression Scheme. *Transportation Research Record: Journal of the Transportation Research Board*, 1990. 1287: 212–222.
5. Gartner, N. H., S. F. Assmann, F. L. Lasaga, and D. L. Hou. A Multi-Band Approach to Arterial Traffic Signal Optimization. *Transportation Research Part B: Methodological*, Vol. 25, No. 1, 1991, pp. 55–74.
6. Zhang, C., Y. Xie, N. H. Gartner, C. Stamatiadis, and T. Arsava. AM-Band: An Asymmetrical Multi-Band Model

for Arterial Signal Coordination. *Transportation Research Part C: Emerging Technologies*, Vol. 58, 2015, pp. 515–531.
7. Gartner, N. Constraining Relations among Offsets in Synchronized Signal Networks. *Transportation Science*, Vol. 6, No. 1, 1972, pp. 88–93.
8. Chang, E. C. P., S. L. Cohen, C. Liu, N. A. Chaudhary, and C. Messer. MAXBAND-86: Program for Optimizing Left-Turn Phase Sequence in Multi-Arterial Closed Networks. *Transportation Research Record: Journal of the Transportation Research Board*, 1988. 1181: 61–67.
9. Chaudhary, N. A., and C. J. Messer. PASSER-IV: A Program for Optimizing Signal Timing in Grid Networks. *Transportation Research Record: Journal of the Transportation Research Board*, 1993. 1421: 82–93.
10. Stamatiadis, C., and N. H. Gartner. MULTIBAND-96: A Program for Variable Bandwidth Progression Optimization in Multi-Arterial Traffic Networks. *Transportation Research Record: Journal of the Transportation Research Board*, 1996. 1554: 9–17.
11. Gartner, N. H., and C. Stamatiadis. Arterial-Based Control of Traffic Flow in Urban Grid Networks. *Mathematical and Computer Modeling*, Vol. 35, No. 5–6, 2002, pp. 657–671.
12. Gartner, N. H., and C. Stamatiadis. Progression Optimization in Large Scale Urban Traffic Networks: A Heuristic Decomposition Approach, Transportation and Traffic Theory. In A. Ceder (ed.), Proc.,14th International Symposium on Transportation and Traffic Theory, Pergamon, New York, NY, 1999, pp. 645–661.
13. Gartner, N. H., and C. Stamatiadis. Progression Optimization Featuring Arterial- and Route-Based Priority Signal Networks. *Journal of Intelligent Transportation Systems*, Vol. 8, No. 2, 2004, pp. 77–86.
14. Tian, Z. Z., M. Varun, and H. C. Liu. Effectiveness of Lead-Lag Phasing on Progression Bandwidth. *Transportation Research Record: Journal of the Transportation Research Board*, 2008. 2080: 22–27.
15. Park, B., C. J. Messer, and T. Urbanik. Traffic Signal Optimization Program for Oversaturated Conditions: Genetic Algorithm Approach. *Transportation Research Record: Journal of the Transportation Research Board*, 1999. 1683: 133–142.
16. Gomes, G. Bandwidth Maximization Using Vehicle Arrival Functions. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 16, No. 4, 2015, pp. 1977–1988.
17. Arsava, T., Y. Xie, N. H. Gartner, and J. Mwakalonge. Arterial Traffic Signal Coordination Utilizing Vehicular Traffic Origin-Destination Information. Proc., 17th International IEEE Conference on Intelligent Transportation Systems (ITSC), Qingdao, China, IEEE, New York, NY, 2014, pp. 2132–2137.
18. Arsava, T., Y. Xie, and N. H. Gartner. Arterial Progression Optimization Using OD-BAND: Case Study and Extensions. *Transportation Research Record: Journal of the Transportation Research Board*, 2016. 2558: 1–10.
19. *IBM ILOG CPLEX Optimization Studio*. https://www.ibm.com/us-en/marketplace/ibm-ilog-cplex/. Accessed July 30, 2017.
20. Trafficware Synchro 6. http://trafficware.infopop.cc/synchro.htm. Accessed July 30, 2017.
21. *TSS-Transport Simulation Systems*. AIMSUN 8. https://www.aimsun.com/aimsun/editions/. Accessed July 30, 2017.
22. Chang, E. C.-P., S. L. Cohen, C. Liu, N. A. Chaudhary, and C. Messer. MAXBAND-86: Program for Optimizing Left-Turn Phase Sequence in Multiarterial Closed Networks. *Transportation Research Record: Journal of the Transportation Research Board*, 1988. 1181: 61–67.

The Standing Committee on Traffic Signal Systems (AHB25) peer-reviewed this paper (18-05652).