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Signal Progression Model for Long Arterial: Intersection Grouping and Coordination

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ABSTRACT Signal progression has been proven as an effective way to improve the operational efficiency of traffic signals at local arterial corridors. Conventional two-way progression models have shown their promising in providing desirable green bandwidth to two-way through traffic along the arterial. However, they may not offer an effective progression plan when a long arterial contains many intersections. Under such condition, it is critical to divide the arterial corridor into a set of subgroups for progression design. Since progression effectiveness is significantly impacted by the way an arterial is decomposed, conducting arterial decomposition as a separated step may keep the result from optimality. To tackle this issue, a novel progressive model is developed to concurrently determine the arterial decomposition strategy and optimize the resulting signal progression plan within each subgroup. With an integrated control objective function, the proposed model can minimize the required number of subgroups while satisfying the operational need (i.e., a minimum bandwidth is required). Also, the proposed model is formulated with a mixed-integer-linear-programming technique that can guarantee a global optimal solution. A numerical example on a field arterial which consists of 15 signalized intersections has verified the effectiveness of the proposed model.

INDEX TERMS Urban long-distance arterial, signal progression, intersection decomposition, mixed-integer-linear-programming.

I. INTRODUCTION

Traffic congestion in urban regions has emerged as a serious social problem that negates the service quality of road infrastructures and increases the environmental pollutions caused by vehicle emissions. The worldwide cities are seeking for ways to improve vehicular mobility along arterial corridors. Signal coordination has been proved as a promising way to achieve this goal since its main objective is to facilitate traffic movements to pass a set of consecutive intersections without stops. Assuming pre-determined green splits, a general signal coordination plan consists of a common cycle length, offsets, and the desired progression time between each pair of adjacent intersections. Particularly, the most well-known models used the green bandwidth as the major performance measure to synchronize traffic signals.

As early as 1960s, Morgan and Little (1964) [1] developed a model to maximize total bandwidths on a two-way arterial. Following the same principle, Little (1966) [2] proposed an advanced model to concurrently optimize the common cycle length, progression speeds and offsets using an integer programming formulation. Later, to more accurately reflect the realistic operations, Little *et al.* (1981) [3] further extended the Maxband model to account the time ratio allocated for left-turn movements and the clearance time of initial queues. Taking traffic flow patterns into account, Gartner *et al.* (1991) [4] developed a variable bandwidth optimization model, named as Multiband, to generate different bandwidth between each pair of adjacent intersections. Later, Stamatiadis and Gartner (1996) [5] extended it into the multi-arterial traffic networks. Given an optimized uniform bandwidth progression plan, Sripathi *et al.* (1995) [6] presented a simplified and efficient method for calculating variable-bandwidths, which can produce near optimal results compared with Multiband model. And then, Gartner and Stamatiadis (2002) [7] applied the Multiband model to an arterial grid network.

Integrated with a bandwidth-based model, a progression optimization program PASSER was developed by the Texas Transportation Institute (Chaudhary *et al.*, 2002) [8]. Considering the progression time uncertainty, Li (2014) [9] proposed a more robust bandwidth model for signal synchronizations. To deal with the heavy turning flows at local arterials, Yang *et al.* (2015) [10] developed a set of signal progression models to simultaneously offer green bands to multiple traffic routes experiencing heavy flows.

Those bandwidth-based models have been proven to be effective on the coordination of traffic signal and most of them emphasize on the progression design along two-way through traffic paths (inbound and outbound direction). However, for a long arterial corridor that includes a large number of intersections, existing two-way progression models such as Maxband may not be capable of producing an effective offset plan. The phenomenon dependents on the signal timing plan and geometry condition of the actual site. With the increasing of number of intersections, directly applying Maxband model may result in narrow or even zero bandwidth along the arterial. Hence, to guarantee an effective signal progression plan, it is essential to decompose the arterial corridor into a set of subgroups. In review of the literature, a few studies have also highlighted this issue. For example, Hooks and Albers (1999) [11] suggested decomposition rules that combine all intersections that are less than 0.8km in one group and split intersections with more than 1.6km apart spacing as decomposition points. For all intersections with spacing between 0.8km and 1.6km, decomposition points were chosen by Coupling Index (CI). Bonneson *et al.* (2009) [12] also suggested to use traffic volumes in both directions of the link and spacing to define a new CI function. Similar to the aforementioned methods, there is an ambiguous range of CI values that left the rest of grouping responsibility on individual judgment based on traffic engineer's experience. Tian and Urbanik (2007) [13] presented a grouping technique that increased efficiency and attainability of the green bandwidth. Their approach consisted of dividing a corridor with ten intersections into three subgroups based on spacing and traffic demand, then optimized each subgroup's green bandwidth, and adjusted offset and phase sequences of boundary intersections in subgroup to connect subgroups for progression. Wu *et al.* (2012) [14] developed a group partition method of coordinated arterials for optimal bandwidth based on comparing traffic volumes (through/turning) at intersections. They compared the bandwidth of every possible subgroup and proved that their initial partitioning was correct but such method is time consuming when the number of intersections in a system increases. Also, there is no criteria for defining 'high' traffic volumes in dividing subgroups. Zhang and Zhang (2014) [15] present a K-means clustering method to decompose a long arterial for coordination. In this study, interruption at intersections with large through volume and minimum turning traffic is suggested to be avoided. The main issue with using K-means clustering method is that the number of K clusters should be defined prior to analysis and it requires at least 100 sample sizes to derive a reliable clustering model.

In summary, despite a large body of related studies have been reported in the literature, an efficient and reliable optimization tool that can decompose the arterial corridor into separated progression subgroups is not yet available. To address to such issue, this study intends to develop an optimization model that can concurrently determine the arterial decomposition plan and optimize the resulting signal progression plan within each subgroup. With an integrated control objective function, the proposed model can minimize the required number of subgroups while satisfying the operational need (i.e., a minimal bandwidth is required). Additionally, the proposed model is formulated with a mixed-integer-linear-programming (MILP) technique that can guarantee a global optimal solution.

II. PROBLEM NATURE AND CRITICAL ISSUES

To coordinate the traffic signal controllers along an arterial corridor, the most well-known model, Maxband (Little *et al.*, 1981), can concurrently generate the offsets between two adjacent intersections, optimize the prevailing speed at each link, and determine the designing of left-turn phase patterns. As shown in Figure 1a, when the number of intersections for through traffic progression is limited to five, the Maxband method can generate sufficient green bandwidths between adjacent signals along both through directions. However, for a long arterial corridor that includes a larger number of intersections, the signal coordination system which directly applies existing two-way progression models such as Maxband may not be able to produce an effective plan. For example, as shown in Figure 1b, the outbound traffic has a zero-green bandwidth and the inbound traffic obtains a narrow one when simultaneously coordinating seven intersections at the same arterial. This phenomenon is relevant to the actual geometry condition and signal timings of these intersections. With the increasing of intersection numbers, the coordination system cannot find an efficient offset plan to accommodate two-way flows.

Hence, to produce an effective coordination plan for a long arterial, it is critical to develop a reliable tool which can divide the arterial into a set of subgroups for signal progression. Figure 2 shows an example of the corridor decomposition where sixteen intersections were separated into three subgroups. In practice, such decomposition work is mainly done with traffic engineers' judgment and no clear standard is available yet. Also, it is noticeable that there is an inevitable tradeoff between reducing number of subgroups and increasing the green bandwidths. When less number of intersections are grouped together, the progression model might be able to generate the larger green bandwidths within a group. In conclusion, a reliable signal coordination model for long corridors shall concurrently accounts for the determination of intersection subgroups and design of signal progression.

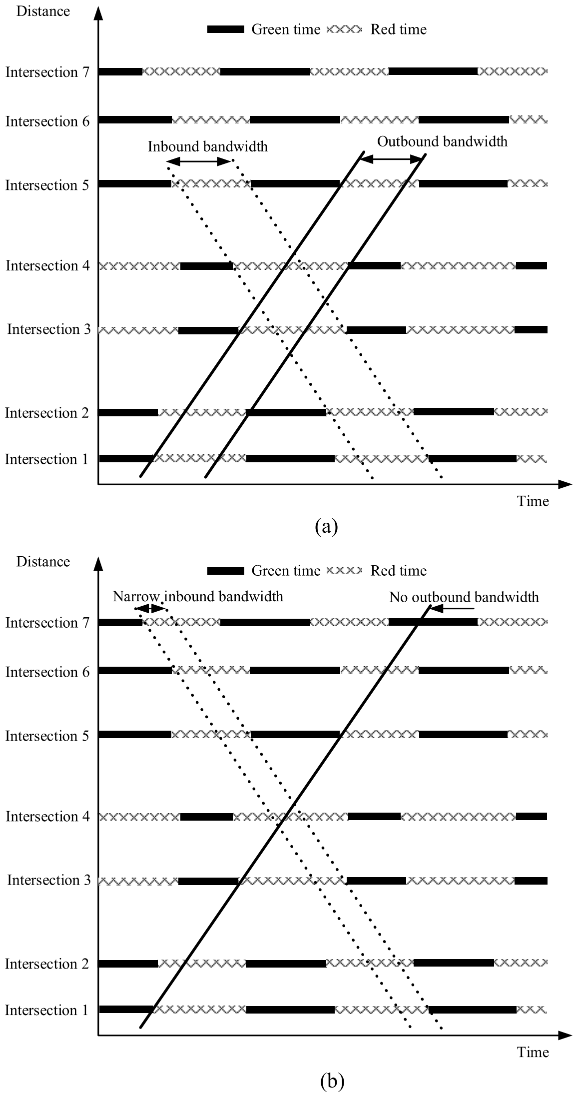

FIGURE 1. Two-way Green Bandwidth at the Same Coordinated Arterial with Maxband Model. (a) Coordinated five intersections. (b) Coordinated seven intersections.

In response to such a need, this study develops a novel signal progression model which can concurrently assign all intersections into different subgroups and design the coordination plan within each subgroup. What's more, the developed model can be formulated with MILP technique to guarantee that a global optimal solution could be obtained within a relatively short time period.

III. MODEL FORMULATION

A. OBJECTIVE FUNCTION

As discussed previously, the proposed model shall be capable of optimizing the arterial decomposition and the progression plan concurrently. To satisfy such need, this study extends Maxband's objective function into the following formulation:

$$Maxmize \sum_{i=1}^{I}(e_i+\bar{e}_i)-\varphi(\sum_{j=1}^{J}y_j)-\eta\sum_{i=1}^{I}(Z_i(f_i+\bar{f}_i)) \quad (1)$$

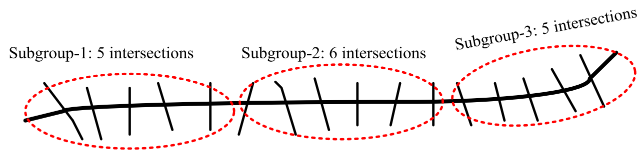

FIGURE 2. An example of the arterial corridor decomposition.

where, e_i ($\bar{e}_i$) is the effective green bandwidth received by intersection i along the outbound (inbound) direction; I represents the total number of intersections at the long arterial corridor; φ and η are weighting factors to dominate the first term; J is the maximal number of subgroups after the arterial decomposition; y_j is a binary variable indicating whether group j contains at least one intersection; Z_i is a binary variable indicating whether intersection i is the decomposition point; and f_i ($\bar{f}_i$) denotes the total traffic volumes of exit segments along the outbound (inbound) direction at intersection i, i.e. the summation of traffic volumes coming from three possible upstream turning directions (through, left, right, except U-turns).

Since a meaningful subgroup should include two or more intersections, J can be obtained as follows:

$$J = \text{mod}(\frac{I}{2}) \quad (2)$$

where, the operator mod(•) returns the integer part of the value in the bracket. y_j, defined as follows, is a binary variable to help determine the number of subgroups after arterial decomposition:

$$y_j = \begin{cases} 1 & \text{if subgroup } j \text{ includes two or more intersections} \\ 0 & \text{if subgroup } j \text{ is empty} \end{cases} \quad (3)$$

Additionally, z_i, is another binary variable to represent whether two adjacent intersections belong one subgroup or not and can be defined as follows:

$$Z_i = \begin{cases} 1 & \text{if intersection } i \text{ and } i+1 \text{ are included} \\ & \text{at the same subgroup} \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

Based on the variables defined above, one can note that the first term in Equation (1) is the total green bandwidth offered to all intersections, the second term is the total number of intersection subgroups, and the third is the total traffic volumes at decomposed intersections. Since the objective function is to minimize the weighted summation of number of subgroups and total traffic volumes of split intersections while guarantee a minimal bandwidth is achieved at each intersection, the weighting factors ϕ and η should be a large positive number (e.g., 100 or more) so that the second and third terms can dominate the first during the optimization process.

IV. MODEL CONSTRAINTS

A. ARTERIAL DECOMPOSITION CONSTRAINTS

Given the existing green splits at each intersection, a set of constraints should be satisfied to ensure that the proposed model can generate a feasible and reasonable arterial decomposition plan. With the maximal number of subgroups, J, that may be used, the following two constrains will ensure those J groups are used in the ascending order:

$$x_{1,1} = 1 \tag{5}$$
$$y_j \geq y_{j+1} \quad \forall j \leq J-1 \tag{6}$$

where, $x_{i,j}$ is a binary decision variable which has the following definition:

$$x_{i,j} = \begin{cases} 1 & \text{if intersection } i \text{ is included in subgroup } j \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

In addition, Equation (8) is used to ensure that each intersection is placed into only one subgroup. Equations (9-10) are to make $y_j = 1$ when any $x_{i,j} = 1$.

$$\sum_{j=1}^{J} x_{i,j} = 1 \quad \forall i \leq I \tag{8}$$
$$y_j \leq \sum_{i=1}^{I} x_{i,j} \quad \forall j \leq J \tag{9}$$
$$y_j \geq \sum_{i=1}^{I} x_{i,j}/I \quad \forall j \leq J \tag{10}$$

Equation (11) will guarantee that if group j includes intersection i, its downstream intersection $i+1$ cannot be included into a group that has an index smaller than j

$$\sum_{k=1}^{j-1} x_{i+1,k} \leq M(1-x_{i,j}) \quad \forall i, j \geq 2 \tag{11}$$

where, M is a large positive number and equals 1000 in this study.

Similarly, Equation (12) is to ensure when group j includes intersection i, its upstream intersection $i-1$ cannot be included into a group that has an index larger than j

$$\sum_{k=j+1}^{J} x_{i-1,k} \leq M(1-x_{i,j}) \quad \forall i \leq N; \ \forall j \leq J-1 \tag{12}$$

B. INTERFERENCE CONSTRAINS

Same as Maxband, the proposed model should also include the interference constraints to bind the green bandwidth with the available green duration at each intersection:

$$w_i + b_j \leq g_i + M(1-x_{i,j}) \quad \forall i \leq I; \ \forall j \leq J \tag{13}$$
$$w_i + \bar{b}_j \leq \bar{g}_i + M(1-x_{i,j}) \quad \forall i \leq I; \ \forall j \leq J \tag{14}$$

As shown in Figure 3, $b_j(\bar{b}_j)$ denotes the outbound (inbound) green bandwidth within subgroup j; $g_i(\bar{g}_i)$ the duration of green time that the outbound (inbound) traffic can obtain at intersection i; and $w_i(\overline{w}_i)$ represents the part of a green duration before (after) the green band for inbound (outbound) traffic at intersection i. It is noticeable that by introducing the number M, both Equations (13-14) will become ineffective when $x_{i,j} = 0$.

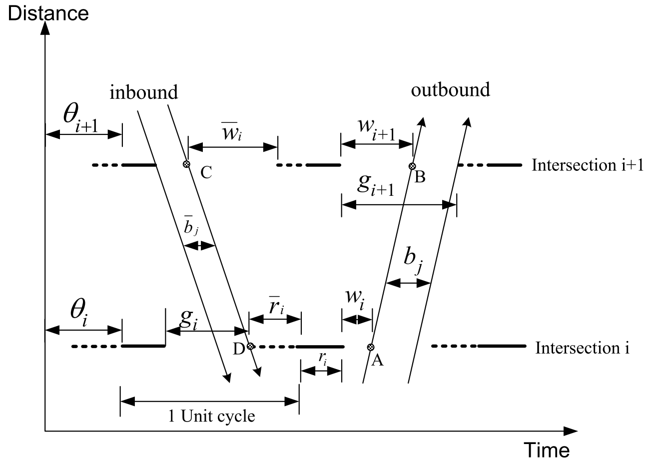

FIGURE 3. Key notations in the proposed model.

Also, to guarantee the effectiveness of signal progression within each intersection subgroup, a minimal green bandwidth, along both outbound and inbound directions, should be introduced as follows:

$$b_j \geq b_{\min} \quad \forall j \leq J \tag{15}$$
$$\bar{b}_j \geq \bar{b}_{\min} \quad \forall j \leq J \tag{16}$$

C. PROGRESSION CONSTRAINTS

Note that the formulations for Maxband are developed for all intersections along the arterial. Hence, its loop integer constraints can be obtained by substituting the two progression constraints of outbound and inbound traffic. However, due to the capability of performing arterial decomposition, the proposed model in this study shall explore new constraints. In particular, the following formulations for the outbound direction are derived to represent the progression from point A to point B in Figure 3 as shown:

$$\begin{aligned} &\theta_i + r_i + w_i + t_i + n_i \\ &\quad \geq M(x_{i,j} + x_{i+1,j} - 2) + \theta_{i+1} + r_{i+1} \\ &\qquad + w_{i+1} + n_{i+1} \quad \forall i \leq I-1; \ \forall j \leq J \end{aligned} \tag{17}$$

$$\begin{aligned} &\theta_i + r_i + w_i + t_i + n_i \\ &\quad \leq M(2 - x_{i,j} - x_{i+1,j}) + \theta_{i+1} + r_{i+1} \\ &\qquad + w_{i+1} + n_{i+1} \quad \forall i \leq I-1; \ \forall j \leq J \end{aligned} \tag{18}$$

where, θ_i is the offset of intersection i; r_i denotes the total red duration at the left side of the green band at intersection i; t_i means the travel time between intersection i and $i+1$; and n_i is an integer variable to represent the number of signal cycles.

Note that by introducing the large positive number M, both Equations (17-18) will become effective only if both intersection i and $i+1$ belong to the same intersection subgroup j (i.e., $x_{i,j} = x_{i+1,j} = 1$). Under such condition, combination of these two constraints will form the following constraint:

$$\theta_i + r_i + w_i + t_i + n_i = \theta_{i+1} + r_{i+1} + w_{i+1} + n_{i+1} \forall i \leq I - 1; \quad \forall j \leq J \tag{19}$$

Similarly, for the inbound traffic, one can use the following constraints to represent the progression from point C to point D in Figure 3 as shown:

$$\theta_{i+1} + \bar{r}_i + \bar{w}_i + t_i + \bar{n}_i \geq M(x_{i,j} + x_{i+1,j} - 2) + \theta_i + \bar{r}_{i+1} + \bar{w}_{i+1} + \bar{n}_{i+1} \quad \forall i \leq I - 1; \ \forall j \leq J \tag{20}$$

$$\theta_{i+1} + \bar{r}_i + \bar{w}_i + t_i + \bar{n}_i \leq M(2 - x_{i,j} - x_{i+1,j}) + \theta_i + \bar{r}_{i+1} + \bar{w}_{i+1} + \bar{n}_{i+1} \quad \forall i \leq I - 1; \ \forall j \leq J \tag{21}$$

where, $\bar{r}_i$ is the total red duration at the right side of the green band at intersection i; and $\bar{n}_i$ denotes an integer variable.

D. INTERSECTION BANDWIDTH CONSTRAINTS

Since both interference and progression constraints are derived to determine the bandwidth $b_j(\bar{b}_j)$ within each intersection subgroup while the objective function is to maximize the total bandwidth offered to all intersections with the intersection outbound (inbound) bandwidth of $e_i(\bar{e}_i)$, this study further introduces a set of constraints to link $e_i(\bar{e}_i)$ to $b_j(\bar{b}_j)$. For outbound directions, such constraint is given as follows:

$$e_i \geq b_j - M(1 - x_{i,j}) \quad \forall i \leq I; \ \forall j \leq J \tag{22}$$

$$e_i \leq b_j + M(1 - x_{i,j}) \quad \forall i \leq I; \ \forall j \leq J \tag{23}$$

With Equations (22-23), one can note that, bandwidth e_i for intersection i will equal bandwidth b_j in subgroup j when intersection i is included in subgroup j (i.e., $x_{i,j} = 1$).

Similarly, for inbound directions, the intersection bandwidth constraints are formulated in the following format:

$$\bar{e}_i \geq \bar{b}_j - M(1 - x_{i,j}) \quad \forall i \leq I; \ \forall j \leq J \tag{24}$$

$$\bar{e}_i \leq \bar{b}_j + M(1 - x_{i,j}) \quad \forall i \leq I; \ \forall j \leq J \tag{25}$$

E. SUBGROUP SPLIT CONSTRAINTS

Based on the literature of subgroup partition method (Bonneson *et al.*, 2009; Tian and Urbanik, 2007; Wu *et al.*, 2012), traffic volumes between two adjacent intersection is one of most important decision variables to impact the performance of signal progression on arterials. Therefore, this study has also imported the total traffic volumes along the progression approaches at the intersection into the decomposition model to guarantee the continuity of signal progression at the high-demand intersections.

Thus, the outbound and inbound constraints about the subgroup decomposition can be formulated at the following expressions:

$$Z_i \geq x_{i,j} - x_{i+1,j} \tag{26}$$

$$Z_i \geq -x_{i,j} + x_{i+1,j} \tag{27}$$

$$\bar{Z}_i \geq \bar{x}_{i,j} - \bar{x}_{i+1,j} \tag{28}$$

$$\bar{Z}_i \geq -\bar{x}_{i,j} + \bar{x}_{i+1,j} \tag{29}$$

V. CASE STUDY

In this section, the proposed mixed-integer-linear-programming model is solved in CPLEX and is operated on a PC with 2.2 GHz, I5-5200 CPU with an 8GB installed RAM, and Windows 10, 64-bit operating system.

A. SITE DESCRIPTION AND MODEL INPUT

To illustrate the applicability and efficiency of the proposed optimization model, the El Cajon Blvd in San Diego, CA, USA, is selected as the study site. As shown in Figure 4, the long arterial corridor includes fifteen signalized intersections. Since the conventional two-way progression model cannot produce an effective progression plan along this corridor, this study will implement the proposed model to decompose this arterial. Based on Equation (2), the maximal number of subgroups, J, is set to seven.

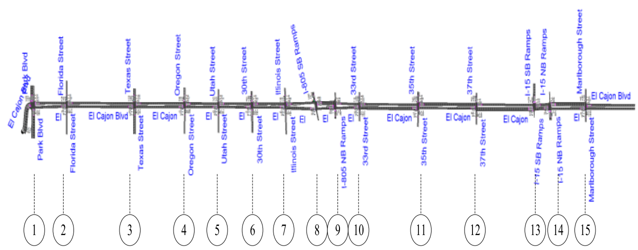

FIGURE 4. The geometric layout of the studied arterial corridor in San Diego, CA.

In this case study, the signal cycle length is set to 120 second, the weighting factor φ and η are set to be 100, and the minimal green bandwidth is set to 14 seconds. Based on the field collected data, other inputs are summarized in the following Table 1.

B. OPTIMIZATION RESULTS

Using the input data presented above, the proposed model is implemented to design signal progression for the target long arterial corridor. As shown in Figure 5, the arterial is decomposed into three subgroups which includes 3, 7, and 5 intersections, respectively. The computation time is 18 minutes and 36 seconds.

The resulting progression plan within each subgroup is shown in Figure 6. In particular, the outbound bandwidths of the three groups are 33s (Figure 6a), 15s (Figure 6b), and 24 s

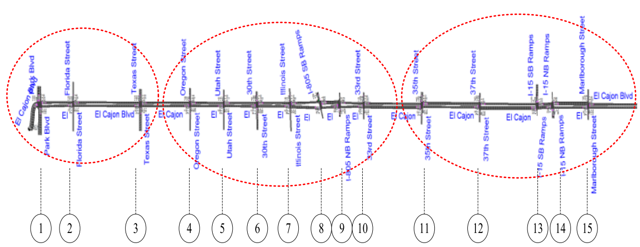

FIGURE 5. The subgroup partition of studied arterial corridor based on developed model.

TABLE 1. The peak-hour demand patterns for the four intersections with respect to cycle length.

Intersection Index	Model Input (unit: signal cycle)							
	OB g_i	OB $\bar{g}_i$	OB r_i	IB $\bar{r}_i$	OB Volume f_i (vph)	IB Volume $\bar{f}_i$ (vph)	OB t_i	IB t_i
1	0.360	0.338	0.247	0.392	878	780	0.125	0.125
2	0.429	0.614	0.239	0.331	938	821	0.249	0.249
3	0.300	0.277	0.123	0.577	1091	1071	0.186	0.186
4	0.602	0.727	0.169	0.228	1153	1168	0.124	0.124
5	0.601	0.673	0.102	0.297	1170	1285	0.124	0.124
6	0.322	0.439	0.184	0.494	1329	1333	0.123	0.123
7	0.505	0.670	0.192	0.303	1499	1471	0.115	0.115
8	0.393	0.467	0.074	0.533	1584	1627	0.067	0.067
9	0.584	0.430	0.000	0.416	1603	1082	0.092	0.092
10	0.389	0.324	0.103	0.509	1686	987	0.218	0.218
11	0.412	0.341	0.119	0.469	1722	1025	0.214	0.214
12	0.491	0.330	0.000	0.509	1753	1096	0.216	0.216
13	0.708	0.803	0.095	0.197	1402	1030	0.053	0.053
14	0.723	0.369	0.000	0.278	1452	896	0.134	0.134
15	0.410	0.302	0.087	0.503	1521	737	NA	NA

Note: "OB" represents "outbound"; "IB" represents "inbound".

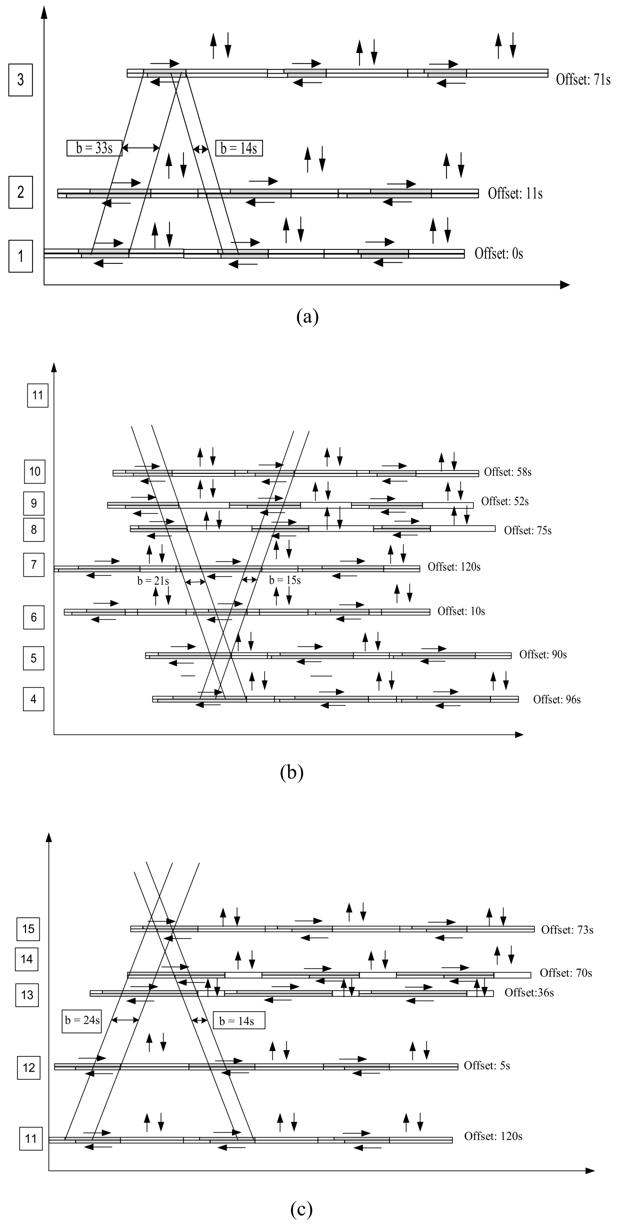

FIGURE 6. The progression plan produced by the proposed model. (a) The resulting green bands in subgroup 1. (b) The resulting green bands in subgroup 2. (c) The resulting green band in subgroup 3.

(Figure 6c), respectively and the inbound bandwidths are 14s (Figure 6a), 21s (Figure 6b), and 14s (Figure 6c), respectively.

Also, for comparison, all 15 intersections on the selected arterial are tested with the two-way Maxband model as a group. However, no feasible solution can be found in such case and it is not possible to design a progression plan that can offer non-zero green bandwidths for both through directions. Hence, for validating the need of decomposition, this study further performs the study on the following two cases:

- Outbound Progression: Only outbound through traffic is considered for progression;
- Inbound Progression: Only inbound through traffic is considered for progression.

As shown in Figure 7a, the maximum green bandwidth, when only outbound traffic is coordinated, is 25 seconds. Similarly, Figure 7b shows that the bandwidth for inbound traffic is 33 seconds.

Based on the resulting green bandwidths as shown in Figure 6 and Figure 7, it is noticeable that both outbound and inbound traffic can obtain 25 and 33 seconds of green band, respectively, when only one-way progression is considered. Using the proposed model, the long arterial has been decomposed into three subgroups. In subgroup 1 and 3, the outbound traffic can obtain relatively large green band while subgroup 2 offers the large green bands for inbound. Hence, one can identify that the three intersections

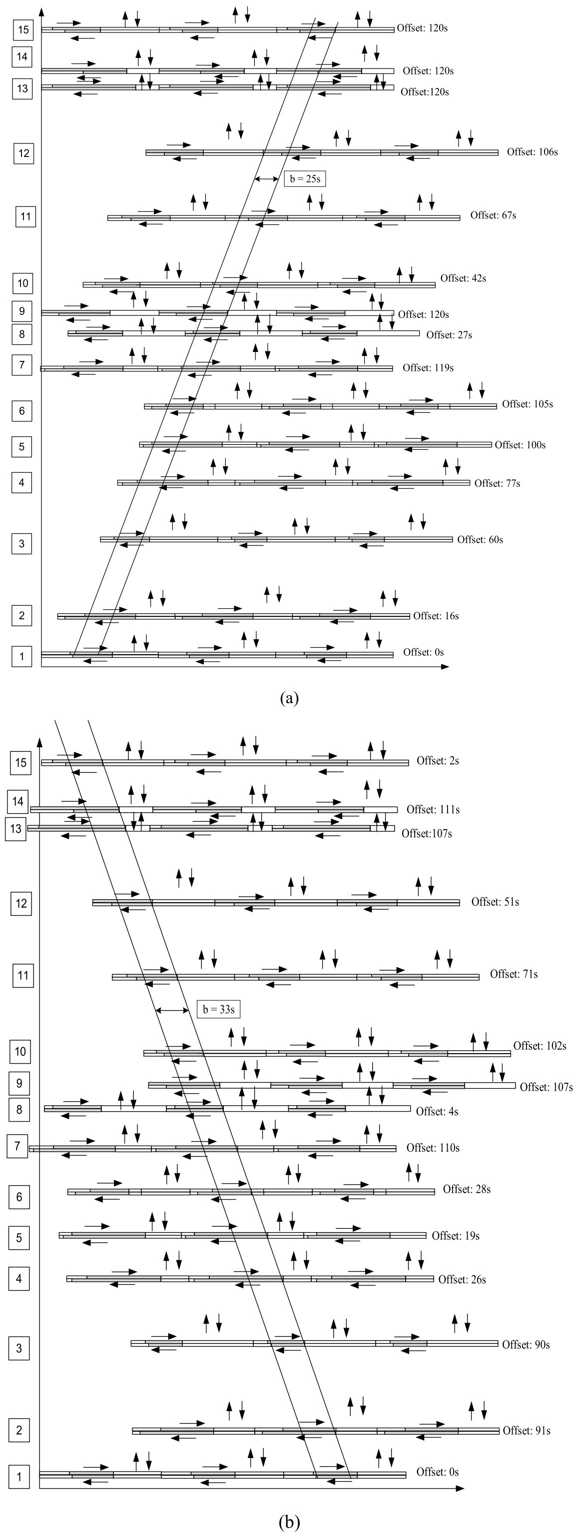

FIGURE 7. **The progression plan produced by one-way progression model. (a) The resulting green bands for outbound traffic. (b) The resulting green band for inbound traffic.**

in subgroup 2 are the operational bottleneck in the progression. They are also the main contributor that leads to no feasible solution when directly applying the Maxband model.

Despite the one-way progression strategy can offer sufficient green band, it is not applicable since the opposing direction is completely ignored.

C. EXPERIMENTAL RESULTS

To illustrate the applicability and efficiency of the proposed model, this study used Vissim 7.0 as a simulation tool for performance evaluation. Recognizing that a simulated system is meaningful only if it can faithfully reflect actual traffic patterns, this study has performed the calibration by minimizing the differences between simulated and field-collected and flow rates at intersections. Three measurement of effectiveness including average intersection delay, average number of stops, and average speed in both the networks are recorded for comparison. To further prove the effectiveness of the proposed model in designing arterial decomposition plan and optimizing offset, we have implemented Synchro for additional comparison.

Based on the experimental results in Table 2, one can observe that the proposed model can clearly outperform the one-way progression strategies. The average vehicle delay under the ''Outbound Only'' and ''Inbound Only'' strategies is increased by 10.9% and 14.8%, respectively, compared with the ones obtained from the proposed model. Synchro can offer better delay reduction performance than the two one-directional models. Regarding the average number of stops, the implementation of three developed methods can yield 4.2%, 6.7%, and 4.2% increasing, respectively, compared with the proposed model. Meanwhile, the comparison of the average speed has also proved the effectiveness of the proposed model. Hence, comparison between the two 'one-way' progression strategies can prove the need of decomposing arterial corridor into subgroups for signal coordination when it is sufficiently long. ''Outbound Only'' performs slightly better due to the larger traffic volume moving along outbound direction. Comparison with Synchro has further indicated the effectiveness of the proposed model in designing signal progression.

TABLE 2. **The arterial corridor performance with different control models.**

Performance Index	Proposed Model	Outbound Only	Inbound Only	Synchro
Average Delay (sec)	41.69	46.23 (+10.9 %)	47.88 (+14.8%)	44.54 (+6.8%)
Average # of Stops	1.19	1.24 (+4.2%)	1.27 (+6.7%)	1.24 (+4.2%)
Average speed (mph)	15.89	15.55 (-2.1%)	15.19 (-4.4%)	15.67 (-1.4%)

VI. CONCLUSIONS

To effectively design signal progression for long arterial corridors, this study proposed a decomposition model that can concurrently divide the intersections into several subgroups and optimize the signal progression plan within each subgroup. By introducing the integrated control objective function, the proposed model can minimize the required number of subgroups and generate the desired two-way bandwidth. The developed model was formulated with a mixed-integer-linear-programming technique that can guarantee a global optimal solution. In tests that used field data from San Diego, California, this study conducted extensive simulation experiments to validate the proposed model. The tested arterial is successfully divided into three subgroups which contains 3, 7, and 5 intersections, respectively. Since no feasible solution can be found by applying Maxband model directly, the one-way progression strategies, "Outbound Only" and "Inbound Only", are tested for comparisons. The optimization results show that the subgroup 2 is identified as the operational bottleneck and nearly minimal green bands are offered. Despite the one-way progression strategy can offer sufficient green band, it is not applicable since the opposing direction is completely ignored. Further simulation evaluation and comparison with Synchro has also proved the effectiveness of the proposed model.

It is noticeable that the proposed model is suitable for implementation when no Origin-Destination information is obtainable. Otherwise, one shall further account for the progression need of heaving left-turning and right-turning volumes. Hence, future research direction along this line will be exploring a new decomposition model when arterial O-D matrix is completely or partially obtainable.

VII. APPENDIX: GENERAL MODEL FORMULATION

In brief, the optimization decomposition model at long-distance arterials can be summarized into a general expression as follows:

$$Maxmize \sum_{i=1}^{I}(e_i+\bar{e}_i)-\varphi(\sum_{j=1}^{J}y_j)-\eta\sum_{i=1}^{I}(Z_i(f_i+\bar{f}_i))$$
$$s.t.\; x_{1,1}=1$$
$$y_j \geq y_{j+1} \quad \forall j \leq J-1$$
$$\sum_{j=1}^{J}x_{i,j}=1 \quad \forall i \leq I$$

A group is counted if it contains intersections:

$$y_j \leq \sum_{i=1}^{I}x_{i,j} \quad \forall j \leq J$$
$$y_j \geq \sum_{i=1}^{I}x_{i,j}/I \quad \forall j \leq J$$

The downstream intersections cannot be included in a group with smaller index and the upstream intersections cannot be included in one with larger index:

$$\sum_{k=1}^{j-1}x_{i+1,k} \leq M(1-x_{i,j}) \quad \forall i,\ j \geq 2$$
$$\sum_{k=j+1}^{J}x_{i-1,k} \leq M(1-x_{i,j}) \quad \forall i \leq N;\ \forall j \leq J-1$$

If intersection i is included in subgroup j, the bandwidth for subgroup j is applied to intersection i:

$$b_j \geq b_{\min} \quad \forall j \leq J$$
$$\bar{b}_j \geq \bar{b}_{\min} \quad \forall j \leq J$$
$$w_i+b_j \leq g_i+M(1-x_{i,j}) \quad \forall i \leq I;\ \forall j \leq J$$
$$w_i+\bar{b}_j \leq \bar{g}_i+M(1-x_{i,j}) \quad \forall i \leq I;\ \forall j \leq J$$
$$\theta_i+r_i+w_i+t_i+n_i \geq M(x_{i,j}+x_{i+1,j}-2)+\theta_{i+1}+r_{i+1}+w_{i+1}+n_{i+1} \quad \forall i \leq I-1;\ \forall j \leq J$$
$$\theta_i+r_i+w_i+t_i+n_i \leq M(2-x_{i,j}-x_{i+1,j})+\theta_{i+1}+r_{i+1}+w_{i+1}+n_{i+1} \quad \forall i \leq I-1;\ \forall j \leq J$$
$$\theta_{i+1}+\bar{r}_i+\bar{w}_i+t_i+\bar{n}_i \geq M(x_{i,j}+x_{i+1,j}-2)+\theta_i+\bar{r}_{i+1}+\bar{w}_{i+1}+\bar{n}_{i+1} \quad \forall i \leq I-1;\ \forall j \leq J$$
$$\theta_{i+1}+\bar{r}_i+\bar{w}_i+t_i+\bar{n}_i \leq M(2-x_{i,j}-x_{i+1,j})+\theta_i+\bar{r}_{i+1}+\bar{w}_{i+1}+\bar{n}_{i+1} \quad \forall i \leq I-1;\ \forall j \leq J$$

The bandwidth at intersection i equals to the bandwidth of subgroup j if it include intersection i:

$$e_i \geq b_j-M(1-x_{i,j}) \quad \forall i \leq I;\ \forall j \leq J$$
$$e_i \leq b_j+M(1-x_{i,j}) \quad \forall i \leq I;\ \forall j \leq J$$
$$\bar{e}_i \geq \bar{b}_j-M(1-x_{i,j}) \quad \forall i \leq I;\ \forall j \leq J$$
$$\bar{e}_i \leq \bar{b}_j+M(1-x_{i,j}) \quad \forall i \leq I;\ \forall j \leq J$$

The decomposition point is an intersection whose downstream one is in a different subgroup:

$$Z_i \geq x_{i,j}-x_{i+1,j} \quad \forall i \leq I-1;\ \forall j \leq J$$
$$Z_i \geq -x_{i,j}+x_{i+1,j} \quad \forall i \leq I-1;\ \forall j \leq J$$
$$\bar{Z}_i \geq \bar{x}_{i,j}-\bar{x}_{i+1,j} \quad \forall i \leq I-1;\ \forall j \leq J$$
$$\bar{Z}_i \geq -\bar{x}_{i,j}+\bar{x}_{i+1,j} \quad \forall i \leq I-1;\ \forall j \leq J$$

Other constraints:

$$w_i, b_j, e_i, \bar{w}_i, \bar{b}_j, \bar{e}_i \geq 0\ 0 \leq \theta_i \leq 1 \quad \forall i \leq I;\ \forall j \leq J$$
$$x_{i,j}, y_j, Z_i, \bar{Z}_i \in \{0,1\} \quad \forall i \leq I;\ \forall j \leq J$$
$$n_i, \bar{n}_i \text{ are integer} \quad \forall i \leq I$$

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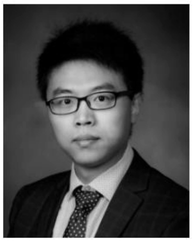

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