Arterial Progression Optimization Using OD-BAND

Case Study and Extensions

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OD-BAND is a progression optimization model that can provide dedicated progression bands for major origin–destination (O-D) flows in an arterial network. The model is an extension of the well-known MAXBAND model and is solved by advanced mathematical programming optimization software. In this paper, the original OD-BAND model is extended in a number of important ways: (*a*) the mathematical formulation is generalized to model all possible O-D flows in an arterial; (*b*) phase sequence optimization is included for all intersections along the arterial; and (*c*) the bandwidths are weighted by the number of street segments that they traverse and their traffic volumes. It is shown that this formulation can provide suitable progression bands for all major O-D flows, including both through bands and cross bands. Simulation results demonstrated that OD-BAND compared favorably with existing arterial traffic signal coordination models MAXBAND and MULTIBAND and could be used as a valuable tool in signal control software. In particular, this approach is most suitable for integrated traffic signal coordination and route guidance in an environment of connected vehicles in which connected vehicles and crowd-sourced data can be used to derive detailed and accurate O-D information. Progression bands can then be established for each major O-D flow, and route guidance can be provided to vehicles to travel within those bands with minimum delay and fuel consumption.

Traffic signal coordination plays an important role in the smooth and effective operation of arterial systems. Coordination can be provided with a common cycle length and appropriate offsets such that a platoon of vehicles can travel along the entire arterial without stopping. Compared with uncoordinated traffic signal control plans, an optimal coordinated control plan typically provides a higher level of traffic service that results in more uniform traffic flows, higher average travel speeds, fewer accidents, and less red light violations. An initial formulation of a progression optimization model based on origin–destination (O-D) was presented in a study by Arsava et al. (*1*). This paper provides a general formulation of the O-D model with extensions and presents a case study that compares its performance with other well-known signal optimization models.

Numerous studies have been conducted to investigate the most appropriate traffic signal timing coordination method that provides uninterrupted flow along arterials. Morgan and Little first proposed an arterial progression bandwidth optimization model using a search algorithm (*2*). Later on, Little developed a mixed-integer linear programming formulation for the problem (*3*). Little et al. developed this formulation into a computer program, which is now widely known as MAXBAND (*4*). In the MAXBAND model, progression bandwidth along an arterial is maximized by adjusting phase sequence, cycle time, and offsets. Bandwidth optimization is done independently from the actual section traffic volumes in each direction of travel. Such uniform bandwidths (inbound and outbound) may not provide optimal control because of an imbalance between demand and supply. In addition, the model does not account for traffic turning in and turning out at each intersection. This feature may adversely affect overall arterial control performance.

The MAXBAND model was later extended by Gartner et al. into MULTIBAND (*5, 6*). MULTIBAND is able to generate progression bands along the arterial direction by taking account of the individual sections' traffic characteristics, such as traffic flow, capacity, and speed limit. Different from MAXBAND, the MULTIBAND model is able to create variable and symmetrical bandwidths with respect to the progression line along the arterial. It was shown that the MULTIBAND model can be very effective in improving arterial performance by providing a better match between demand and supply. As a further improvement of MULTIBAND, Zhang et al. developed the AM-BAND model by relaxing the symmetrical progression band requirement in MULTIBAND (*7*). This flexibility allows the AM-BAND model to better utilize the available green times in each progression direction.

Several other traffic signal coordination methods have also been developed. Chang et al. formulated the MAXBAND-86 program for optimizing left-turn phase sequence in multiarterial closed networks (*8*). Stamatiadis and Gartner formulated MULTIBAND-96, which is a network version of the MULTIBAND model (*9*). Lin et al. developed a mixed-integer nonlinear programming model for arterial traffic signal coordination (*10*). This nonlinear model is an enhanced version of the maximum progression bandwidth algorithm proposed by Tsay and Lin (*11*). Other researchers focused on arterial signal coordination problems such as lead–lag phasing sequence optimization (*12*) and signal coordination under oversaturated traffic conditions (*13*).

The aforementioned models consider turning movement traffic counts from individual intersections as the model input. They do not take into account the origins and destinations of those vehicles. It can be shown that the same turning movement traffic count pattern may correspond to different O-D flow patterns. Ignoring such O-D information in arterial traffic signal coordination is likely to lead to suboptimal control performance. In some related studies, a concept of signal timing with vehicle routing was proposed by Gazis (*14*)

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and Gazis and Potts (*15*); however, the use of vehicular O-D data was not considered. The first notion of using O-D data for traffic signal control was found in work by Gartner and Stamatiadis (*16*). Recently, Arsava et al. (*1*) formulated an OD-BAND model for a specific arterial with three intersections. In that model, major O-D flows, instead of turning movement counts, were considered individually, and a separate progression band was created for each of them. Different from all previous arterial traffic signal coordination methods, this OD-BAND approach creates progression bands that are not necessarily along the arterial. The bands can also correspond to major O-D flows that enter the arterial from one side street and exit it from another.

The main contribution of this study is to improve and generalize the original OD-BAND model proposed by Arsava et al. (*1*). The mathematical formulation is generalized to model all possible O-D flows of an arterial; phase sequence optimization is considered; and the objective function is revised, in which bandwidths are weighted by the number of street segments they traverse and by their traffic volumes.

PROBLEM DESCRIPTION

In the original OD-BAND model, the objective was to maximize the sum of all progression bandwidths weighted by the traffic volume to saturation flow ratio corresponding to each O-D flow. Through bands, which traverse the entire arterial, travel through the same number of road sections. However, cross bands, which enter the arterial at one intersection and exit it at another, travel through a different number of road sections. Maximizing such a weighted sum of progression bandwidths may not provide the most efficient control solution. It is advantageous to identify major O-D flows that traverse more sections and allocate their progression bands a higher priority. Therefore, weights in the objective function of the original OD-BAND model were modified by considering the number of sections that a progression band has to traverse. In this way, a progression band (for a major O-D pair) that traverses more sections is assigned a higher weight than O-D progression bands that traverse fewer sections. Such a weighting strategy is expected to further improve the performance of the OD-BAND model, especially when there are major O-D flows that travel through a different number of intersections.

To illustrate the extensions to the original OD-BAND formulation, a case study was conducted. An arterial network with five intersections, as shown in Figure 1, was considered for the case study. This network has 12 O-D nodes (numbered from 1 to 12 in Figure 1) and 17 O-D traffic streams, as shown in Table 1. Seven of these O-D streams are considered major, and progression bands were allocated for them. These major O-D pairs are shown in Figure 2 and listed in

TABLE 1 O-D Matrix for Case Study Network

Origin	Destination	Demand (vph)
2	3	100
3	2	400
4	5	100
5	4	250
6	7	50
7	6	100
8	9	200
9	8	200
10	11	100
11	10	100
1	11[a]	400
3	12[a]	350
5	10[a]	250
7	8[a]	250
10	1[b]	350
12	1[b]	400
8	5[b]	250
Total demand		3,850

NOTE: vph = vehicles per hour.
[a]Major outbound O-D pair.
[b]Major inbound O-D pair.

Table 1. The characterization of major is based on volume of traffic and the significant portion of the arterial that is used. (Several O-D flows simply cross the arterial without using any portion of it.).

In the following section, the extended OD-BAND model is formulated with a revised objective function. Several additional decision variables are introduced for optimizing the sequence of left-turn phases. All intersections are assumed to be controlled by a pretimed strategy. The green time distribution between the movements is calculated on the basis of their ratios of traffic volume to saturation flow.

METHODOLOGY

To facilitate the introduction of the proposed extensions, a time–space diagram for the case study network is presented in Figure 3. This time–space diagram illustrates the relationships between the variables and the progression bands for major O-D streams (see Figure 2). Before the

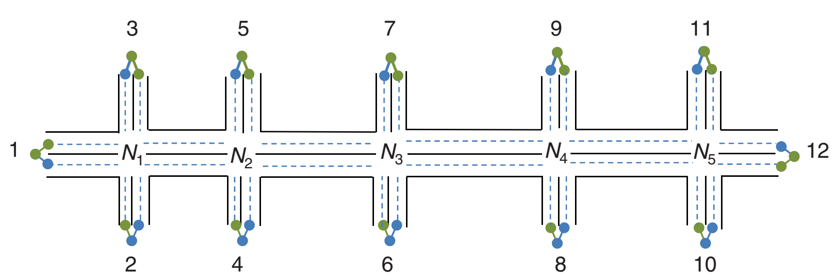


FIGURE 1 Case study network (*N* = intersection number).

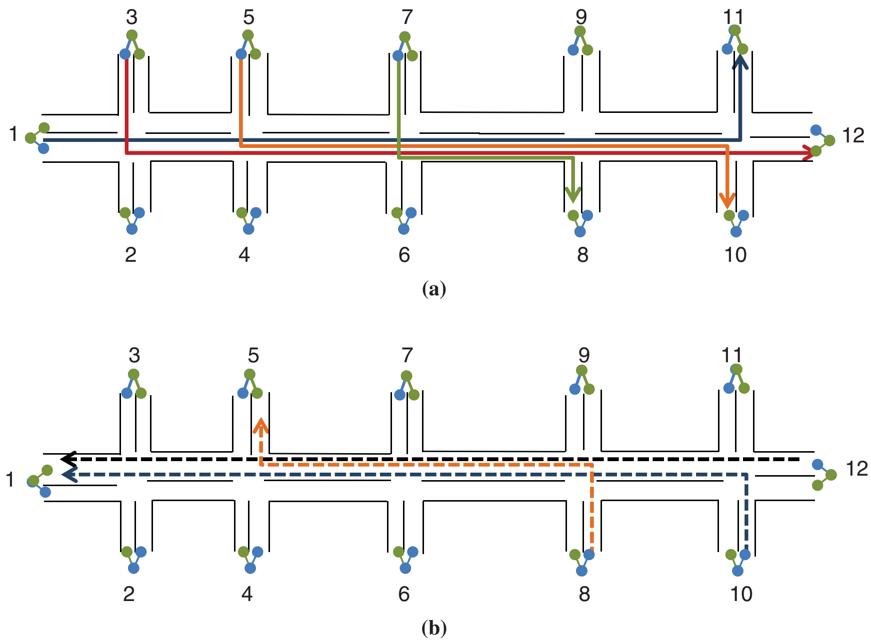


FIGURE 2 Major O-D streams: (*a*) outbound flow pattern and (*b*) inbound flow pattern.

extended OD-BAND model is introduced, the following variables are defined. Some of these variables also appear in Figure 3.

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 O-D pair;
$a_{(o,d)}(i)(\bar{a}_{(o,d)}(i))$ = 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);
$x_{N_s N_e i}(\bar{x}_{N_s N_e i})$ = 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 corresponding progression band information (first, last, current intersection, respectively);
$z = 1/C$ = signal frequency (cycles per second);
k = ratios of inbound volume to outbound volume of arterial progression band;
$k_{o,d}(j)(\bar{k}_{o,d}(j))$ = ratios of outbound (inbound) traffic volume turned into main street from side street to outbound (inbound) arterial through traffic volume;
$\phi_{i,i+1}(\bar{\phi}_{i,i+1})$ = internode offsets (cycles) at intersection N_i (cycles);
Δ_i = internode offset, time difference between center of r_i and nearest center of $\bar{r}_i$ at intersection N_i (cycles);
δ_i, $(\bar{\delta}_i)$ = 0/1 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);
$d_{i,i+1}(\bar{d}_{i,i+1})$ = distance between N_i and N_{i+1} outbound (inbound) (ft);
$G_i(\bar{G}_i)$ = outbound (inbound) green time for through traffic at S_i (cycles);
$e_i, f_i(\bar{e}_i, \bar{f}_i)$ = lower or upper limits on outbound (inbound) speed (ft/s) at section i;
g_i, $h_i(\bar{g}_i, \bar{h}_i)$ = lower or upper limits on change in outbound (inbound) speed (ft/s) at section i;
$V(\bar{V})$ = outbound (inbound) arterial through volume;
$V_{(o,d)}(\bar{V}_{(o,d)})$ = outbound (inbound) traffic volume of specific O-D pair;
$S(\bar{S})$ = outbound (inbound) saturation flow rate;
$S_{(o,d)}(\bar{S}_{(o,d)})$ = outbound (inbound) saturation flow of specific O-D pair;
n = total number of intersections;
$N_s(N_e)$ = intersection number at which progression band started (ended);

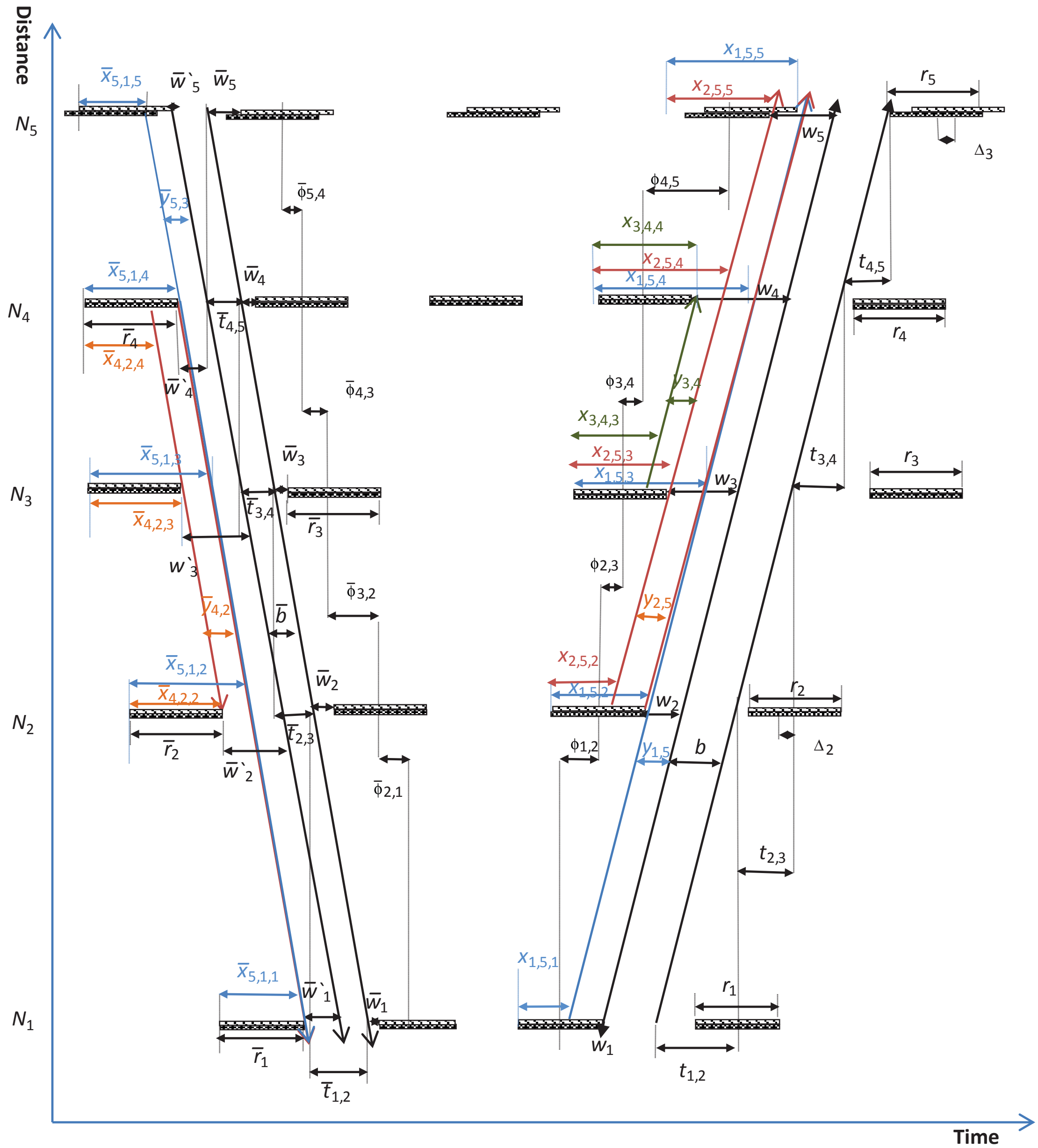


FIGURE 3 Time–space diagram of case study network.

i = index variable representing intersection number and corresponding downstream (upstream) section for outbound (inbound) traffic;
j = index variable representing the note for specific O-D pair; and
p = number of O-D pairs for which dedicated bands are sought.

The authors distinguish between through bands that traverse the entire arterial and cross bands that join and leave the arterial at intermediate intersections. The variables $y_{N_s,N_e}(\bar{y}_{N_s,N_e})$ represent the width of the progression bands created for outbound (inbound) major O-D pairs that join the arterial from side streets. (Therefore, they are termed cross bands.) N_s and N_e in y_{N_s,N_e} indicate the first and the last intersection numbers at which a cross band starts and ends, respectively. $V_{(\text{od})}(\bar{V}_{(\text{od})})$ and $S_{(\text{od})}(\bar{S}_{(\text{od})})$ are the traffic flow and saturation flow rates, respectively, of an outbound (inbound) major O-D pair. The subscripts indicate the origin and destination node numbers. For all major O-D pairs with a side street origin in Figure 2, a lag left turn is considered when they first join the arterial. Thus, the progression bands corresponding to these O-D pairs all start in the middle of a red interval along the arterial direction. Phase sequence optimization is considered for all left turns along the arterial direction through additional constraints and the variables Δ_i, L_i, R_i, and δ_i. In the objective function of the new model, progression bands are weighted by the ratios of traffic volume to saturation flow for all sections they traverse. The following decision variables are considered to maximize the objective function in Equation 1: 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}, $\bar{y}_{N_s,N_e}$, δ_i, $\bar{\delta}_i$.

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

Part "a*" is for O-D pairs that travel along the outbound direction, and part "b*" is for O-D pairs that travel along the inbound direction.

where

$$a_i = \frac{V_i}{S_i}$$

$$\overline{a}_i = \frac{\overline{V}_i}{\overline{S}_i}$$

$$a_{\text{od}}(i) = \frac{V_{o,d}}{S_{o,d}}$$

$$\overline{a}_{\text{od}}(i) = \frac{\overline{V}_{o,d}}{\overline{S}_{o,d}} \tag{2}$$

subject to Constraints 3 through 20:

$$\frac{1}{C_2} \le z \le \frac{1}{C_1} \tag{3}$$

$$(1-k) * \overline{b} \ge (1-k) * k * b \tag{4}$$

$$(1-k_{\text{od}}(j)) * y_{N_s,N_e} \ge (1-k_{\text{od}}(j)) * k_{\text{od}}(j) * b \quad \text{where } j = \begin{cases} \text{for} & \text{O-D} \\ 1 & (3,12) \\ 2 & (5,10) \\ 3 & (7,8) \end{cases} \tag{5}$$

$$(1-\overline{k}_{\text{od}}(j)) * \overline{y}_{N_s,N_e} \ge (1-\overline{k}_{\text{od}}(j)) * \overline{k}_{\text{od}}(j) * \overline{b} \quad \text{where } j = \begin{cases} \text{for} & \text{O-D} \\ 1 & (8,5) \\ 2 & (10,1) \end{cases} \tag{6}$$

$$\begin{cases} w_i + b \le 1 - r_i \\ \overline{w}_i + \overline{b} \le 1 - \overline{r}_i \\ \overline{w}_i\grave{} + \overline{b} \le 1 - \overline{r}_i \end{cases} \quad i = 1, \ldots, n \tag{7}$$

$$\begin{cases} \left(\dfrac{d_i}{f_i}\right) z \le t_i \le \left(\dfrac{d_i}{e_i}\right) z \\ \left(\dfrac{\overline{d}_i}{\overline{f}_i}\right) z \le \overline{t}_i \le \left(\dfrac{\overline{d}_i}{\overline{e}_i}\right) z \end{cases} \quad i = 1, \ldots, n-1 \tag{8}$$

$$\begin{cases} \left(\dfrac{d_i}{h_i}\right) z \le \left(\dfrac{d_i}{d_{i+1}}\right) t_{i+1} - t_i \le \left(\dfrac{d_i}{g_i}\right) z \\ \left(\dfrac{\overline{d}_i}{\overline{h}_i}\right) z \le \left(\dfrac{\overline{d}_i}{\overline{d}_{i+1}}\right) \overline{t}_{i+1} - \overline{t}_i \le \left(\dfrac{\overline{d}_i}{\overline{g}_i}\right) z \end{cases} \quad i = 1, \ldots, n-2 \tag{9}$$

$$(w_i + \overline{w}_i) - (w_{i+1} + \overline{w}_{i+1}) + (t_i + \overline{t}_i) + \delta_i L_i - \overline{\delta}_i \overline{L}_i - \delta_{i+1} L_{i+1} + \overline{\delta}_{i+1} \overline{L}_{i+1} - m_i = (r_{i+1} - r_i) \quad i = 1, \ldots, n-1 \tag{10}$$

$$\overline{w}_i\grave{} + \overline{b} + \overline{w}_i = 1 - \overline{r}_i \quad i = 1, \ldots, n \tag{11}$$

$$\overline{r}_i - \overline{r}_{i+1} + \overline{w}_i\grave{} - \overline{w}_{i+1}\grave{} = w_{i+1} - w_i \quad i = 1, \ldots, n-1 \tag{12}$$

$$x_{N_s,N_e,i} \ge r_i \quad i = N_s + 1, \ldots, N_e \tag{13}$$

$$\overline{x}_{N_s,N_e,i} \ge \overline{r}_{\text{i}} \quad i = N_s - 1, \ldots, N_e \tag{14}$$

$$\begin{cases} y_{N_s,N_e} + x_{N_s,N_e,i} \le r_i \\ \overline{x}_{N_s,N_e,i} + \overline{y}_{N_s,N_e} \le \overline{r}_i \end{cases} \quad i = N_s \tag{15}$$

$$x_{N_s,N_e,i} - x_{N_s,N_e,i+1} = w_i - w_{i+1} - r_{i+1} + r_i \quad i = N_s, \ldots, N_e - 1 \tag{16}$$

$$\overline{x}_{N_s,N_e,i+1} - \overline{x}_{N_s,N_e,i} = \overline{w}_{i+1}\grave{} - \overline{w}_i\grave{} + \overline{r}_{i+1} - \overline{r}_i \quad i = N_e, \ldots, N_s - 1 \tag{17}$$

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

$$\sum \overline{y}_{N_s,N_e} + \overline{b} \le 1 - \overline{r}_i \quad i = \min(N_s) - 1, \ldots, \max(N_e) \tag{19}$$

$$b, \overline{b}, z, w_i, \overline{w}_i, \overline{w}_i\grave{}, t_i\ \overline{t}_i, x_{N_s,N_e,i}, \overline{x}_{N_s,N_e,i}, y_{N_s,N_e}, \overline{y}_{N_s,N_e}, \delta_i, \overline{\delta}_i \ge 0 \quad i = 1, \ldots, n \tag{20}$$

The optimization objective is to maximize a weighted sum of the progression bands. For each progression band, its weight is calculated as the sum of O-D flow to saturation flow ratios of all sections along its path. The objective function is divided into two parts: the first maximizes through bandwidths and the second maximizes cross bandwidths. In Constraint 2, $a_i(\overline{a}_i)$ and $a_{\text{od}}(\overline{a}_{\text{od}})$ are the section-weighted coefficients for outbound (inbound) through bands and cross bands, respectively. Constraint 3 defines the upper and lower limits for the cycle time along a particular path. Constraints 4, 5, and 6 provide a wider band for the O-D traffic with a higher volume. Constraints 7 and 11 ensure that all through bands are within the available green time. Constraint 8 defines the upper and lower limits of travel speed. Constraint 9 restricts the speed changes to ensure these changes are limited. Constraint 10 is the loop integer constraint that guarantees the synchronization of the traffic signals along the arterial, and Constraint 12 defines the relationship between the left (right) boundary of a through band with respect to the end of previous (beginning of next) red interval along the inbound direction. Compared with the original OD-BAND model formulation, Constraint 10 is extended with additional decision variables (Δ_i, L_i, R_i, and δ_i) to optimize the sequence of left-turn phases along the arterial direction. Four possible left-turn phases are considered and are presented in Figure 4. All left turns in this study are protected only. Possible sequences of left-turn phases, similar

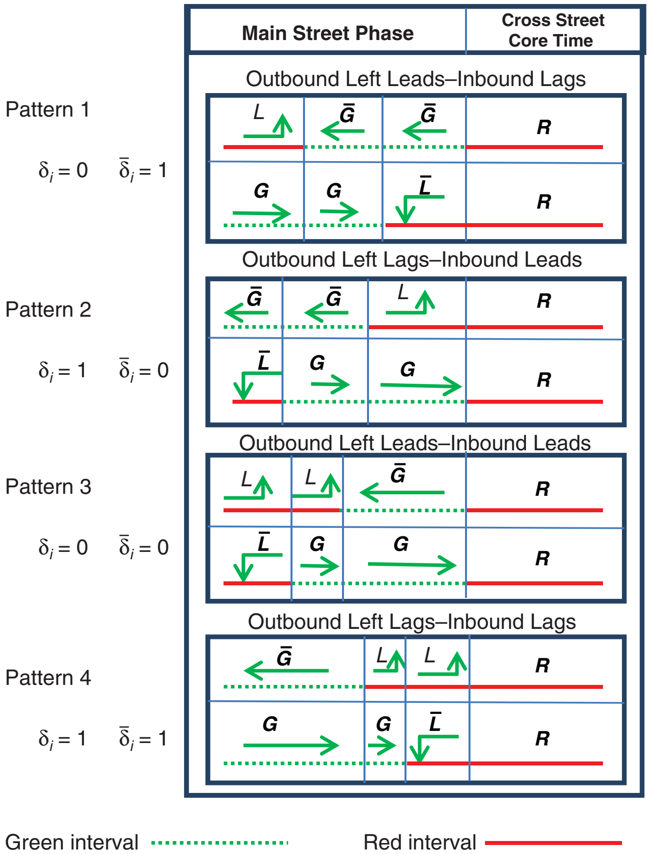


FIGURE 4 Possible left-turn patterns [$G(\bar{G})$ = green time for outbound (inbound) through traffic; R = common (core) red time for through traffic movement along arterial direction].

to MAXBAND, are described in Equation 21. This extension to the original OD-BAND model allows one to select the most appropriate left-turn phasing scheme to maximize the weighted total progression bandwidth.

$$\Delta_i = \frac{1}{2}\left[(2\delta_i - 1)L_i - \left(2\bar{\delta}_i - 1\right)\bar{L}_i\right] \tag{21}$$

where $L_i(\bar{L}_i)$ is green time for outbound (inbound) left-turn traffic and $\delta_i(\bar{\delta}_i)$ is a binary decision variable.

Constraints 16 and 17 ensure that traffic signals are synchronized along the path of a progression band. They are derived by substituting Equation 23 into Equation 22.

$$-r_i + x_{N_s,N_e,i} + t_i = -\frac{1}{2}r_i + \phi(i, i+1) - \frac{1}{2}r_{i+1} + x_{N_s,N_e,i+1} \qquad i = 1, 2 \tag{22}$$

where

$$\phi(i, i+1) = \frac{1}{2}r_i + w_i + t_i - w_{i+1} - \frac{1}{2}r_{i+1} \qquad i = 1, 2 \tag{23}$$

Constraint 15 ensures that vehicles from side streets join the arterial only when the arterial direction signal is red; Constraints 13, 14, 18, and 19 provide uninterrupted flows to cross bands and make sure they do not infringe on the red intervals in the arterial direction. Constraint 20 restricts the decision variables to be nonnegative.

The result is a more general and compact formulation of the OD-BAND model. For the case study network, the number of constraints was reduced from 33 to only 20. More details on the OD-BAND model can be found in work by Arsava (*17*). This simplification makes the new formulation easier to understand and implement.

STUDY DESIGN

Using the case study network (shown in Figure 1) and the demand data in Table 1, the new model formulation was coded as a mixed-integer linear program in CPLEX (*18*). The IBM ILOG CPLEX Optimization Studio is an analytical decision support tool kit that enables rapid development and deployment of optimization models using mathematical and constraint programming. It combines an integrated development environment with high-performance optimizer solvers (*18*). Once the decision variables of the problem are optimized, they are used to derive the optimum signal timing plan. The performance of the OD-BAND optimal control plan was compared with those generated by the MAXBAND and MULTIBAND models, which are also coded as a mixed-integer linear program in CPLEX for the same network and demand pattern. The three timing plans were evaluated using Aimsun (*19*) with exactly the same traffic input data. Each timing plan was simulated 20 times with the same set of random seed numbers. The results were averaged and then compared. A simulation duration of approximately 1 h was chosen, and the time intervals between two consecutive vehicle arrivals were sampled from a truncated normal distribution. The mean time headway was set to $1/\lambda$ s, where λ is the mean input flow rate (vehicles per second) with a 10% variance.

Two through lanes and one exclusive turning lane were coded for the arterial and side streets at each intersection. A saturation flow rate of 1,900 vehicles per hour per lane was used. The speed limit was set to 45 ft/s for all sections. Turning speeds were assigned randomly between 17 and 39 ft/s by Aimsun. Lost time per phase was coded as 4 s (3 s of yellow time and 1 s of all-red time). The number of phases at each intersection was defined on the basis of the turning movements. Phase sequence for the arterial direction was optimized by the three models. All possible phase sequences are defined in Figure 4, and the optimized phase sequences are shown in Figure 5.

RESULTS

In this section, the traffic control plans generated by MAXBAND, MULTIBAND, and the OD-BAND model are compared according to overall network performance, path performance, and section performance. The corresponding time–space diagrams are shown in Figures 6*a*, *b*, and *c*, respectively. All three models can optimize left-turn phase sequence along the arterial direction. The optimal left-turn phase sequences for the case study network are presented in Figure 5. For example, MULTIBAND and OD-BAND select lag left turn for the outbound traffic at Intersection 5, whereas MAXBAND selects lead left turn in this case.

In Table 2, the overall network performances of all models are compared according to the following measures of effectiveness: delay time, stop time, number of stops, speed, and vehicles reaching destination. Average delay time is defined as the time difference

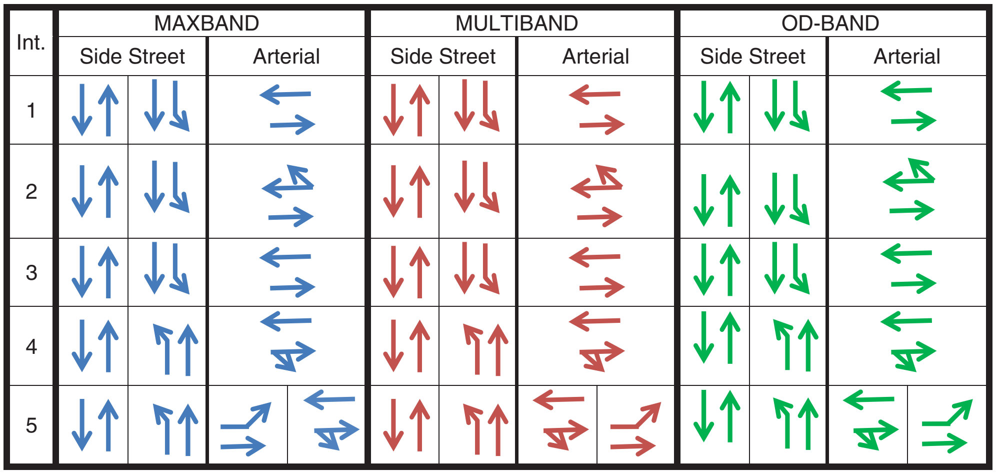
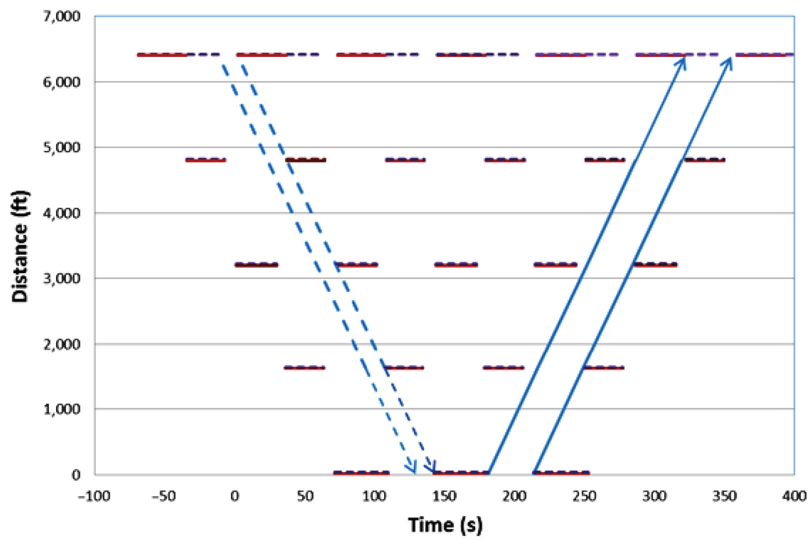
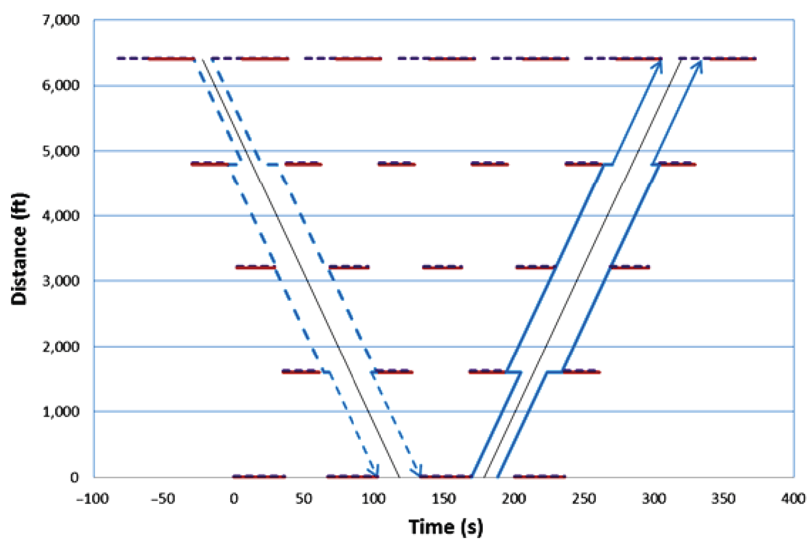


FIGURE 5 Control plan for each intersection (model output) (int. = intersection).



(a)



(b)

FIGURE 6 Time–space diagrams for comparison of three models.

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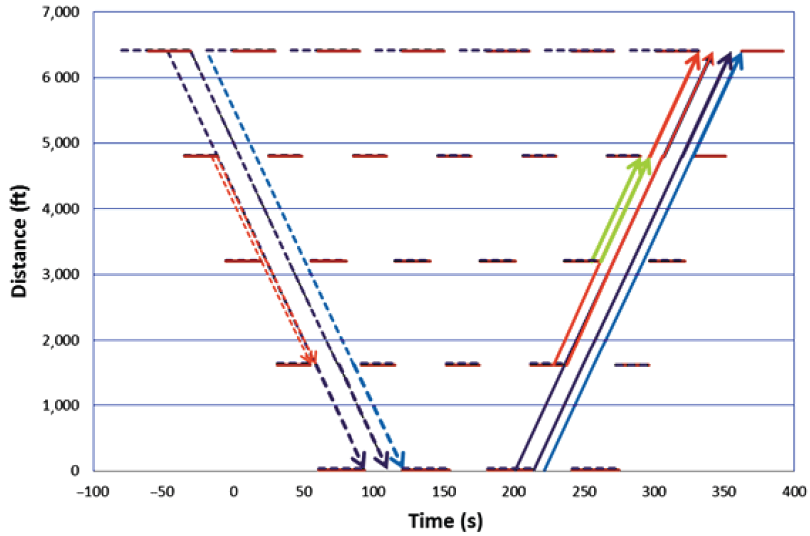

(c)

FIGURE 6 *(continued)* Time–space diagrams for comparison of three models.

between expected travel time and actual travel time measured in second per mile per vehicle; stop time is defined as the average time spent at a standstill per vehicle per mile; number of stops is the average number of stops per vehicle per mile; speed is specified as the average speed of all vehicles that have reached the destination; and vehicles reaching destination is determined as the number of vehicles that have exited the network at the end of the simulation period (*20*). As can be seen in Table 2, the OD-BAND model outperforms MAXBAND and MULTIBAND for all measures of effectiveness except vehicles reaching destination. Because the same set of random seed numbers was used for all three control models, they have the same result for vehicles reaching destination. The optimal control plan of the OD-BAND model generates the lowest number of stops, lowest network delay, and the highest travel speed. As will be shown below, OD-BAND has unique advantages when specific path flow performance is considered.

In addition to the overall network performance, these models are compared according to path performance. Major paths are defined as the major O-D pairs in Table 1. The average travel times for these major paths were calculated. Travel time was calculated as the average time a vehicle needs to travel 1 mi between its origin and destination. In Table 3, the average travel times of each O-D pair are presented. For almost all major O-D pairs, OD-BAND performs the best, with the lowest travel time and standard deviation values. Because MULTIBAND and MAXBAND focus solely on providing uninterrupted flows along the arterial, it is not surprising for

TABLE 2 Overall Network Performance

Measure of Effectiveness	MAXBAND	SD	MULTIBAND	SD	OD-BAND	SD
Average delay time (s/mi)	56.10	0.79	47.78	0.33	43.19	0.26
Stop time (s/mi)	47.52	0.78	40.35	0.33	35.81	0.25
Number of stops (vpm)	0.08	0.00	0.08	0.00	0.07	0.00
Speed (mph)	21.78	0.06	22.86	0.03	23.16	0.03
Vehicles reaching destination	3,849	4.63	3,849	4.63	3,849	4.63

TABLE 3 O-D–Based Travel Time

O-D	MAXBAND	SD	MULTIBAND	SD	OD-BAND	SD
12 to 1	291.40	0.60	273.43	0.79	281.45	0.63
10 to 1	257.94	0.56	242.54	0.38	240.05	0.56
8 to 5	159.52	1.04	152.00	0.62	148.11	0.79
5 to 10	201.07	0.69	195.56	0.47	189.01	0.78
1 to 11	273.22	0.80	239.72	1.47	256.88	0.65
7 to 8	112.97	0.66	108.32	0.47	99.79	0.37
3 to 12	255.09	0.57	240.06	0.46	245.44	1.14

MULTIBAND to outperform OD-BAND on O-D Pairs 12 to 1, 3 to 12, and 1 to 11. However, when network performance is considered, the effectiveness of OD-BAND becomes more apparent (Table 2). In addition, the OD-BAND model aims to provide progression bands for all major O-D streams, including both through bands and cross bands. As is evident by the data in Table 3, the OD-BAND approach significantly reduces the average travel time of vehicles that join the arterial from the side streets.

In addition to the average travel times for major O-D pairs, it is interesting to compare delay times for road sections along the arterial direction. Although MULTIBAND performs better than MAXBAND and OD-BAND for O-D pairs 12 to 1, 3 to 12 and 1 to 11, these O-D pairs consist of several shared sections along the arterial. Section performance data provide rich information for evaluating and comparing the three models. The delay times of sections shared by major O-D pairs are calculated and the results are detailed in work by Arsava (*17*). Of the 10 shared sections, OD-BAND generates the lowest link delay times for seven of them. MULTIBAND generates the lowest delay for two of them, and MAXBAND generates the lowest delay for only one.

To further compare these three models, their time–space diagrams were prepared and are presented in Figure 6. The blue lines (solid and dashed) represent the trajectories of the first and last vehicles that can pass through one or more intersections along the arterial without stopping. In the time–space diagram for MULTIBAND, these blue trajectory lines are not continuous because the progression bandwidths are proportional to each section's traffic volume and saturation flow rate. The purple lines in the OD-BAND time–space diagram represent the trajectories for vehicles from 3 to 12 and 10 to 1; the red lines are for vehicles from 5 to 10 and 8 to 5; and the green lines are for O-D Pair 7 to 8. Because some progression bands share common boundaries, the lines may overlap. OD-BAND creates dedicated progression bands for each major O-D pair, whereas MAXBAND and MULTIBAND produce progression bands for through traffic along the arterial only. MAXBAND and MULTIBAND fail to provide continuous flow for traffic joining the arterial from the side streets. MULTIBAND generates more flexible progression bands than MAXBAND, but it cannot properly handle the traffic from 5 to 10, 7 to 8, and 8 to 5. When vehicles from these O-D pairs join the arterial, they have to stop at the next intersection and create queues on approaches along the arterial; these queues reduce the overall network traffic control performance. These time–space diagrams demonstrate the unique advantage of the OD-BAND model, which is capable of generating continuous cross bands when there is significant O-D demand for such traffic. Such a model will become increasingly valuable with the advent of connected vehicle technology where route selection (i.e., traffic assignment) and signal control are calculated simultaneously.

CONCLUSIONS AND DISCUSSION OF RESULTS

This research extends the original OD-BAND model that uses vehicular O-D information for arterial traffic signal coordination (*1*). First, the mathematical formulation was generalized to model all possible O-D flows of an arterial system. Second, the objective function was revised so that bandwidths are weighted by the number of street segments they traverse and their volume-to-saturation flow ratios. In this way, major O-D flows that traverse numerous sections gain higher priority. Third, the left-turn phase sequences along the arterial direction were optimized to provide maximum progression bandwidths. The OD-BAND model was then compared with traditional progression bandwidth optimization models MAXBAND and MULTIBAND. The latter models are programmed to produce uniform and varying progression bands, respectively, along the arterial direction only. They use the traffic volumes at individual intersections irrespective of their origins and destinations. It is shown that disregarding such significant traveler information (i.e., O-D demands) leads to unbalanced progression bands that negatively affect overall system performance.

The modified OD-BAND model was formulated as a mixed-integer linear program and solved in the CPLEX Optimization Studio. In addition, the MAXBAND and MULTIBAND models were applied and their optimum timing plans were calculated. All three optimized signal timing plans were coded in Aimsun. The timing plans were evaluated and compared at the network, O-D pair, and section levels for travel time, delay time, number of stops, speed, and vehicles reaching destination. In all cases, the modified OD-BAND model performed the best overall. The OD-BAND model generates separate progression bands for each O-D pair and was shown to improve the network performance significantly. MAXBAND and MULTIBAND generate wider progression bands along the arterial direction while ignoring the traffic that joins the arterial from side streets. These approaches can lead to initial queues along the arterial direction that disrupt the arterial through traffic.

For the case study, seven major O-D pairs with different travel distances were selected to demonstrate the importance of maximization of progression bandwidth on the basis of O-D pairs. The width of each progression band was weighted by the number of road sections that it traverses. On the basis of Aimsun simulation results, the proposed model is found to be very effective, and it outperforms MAXBAND and MULTIBAND. The unique capability of the OD-BAND model in generating both through bands and cross bands that correspond to different O-D demands is most suitable for integrated network traffic signal coordination and route guidance in an environment of connected vehicles, in which connected vehicles and crowd-sourced data can be used to derive detailed and accurate O-D information. Progression bands can then be established for each major O-D flow, and route guidance can be provided to vehicles to travel within those bands with minimum delay and fuel consumption (*21*). The development of such strategies for network traffic signal coordination is the subject of further research.

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