# Optimization of Variable Approach Lane Use at Isolated Signalized Intersections

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**The variable approach lane (VAL) at an isolated signalized intersection is an effective way to handle the variation of arrival traffic at intersection approaches by reallocating the space resource according to the time-varying demand volumes. This study developed a model that simultaneously optimizes VAL use and signal timings, with the objective of minimizing the average intersection delay. The model constraints mainly include three parts: VAL use, signal timings, and degree of saturation. The application of the model was demonstrated through two numerical examples. The findings support the notion that the optimization algorithm can effectively reduce traffic delay. However, the benefits of VALs for intersection performance varied under different traffic conditions. One VAL installed on a single approach can effectively reduce cycle length and average delay when the left-turn traffic on that approach is greater than 600 passenger cars units per hour (pcu/h). VALs installed on two opposing approaches provided optimal solutions in 58 of 81 traffic combinations. The average delay decreased by more than 20%, with the exception that no VAL was needed when the left-turn traffic in both approaches was 200 pcu/h. Simulation of the scenarios in Vissim showed similar results of the model under different conditions, which verified the model's validity. The results suggest that the availability of VALs provided the intersection with improved capacity to deal with large traffic fluctuations.**

Roadway intersections can become a travel bottleneck when conflicting traffic movements compete for the same space at the same time. The time and space resources at an intersection must be optimally allocated. Conventional optimization strategies often focus on allocating the time resource, that is, optimizing traffic signal timings. Lane configuration and use, once determined, remain unchanged for a long period (e.g., months or years), leaving little flexibility for reallocating the space resource. In reality there is often an imbalance of lane utilization on an intersection approach: long queues of vehicles wait at some lanes but few or no vehicles at others on the same approach because of the fixed lane use strategy.

To make full use of the space resource at an intersection, the concept of the variable approach lane (VAL) has been proposed. The VAL is an active traffic management operational strategy, the aim of which is to maximize the efficiency of the facility during recurrent and nonrecurrent congestion (*1*). When a VAL is applied at an intersection, the lane function (e.g., traffic movement or direction) can be changed to respond to the spatial variation of traffic demand over time. It is expected that this measure, combined with optimization of signal timings, would provide enhanced intersection capacity compared with optimization of signal timings only.

Variable lanes on road segments, commonly referred to as reversible lanes, have already been put into use throughout the world for decades. Wolshon and Lambert provided a synthesis of reversible lane practices, which summarized the range of reversible lane applications (*2*). It was found that the majority of reversible lane applications were able to achieve the operational objectives with high levels of public acceptance. The VAL concept can be considered an extension of reversible lanes at an intersection, because the underlying ideas are similar: taking advantage of underutilized lanes and reallocating the road space resource more efficiently under time-varying traffic conditions.

There have been some positive applications of VALs in China, the Netherlands, and the United States (*3–5*), where the designated lane can function as a left-turn lane or a through lane to accommodate varying left-turn and through traffic. Before VALs can be widely deployed, many issues, such as the warrant for their use, operational efficiency, safety impact, and design and implementation requirements, need to be resolved. Furthermore, in a more advanced application, when dynamic functional change of the VAL is required, accurate traffic demand estimation is indispensable. If the detection technology allows for estimation of traffic demand in real-time, VALs will become a more prevalent solution for mitigating intersection congestion. There are great prospects as well as challenges for VALs. However, limited studies have been conducted so far.

This study aimed to develop an optimization method for VALs, which is essential for application of VALs. An optimization model of VAL use and signal timings for an intersection was proposed that simultaneously optimizes time and space resources. The operational effectiveness of VALs was evaluated to verify the traffic conditions that warrant its use.

## LITERATURE REVIEW

There has been extensive research on traffic signal optimization, but only a limited number of studies on variable lane use. In general, after an intersection layout is determined, it is not changed for a relatively long time. In contrast, traffic signals can be adjusted to adapt to the fluctuation of traffic demands, by developing different timing plans for different time periods or by using an adaptive signal control system. Operations of VALs can refer to the approaches, by changing the lane function in different analysis periods that are previously determined, or in a more dynamic way based on real-time traffic estimates.

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A proper control strategy is critical for the successful implementation of VALs, especially during transition periods. Jella et al. conducted research on the signing technology for the dynamic lane assignment sign system in Houston, Texas, and demonstrated a high potential for fiber optics signs to deliver information effectively to drivers for dynamic lane assignment (*3*). Harvey and Bullock developed a traffic signal cabinet interface for dynamic lane assignment signs, and recommended a distributed control model because of its simple cabinet retrofit and inherent malfunction management capabilities (*4*).

Lam et al. developed the first integrated model for lane use and signal phase designs (*6*). The primary objective was to minimize the sum of flow ratios of all phases by determining the best combination of lane use and phase plan. A mixed integer linear programming model was introduced and evaluation was based on data collected in Shenzhen, China. The TRANSYT-7F program was used to produce the best cycle length and phase timing and compute the performance indexes. The results indicated that the integrated design performed better in terms of overall delay, stops, and fuel consumption.

Wong and Wong proposed lane-based optimization models with the objectives of maximizing capacity, minimizing cycle length, and minimizing delay (*7, 8*). The optimal lane-marking designs and complicated signal phases and timings can be formed automatically. Numerical examples were provided to demonstrate the effectiveness of the models. This work was further extended by relaxing the number of approach lanes in each traffic arm to maximize reserve capacity at the intersection (*9*). The results showed that when extra lanes were added, reserve capacity kept improving. Meanwhile, the optimized cycle lengths were all binding at the maximum allowable limit when the objective was to maximize reserve capacity.

The work by Lam et al. (*6*) and Wong and Wong (*7, 8*) formulated the theoretical framework for the simultaneous optimization of lane use and signal strategy for isolated intersections, and laid a solid foundation for further studies in this field. Zeng et al. proposed a dynamic lane-use model that combined lane use and signal phase optimization to minimize the sum of the critical flow ratios (*10*). Simulation results in Vissim showed that the model can effectively improve the utilization of time and space resources at intersections and reduce traffic delay and queue length.

Zhang and Wu presented a mathematical model of dynamic lane grouping (DLG), in which the optimal lane allocation was determined by minimizing the maximum flow ratio (*11*). When total demand was constant, the maximum flow ratio, as well as the average delay of DLG, remained almost unchanged for the full spectrum of spatial demand variation. Comparison of DLG with real-time adaptive signal timing indicated that the more varying the traffic was, the more benefits the DLG could provide to reduce average delay. Issues related to the implementation of the DLG algorithm, such as the upstream impacts, safety constraints, traffic demand estimation, integration with existing traffic signal control strategies, and so forth, were also discussed in the paper. Zhao et al. formulated a model to minimize the sum of the critical flow ratios (primary objective) and the differences between the critical flow ratios and the noncritical flow ratios (secondary objective) (*12*). The accuracy and computation time of the model were tested, and it was shown that the model can meet the real-time requirement of dynamic lane assignment.

Previous research has provided good references for further investigations of the VAL concept, which is essentially a lane-based optimization strategy as well. Although the findings all proved the effectiveness of the methods by numerical examples or simulations, the levels of benefits provided by this strategy under varying traffic conditions were still unclear. When setting up a warrant for the implementation of VALs at an intersection, or determining the change in lane use during operations, evaluations of VALs under a wide range of traffic demands are critical, and in-depth analysis is required.

## MODEL FORMULATION

This study focused on VAL use at an isolated signalized intersection. Before proceeding to the formulation of the model, some basic assumptions must be made:

1. At least one approach of the intersection implements one or more VALs, and the VAL would function as a left-turn or through lane.
2. At least one exclusive left-turn lane is provided in the approach with a VAL. In case the variable lane serves as a through lane, left-turn traffic can still be accommodated.
3. Four or more lanes are present in the approach with a VAL, so that, excluding the VAL, there are at least three lanes for left-turn, through, and right-turn traffic to run separately. In case a shared through and right-turn lane exists, at least three lanes in total are present in the approach to ensure normal operations of traffic flow in all directions.
4. When VALs change the functions, the number of exit lanes is no less than the number of lanes required by traffic movements running simultaneously to the exit. Thus, in modeling there is no need to add constraints on the exit lanes.
5. Left-turn and through traffic demands exhibit variations with time. This is a prerequisite for VAL implementation, which gives potential for operational improvement by utilizing the technique.

At a typical intersection with four legs, there are 12 vehicle movements, as shown in Figure 1*a*. Figure 1*b* illustrates a standard National Electrical Manufacturers Association (NEMA) phasing scheme, assigning west and east approach movements to Phases 1, 2, 5, and 6, and south and north approach movements to Phases 3, 4, 7, and 8. The eight discrete phases are assigned to two rings and organized in a sequence to avoid conflicting movements. By adopting this phase scheme, the protected left-turn phasing is always provided. The sequence of phases in the same ring and on the same side of the barrier is not fixed but changes to lead, lag, or lead–lag phasing, providing some flexibility to select an appropriate scheme for the specific site conditions.

Figure 1*c* displays a scheme that allows all movements of an approach to operate at the same time, a special case of the scheme in Figure 1*b* after restricting phases only to concurrent movements of the same approach. When there is not enough space for left turns from opposing approaches to move concurrently, or a shared left–through lane exists, this phasing scheme is commonly used. Permissive left-turn phasing may be provided, as shown in Figure 1*d*, under low traffic volume conditions.

Moreover, the phase schemes in the two barriers are not necessarily the same. For example, NEMA phasing may be adopted for eastbound and westbound movements, while permissive phasing can be adopted for northbound and southbound movements. In this study, the phase scheme in Figure 1*b* was used to formulate the model constraints, and the parameters for signal timings were optimized accordingly. When other types of phase schemes are more appropriate, related constraints can be adjusted with ease.

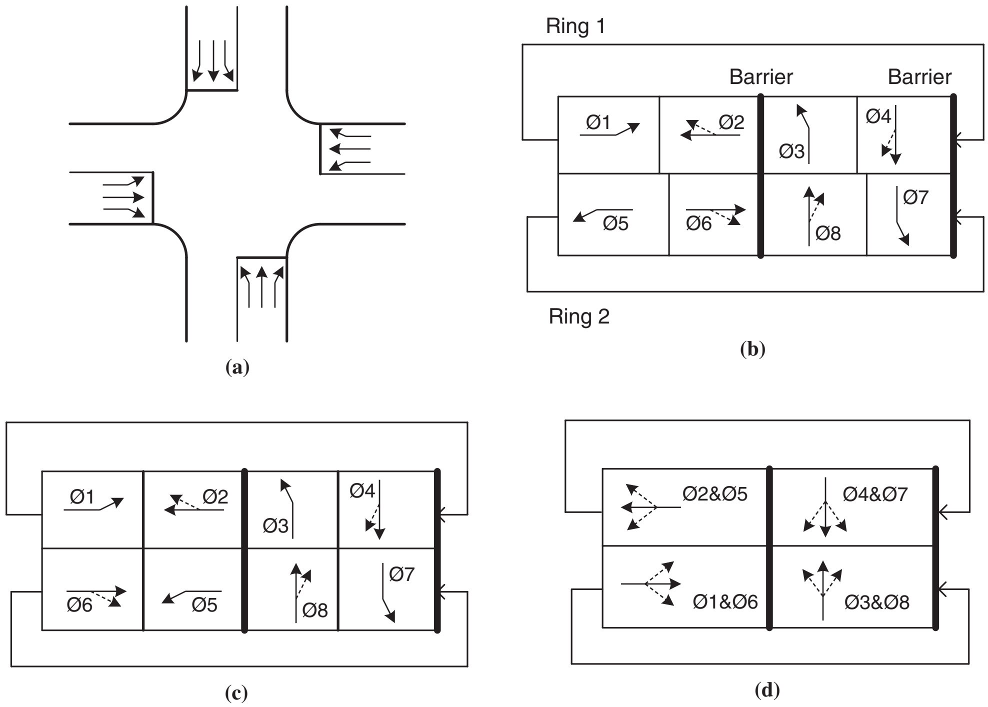


FIGURE 1 Phase schemes for four-legged intersection: (*a*) typical intersection with four legs, (*b*) standard NEMA phasing scheme, (*c*) scheme that allows all movements of an approach to operate at the same time, and (*d*) permissive left-turn phasing.

## Objective Function

To evaluate intersection performance, the most commonly used measures are delay, queue length, and vehicle stops, which are all related (*13*). In previous studies, researchers have selected capacity, cycle length, delay, flow ratio, and so forth as the optimization objectives for their models. In this study, average delay per vehicle was adopted as the measure of effectiveness to assess the effects of VAL implementation at an intersection, because traffic delay is a direct measure of the operational quality of an intersection.

Thus, the objective of the model is set to minimize average delay per vehicle at an intersection by simultaneously optimizing VAL use and signal timings. The total delay for each lane group at the intersection was calculated with the formula in the 2000 *Highway Capacity Manual* (*14*), in which the incremental delay factor was set to 0.5 for pretimed controllers, the upstream filtering adjustment factor was set to 1 for analysis of an isolated intersection, and no initial queue delay from the previous analysis period was assumed. To minimize average delay per vehicle for the whole intersection, the objective function of the model is given by

$$\min d = \frac{\sum_{i=1}^{l} d_i q_i}{\sum_{i=1}^{l} q_i} \quad (1)$$

where

$d$ = average delay per vehicle at intersection (s/vehicle),
$d_i$ = total vehicle delay for lane group $i$ (s),
$q_i$ = flow rate for lane group $i$ (vehicles/h), and
$l$ = total number of lane groups.

## Constraints

Many previous studies have divided the optimization procedure into two steps. The first step was to build an integrated model of lane uses and signal phases, and then in the second step, signal parameters such as cycle length (sometimes it was set to a fixed value) and green times were optimized with conventional methods. In this study, since the phase scheme was set beforehand, signal timings were optimized simultaneously with lane uses. The constraints of the model mainly include three parts: (*a*) VAL use, (*b*) signal timings, and (*c*) degree of saturation.

### *VAL Use*

The VAL can function as a left-turn lane or a though lane, depending on the traffic demands of the approach. A group of binary variables can be defined to control the change of the lane function. A value of 0 means the lane functions as a through lane, and a value of 1 means a left-turn lane. The constraints can be expressed as

$$\alpha_v = \{0, 1\} \qquad \forall v \in [1, 2, 3, \ldots, n] \quad (2)$$

where $\alpha_v$ is a binary variable indicating the function of the VAL $v$, and $n$ is the number of variable approach lanes at the intersection.

### *Signal Timings*

**Cycle Length** Cycle length is the sum of effective green times and lost times in each ring of the phase scheme. If the cycle length is too short, the proportion of lost time increases, which leads to reduced capacity and excessive delay; if cycle length is too long, there would be a minimal increase in capacity but a significant increase in delay. Thus, cycle length should be within a feasible range, specified as

$$C_{\min} \le C \le C_{\max} \tag{3}$$

where $C_{\min}$ is the minimum cycle length (s), and $C_{\max}$ is the maximum cycle length (s).

**Minimum Green Time** On the basis of the phase scheme in Figure 1*b*, effective green time for each phase should be no less than the minimum green time required to ensure the safety of vehicle operations and pedestrians crossing the street, as follows:

$$g_{jk} \ge g_{jk\min} \qquad \forall j \in [1, 2], k \in [1, 2, 3, \ldots, m_j] \tag{4}$$

where

$g_{jk}$ = effective green time for phase $k$ in ring $j$ (s),
$g_{jk\min}$ = minimum effective green time for phase $k$ in ring $j$ (s), and
$m_j$ = number of discrete phases in ring $j$ of the phase scheme.

Effective green time is related to actual green time as follows:

$$g_{jk} = G_{jk} + I_{jk} - t_{Ljk} \qquad j = 1, 2, k = 1, 2, 3, \ldots, m_j \tag{5}$$

where $G_{jk}$ is actual green time for phase $k$ in ring $j$ (s), and $t_{Ljk}$ is total lost time for phase $k$ in ring $j$ (s).

**Phase Scheme** On the basis of the phase scheme shown in Figure 1*b*, a signal cycle consists of all phases in a ring. Meanwhile, phase pairs within the same barrier must end simultaneously. For example, phase Pair 1 and 2, and Phase Pair 5 and 6 have to end simultaneously, and so do Phase Pair 3 and 4, and Phase Pair 7 and 8. The constraints can be expressed as

$$C = \sum_{k=1}^{m_j} \left(G_{jk} + I_{jk}\right) \qquad \forall j \in [1, 2] \tag{6}$$

$$C_1 = \sum_{k=1}^{m_{j1}} \left(G_{jk} + I_{jk}\right) \qquad \forall j \in [1, 2] \tag{7}$$

where

$I_{jk}$ = inter-green time between phase $k$ and its following phase in ring $j$ (s),
$C_1$ = total actual green time and inter-green time for phases in ring $j$ within Barrier 1, and
$m_{j1}$ = number of discrete phases in ring $j$ within Barrier 1.

Additional constraints may be added to meet special requirements. For example, if the phase scheme in Figure 1*c* is adopted, the sums of green and inter-green time for Phases 1 and 6, and Phases 3 and 8 should be equal, respectively.

### *Maximum Acceptable Degree of Saturation*

Degree of saturation is an important indicator of traffic operations. To avoid a traffic breakdown at an intersection, the degree of saturation should be controlled so as not to exceed a maximum acceptable value. The constraint is written as

$$x_i \le x_{i\max} \tag{8}$$

where $x_i$ is the degree of saturation for lane group *i,* and $x_{i\max}$ is the maximum acceptable degree of saturation for lane group *i.*

### Optimization Model

An integrated optimization model of VAL use and signal timings can be formulated, with the objective function to minimize the average delay of the intersection in Equation 1 under the constraints in Equations 2 through 8. The proposed model is a mixed integer nonlinear problem and can be solved by programming in the mathematical software MATLAB (*15*).

## NUMERICAL EXAMPLES

In this section, two cases are presented (*a*) to illustrate the application of the model, and (*b*) to assess the effectiveness of the use of VALs. A four-legged signalized intersection with four approach lanes in the eastbound (EB) and westbound (WB) lanes and three approach lanes in the southbound and northbound directions was considered. In each approach, there was an exclusive left-turn lane, so it was reasonable to provide the protected left-turn phasing shown in Figure 1*b*, and the rest were through lanes. For simplicity of illustration, it was assumed that right-turn traffic ran separately via proper channelization and had little impact on the VAL use and signal timings at the intersection, so it was not shown in the case study.

### Case 1. VAL Installed at a Single Approach

In Case 1, it was assumed that on the EB approach, there was a variable lane between the left-turn and through lanes, which could change to a left-turn lane or a through lane depending on traffic conditions. The intersection layout is shown in Figure 2*a.*

The traffic data are presented in Table 1 for each movement at the intersection. The study tested different combinations of traffic in the EB approach, where a VAL was located, by changing the left-turn and through traffic demands from 300 to 700 passenger car units per hour (pcu/h) and 700 to 1,100 pcu/h, respectively.

For minimum green time, Guidelines for Traffic Signals (RiLSA) (*16*) specified that under normal circumstances, minimum green time for the vehicle movement phase was set to 10 s; for the through movement phase of the major arterial, a minimum green time of 15 s was recommended. In this study, minimum green time for left-turn traffic was set to 10 s. Considering the possible pedestrian crossing movement concurrent with through movement, minimum green times for EB and WB and southbound and northbound through movements were set to 15 and 20 s, respectively. Minimum and maximum cycle lengths were set to 60 and 150 s, respectively. Total lost times per phase and inter-green time were both 3 s. Saturation flow rates for left-turn and through lanes were 1,550 and 1,800 pcu/h, respectively. In practice, the saturation flow rate may be observed in the field or estimated by $S = S_b \times f(F_i)$, where $S$ is the saturation flow rate of the lane (pcu/h); $S_b$ is the basic saturation flow rate of the lane (pcu/h); and $f(F_i)$ is the adjustment factor. The maximum degree of saturation was set to 0.9.

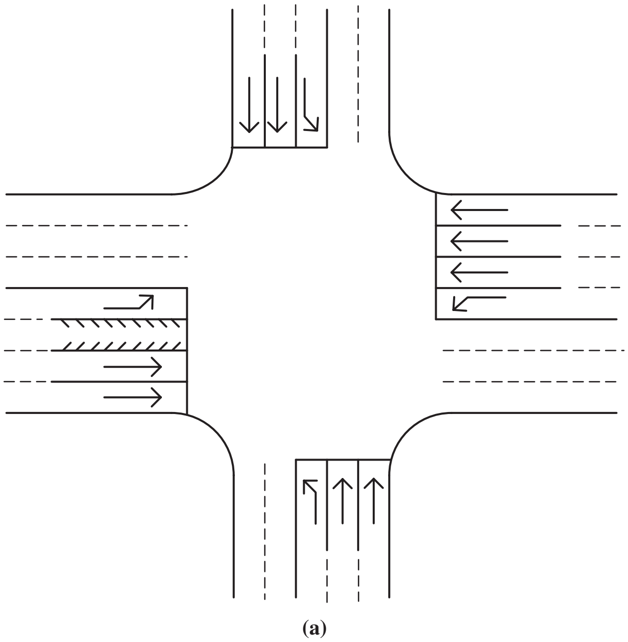


**FIGURE 2 Intersection layout: (*a*) Case 1 and (*b*) Case 2.**

The optimization results are summarized in Table 2. As was expected, under different combinations of left-turn and through traffic volumes, the function of the VAL changes. When left-turn traffic remained unchanged, by increasing the through traffic, the VAL changed from a left-turn lane to a through lane; similarly, when through traffic was the same, increasing the left-turn traffic caused the VAL to change from a through lane to a left-turn lane.

Cycle length and average delay generally increased with increases in traffic. When the VAL changed from a left-turn lane to a through lane with an increase of through traffic, cycle length decreased slightly, suggesting the effects of joint optimization of space and time resources. For fixed lane use (i.e., the VAL is fixed as a through lane), cycle length and average delay increased substantially, especially under high-volume conditions. When left-turn traffic increased to 700 pcu/h, the model could no longer find an optimal solution with fixed lane use.

The percentages of reduction in cycle length and average delay were obtained by comparing the two circumstances, with a VAL versus fixed lane use, with the latter as the base case. Setting up a VAL could reduce the cycle length and average delay when left-turn traffic was relatively high (600 to 700 pcu/h), and could improve the operational efficiency of the intersection. When left-turn traffic was low (300 to 400 pcu/h), the VAL would generally serve as a through lane, and the reduction in average delay would be minimal or zero.

VAL use under different traffic conditions is shown in Figure 3, where the dashed line represents the boundary for the function change of VALs. Below the dashed line, the VAL functions as a through lane, and above, as a left-turn lane. In several cases shown in Table 2, the benefits of VALs are negligible from the practical viewpoint. The solid line was added to represent the boundary for the practical consideration of installing a VAL (10% or more reduction in average delay). Figure 3 only applies to the case described in this section, but similar results can be obtained for intersections with different geometries and traffic conditions, following the same procedure and method.

## Case 2. VAL Installed in Two Opposing Approaches

In Case 2, there were two VALs in the EB and WB approaches, as displayed in Figure 2*b*, and in addition to the variable lanes, the approach had one left-turn lane and one through lane. To evaluate the effectiveness of VALs under different traffic conditions, three levels of traffic demand—low, medium, and heavy loads—were considered for left-turn and through movements in the EB and WB approaches. The traffic data are presented in Table 1 for each movement at the intersection. For left-turn movements, the three levels

**TABLE 1 Traffic Volumes for Turn Movements**

| | | Traffic (pcu/h) by Approach | | | |
|---|---|---|---|---|---|
| Case | Movement | EB | WB | Southbound | Northbound |
| 1 | Left | 300–700 | 400 | 180 | 210 |
| | Through | 700–1,100 | 1,100 | 750 | 680 |
| 2 | Left | 200, 700, 1,200 | 200, 700, 1,200 | 180 | 210 |
| | Through | 300, 800, 1,300 | 300, 800, 1,300 | 750 | 680 |

**TABLE 2 Model Optimization Results and Simulation Results: Case 1**

| | | | With VAL | | Fixed Lane Use[a] | | | | |
|---|---|---|---|---|---|---|---|---|---|
| LT Traffic (pcu/h) | THR Traffic (pcu/h) | VAL (pcu/h) | Cycle Length (s) | Average Delay (s) | Cycle Length (s) | Average Delay (s) | Reduced Cycle Length (%) | Reduced Average Delay (%)[b] | Simulation Reduced Average Delay (%)[b] |
| 300 | 700 | 0 | 78.8 | 36.5 | 78.8 | 36.5 | 0 | 0 | 0 |
| | 800 | 0 | 78.0 | 37.0 | 78.0 | 37.0 | 0 | 0 | 0 |
| | 900 | 0 | 79.6 | 37.7 | 79.6 | 37.7 | 0 | 0 | 0 |
| | 1,000 | 0 | 81.4 | 38.6 | 81.4 | 38.6 | 0 | 0 | 0 |
| | 1,100 | 0 | 84.6 | 39.5 | 84.6 | 39.5 | 0 | 0 | 0 |
| 400 | 700 | 1 | 82.0 | 37.7 | 83.6 | 40.2 | 1.8 | 6.1 | 4.8 |
| | 800 | 1 | 87.2 | 39.7 | 83.8 | 40.4 | –4.0 | 1.7 | 4.3 |
| | 900 | 0 | 84.3 | 40.8 | 84.3 | 40.8 | 0 | 0 | 0 |
| | 1,000 | 0 | 85.4 | 41.2 | 85.4 | 41.2 | 0 | 0 | 0 |
| | 1,100 | 0 | 86.9 | 41.9 | 86.9 | 41.9 | 0 | 0 | 0 |
| 500 | 700 | 1 | 82.0 | 38.3 | 98.6 | 46.5 | 16.8 | **17.5** | **17.1** |
| | 800 | 1 | 87.2 | 40.2 | 98.7 | 46.4 | 11.6 | **13.3** | **14.5** |
| | 900 | 1 | 93.5 | 42.6 | 98.7 | 46.4 | 5.3 | 8.3 | 8.4 |
| | 1,000 | 1 | 102.8 | 45.5 | 98.9 | 46.4 | 3.9 | 2.0 | 1.6 |
| | 1,100 | 0 | 99.0 | 46.6 | 99.0 | 46.6 | 0 | 0 | 0 |
| 600 | 700 | 1 | 82.4 | 39.1 | 139.7 | 62.1 | 41.0 | **37.1** | **38.8** |
| | 800 | 1 | 87.4 | 40.8 | 139.7 | 61.7 | 37.4 | **33.9** | **37.2** |
| | 900 | 1 | 93.5 | 43.0 | 139.7 | 61.4 | 33.1 | **30.0** | **31.1** |
| | 1,000 | 1 | 102.8 | 45.9 | 139.7 | 61.1 | 26.4 | **24.9** | **24.8** |
| | 1,100 | 1 | 114.1 | 50.0 | 139.7 | 60.9 | 18.3 | **18.0** | **17.5** |
| 700 | 700 | 1 | 84.0 | 40.1 | — | — | — | — | — |
| | 800 | 1 | 88.0 | 41.5 | — | — | — | — | — |
| | 900 | 1 | 93.6 | 43.5 | — | — | — | — | — |
| | 1,000 | 1 | 102.8 | 46.5 | — | — | — | — | — |
| | 1,100 | 1 | 114.1 | 50.3 | — | — | — | — | — |

NOTE: LT = left turn; THR = through; — = no results were obtained.
[a]Fixed lane use means that the VAL is fixed as a through lane.
[b]Boldface entries indicate more than a 10% reduction in average delay.

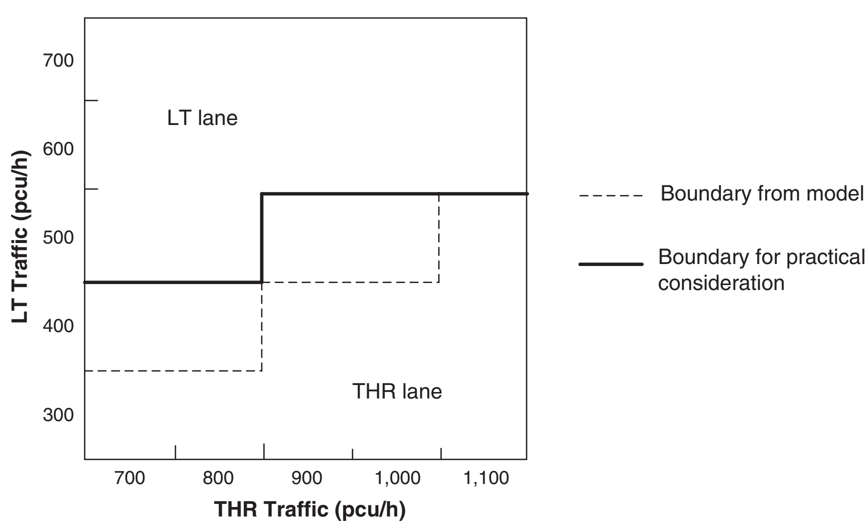


**FIGURE 3 VAL function by traffic condition.**

were 200, 700, and 1,200 pcu/h, and for through movements, 300, 800, and 1,300 pcu/h, resulting in 81 combinations. The southbound and northbound traffic demands were set the same as in Case 1. The parameters that were needed to solve the optimization model remained the same as in Case 1.

The results under different traffic conditions are shown in Table 3 and Figure 4. Among the 81 traffic combinations, 23 cases were unable to meet the constraints set by the model and were unsolved (not listed in the table). The values in the columns for EB VAL and WB VAL can be 0, 1, or 2, meaning that 0, 1, or 2 VALs were converted to left-turn lanes on that approach. The general trend is similar to that of Case 1. When left-turn and through demands on one approach were constant, for the opposing approach the VALs may change from two left-turn lanes to one, or from one to zero, by increasing the through traffic. When through traffic remained unchanged and left-turn traffic increased, the opposite result was observed.

The lane function change may be affected by the presence of the VAL in the opposing approach. As an example, when EB left-turn and through traffic were 200 and 800 pcu/h, respectively, and the WB left-turn traffic was 1,200 pcu/h, with the increase of the WB through traffic, the VAL in the EB lanes first changed from zero to one left-turn lane because more green split was given to its conflicting phase, the opposing through traffic. Then the VAL changed from one left-turn lane to zero again, because the opposing through traffic used an extra lane, so the signal released some of the green split. This is a great illustration of simultaneous optimization of time and space resources and interactions between VALs in opposite approaches.

In general, when traffic demand for a movement (left-turn or through) increased, the time and space resources of the intersection would be reallocated. The changes in signal timings and VAL use affected not only the movement with increased demand, but also the other movements in the same and opposite approaches, which were all competing for limited time and space resources. Specifically, left-turn and through traffic in the same approach were competing for the space resource, and left-turn and through traffic in the opposing approach were competing for the time resource. Finally a balance would be achieved.

The optimization results for fixed lane use (i.e., all VALs function as through lanes) are also presented in Table 3 for comparison. Among the 81 traffic combinations, only 16 were solved, indicating that the VAL could make the intersection more adaptable to traffic fluctuations than fixed lane use. For the unsolved cases, the program provided a suboptimal solution, meaning that certain constraints in the model were not met.

Overall, the presence of VALs in two opposing approaches can effectively reduce average delay. As shown in Figure 4, reductions in average delay were minimal for nine cases, in which EB and WB left-turn traffic demands were both 200 pcu/h, which can be accommodated by one exiting left-turn lane and no VAL is needed. For the other cases, reductions in average delay were all larger than 20%. Many of the cases show a reduction of between 60% and 80%. The maximum reduction in average delay was about 151 s (77%). Cycle length was reduced by as much as 79 s (53%).

### Simulation Analysis

The effects of VAL use were further examined in the traffic simulation software Vissim (*17*). Scenarios with and without VALs under varying traffic conditions in Cases 1 and 2 were simulated. The simulation time was set to 4,500 s, and data were recorded from 900 s to ensure a stable traffic flow. Multiple-run mode was adopted to mitigate bias caused by the stochastic process of the simulation. The number of runs was set to 10, with different random seeds, and the average of the results was used to evaluate traffic operations.

The simulation results for Case 1 showed that reductions in average delay because of VAL use were very close to the model results. The use of VALs was more effective under higher left-turn demand (600 pcu/h) than lower left-turn demand (300 to 400 pcu/h), for which the VAL served as a through lane in most cases.

Average delays at the intersection for the scenarios in Case 2 are presented in Table 3. For scenarios with fixed lane use, simulation for 25 scenarios failed, in which less than 90% of input traffic demands were discharged at the end of the simulation because of the excessive delay. This finding indicated that under such traffic conditions, intersection operations with fixed lane use would fail. For the rest of the scenarios, changes in average delay under different conditions showed a similar trend as the model results. The use of VALs could effectively reduce average delay, and the percentages of reduction were very close to those of the model results, as shown in Figure 4.

## CONCLUSIONS

Given the varying traffic demands on the approaches to an intersection, some lanes are underused while others are overloaded. This study formulated an integrated mathematical model to optimize the use of VALs and signal timings, with the aim to minimize average intersection delay. The model can be applied easily to evaluate the benefits of VALs under different intersection geometries and traffic conditions. Two numerical cases for VALs installed in a single approach and in two opposing approaches were conducted and analyzed. The results show that the model can optimally allocate space and time resources, and improve the performance of the intersection.

The benefits of providing VALs under different traffic conditions were presented. For one VAL installed on a single approach, when the left-turn traffic of that approach was less than 600 pcu/h, reductions in average delay and cycle length were small (less than 10%). For the practical consideration of installing VALs, the range of traffic conditions under which a VAL is effective in reducing the average delay was obtained. VALs installed on two opposing approaches provided the intersection with better capabilities to cope with a wider range of traffic fluctuations and ensure smooth traffic operations. The change of the lane function depended not only on the traffic variations of the approach, but also on the lane use of the opposing approaches. The allocation of the space resource was achieved by coordinated optimization of both approaches, combined with signal timing optimization.

Among the 81 traffic combinations with fixed lane use, only 16 cases (28.4%) were able to obtain the optimization results, but with a VAL, the cases with optimal solutions increased to 58 (80.2%). With a VAL, average delay decreased by more than 20%, except for nine cases in which left-turn traffic demands in both approaches were 200 pcu/h and no VAL was actually required. Further examination of the use of VALs in the simulation software Vissim verified the effectiveness of VALs in reducing average delay at an intersection. It was found that the intersection could be more adaptable to large traffic variations with VALs, and the operational efficiency of the intersection could be greatly improved under such circumstances.

**TABLE 3 Model Optimization Results and Simulation Results: Case 2**

| | Traffic (pcu/h) | | | With VAL | | | | Fixed Lane Use[a] | | Simulation Average Delay (s) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EB LT Traffic (pcu/h) | EB THR | WB LT | WB THR | EB VAL | WB VAL | Cycle Length (s) | Average Delay (s) | Cycle Length (s) | Average Delay (s) | With VAL | Fixed Lane Use |
| 200 | 300 | 200 | 300 | 1 | 1 | 68.1 | 26.1 | 71.5 | 29.4 | 23.1 | 24.3 |
| | | | 800 | 1 | 0 | 70.1 | 28.2 | 70.1 | 29.9 | 25.0 | 24.8 |
| | | | 1,300 | 1 | 0 | 76 | 30.6 | 75.7 | 33.3 | 26.9 | 27.6 |
| | | 700 | 300 | 1 | 2 | 72.9 | 30.2 | 135.4 | 59.0 | 25.6 | 45.6 |
| | | | 800 | 1 | 1 | 81.5 | 33.1 | 135.4 | 54.9 | 27.9 | 42.4 |
| | | | 1,300 | 1 | 1 | 92.2 | 37.1 | 135.4 | 52.2 | 31.5 | 42.0 |
| | | 1,200 | 300 | 1 | 2 | 85.7 | 35.1 | 150.0[b] | 144.3[b] | 29.6 | — |
| | | | 800 | 1 | 1 | 106.6 | 42.4 | 150.0[b] | 128.7[b] | 35.1 | — |
| | | | 1,300 | 1 | 1 | 106.6 | 41.8 | 150.0[b] | 122.4[b] | 36.7 | — |
| | 800 | 200 | 300 | 0 | 1 | 70.1 | 28.2 | 70.1 | 29.9 | 25.0 | 24.8 |
| | | | 800 | 0 | 0 | 68.7 | 30.1 | 68.7 | 30.1 | 24.8 | 25.0 |
| | | | 1,300 | 1 | 0 | 78.2 | 32.2 | 75.8 | 33.0 | 26.9 | 27.0 |
| | | 700 | 300 | 0 | 2 | 71.3 | 31.9 | 150.0[b] | 71.8[b] | 26.0 | 55.9 |
| | | | 800 | 0 | 1 | 78.7 | 35.9 | 150.0[b] | 66.7[b] | 28.7 | 51.6 |
| | | | 1,300 | 1 | 1 | 94.3 | 40.5 | 150.0[b] | 63.7[b] | 32.8 | 50.7 |
| | | 1,200 | 300 | 0 | 2 | 82.5 | 37.2 | 150.0[b] | 165.1[b] | 30.6 | — |
| | | | 800 | 1 | 2 | 111.4 | 48.7 | 150.0[b] | 149.1[b] | 38.8 | — |
| | | | 1,300 | 0 | 1 | 115.8 | 50.2 | 150.0[b] | 138.2[b] | 40.8 | — |
| | 1,300 | 200 | 300 | 0 | 1 | 76 | 30.6 | 75.7 | 33.3 | 26.9 | 27.6 |
| | | | 800 | 0 | 1 | 78.2 | 32.2 | 75.8 | 33.0 | 26.9 | 27.0 |
| | | | 1,300 | 0 | 0 | 79.1 | 34.0 | 79.1 | 34.0 | 27.2 | 27.5 |
| | | 700 | 300 | 0 | 2 | 79.1 | 36.0 | 150.0[b] | 88.2[b] | 29.4 | 75.0 |
| | | | 800 | 0 | 1 | 91.9 | 41.5 | 150.0[b] | 81.8[b] | 33.4 | 74.0 |
| | | | 1,300 | 0 | 1 | 98.6 | 44.3 | 150.0[b] | 76.1[b] | 36.2 | 77.5 |
| | | 1,200 | 300 | 0 | 2 | 101 | 45.9 | 150.0[b] | 196.7[b] | 37.2 | — |
| 700 | 300 | 200 | 300 | 2 | 1 | 72.9 | 30.2 | 135.4 | 59.0 | 25.6 | 45.6 |
| | | | 800 | 2 | 0 | 71.3 | 31.9 | 150.0[b] | 71.8[b] | 26.0 | 55.9 |
| | | | 1,300 | 2 | 0 | 79.1 | 36.0 | 150.0[b] | 88.2[b] | 29.4 | 75.0 |
| | | 700 | 300 | 2 | 2 | 72.1 | 33.4 | 135.4 | 59.7 | 26.2 | 45.3 |
| | | | 800 | 2 | 1 | 80.7 | 37.8 | 150.0[b] | 70.0[b] | 29.8 | 79.1 |
| | | | 1,300 | 2 | 1 | 105.8 | 47.1 | 150.0[b] | 87.1[b] | 38.4 | 90.8 |
| | | 1,200 | 300 | 1 | 2 | 86.6 | 37.0 | 150.0[b] | 131.9[b] | 34.6 | — |
| | | | 800 | 1 | 1 | 106.6 | 45.7 | 150.0[b] | 133.3[b] | 36.2 | — |
| | | | 1,300 | 2 | 1 | 139.7 | 58.0 | 150.0[b] | 131.8[b] | 67.5 | — |
| | 800 | 200 | 300 | 1 | 1 | 81.5 | 33.1 | 135.4 | 54.9 | 27.9 | 42.4 |
| | | | 800 | 1 | 0 | 78.7 | 35.9 | 150.0[b] | 66.7[b] | 28.7 | 51.6 |
| | | | 1,300 | 1 | 0 | 91.9 | 41.5 | 150.0[b] | 81.8[b] | 33.4 | 74.0 |
| | | 700 | 300 | 1 | 2 | 80.7 | 37.8 | 150.0[b] | 70.0[b] | 29.8 | 79.1 |
| | | | 800 | 1 | 1 | 92 | 43.8 | 150.0[b] | 75.2[b] | 33.5 | 56.1 |
| | | 1,200 | 300 | 1 | 2 | 94.9 | 44.1 | 150.0[b] | 155.2[b] | 34.1 | — |
| | 1,300 | 200 | 300 | 1 | 1 | 92.2 | 37.1 | 135.4 | 52.2 | 31.0 | 42.0 |
| | | | 800 | 1 | 1 | 94.3 | 40.5 | 150.0[b] | 65.0[b] | 32.8 | 50.7 |
| | | | 1,300 | 1 | 0 | 98.6 | 44.3 | 150.0[b] | 77.0[b] | 36.2 | 77.5 |
| | | 700 | 300 | 1 | 2 | 105.8 | 47.1 | 150.0[b] | 85.2[b] | 38.4 | 90.8 |
| 1,200 | 300 | 200 | 300 | 2 | 1 | 85.7 | 35.1 | 150.0[b] | 144.3[b] | 29.0 | — |
| | | | 800 | 2 | 0 | 82.5 | 37.2 | 150.0[b] | 165.1[b] | 30.6 | — |
| | | | 1,300 | 2 | 0 | 101 | 45.9 | 150.0[b] | 196.7[b] | 37.2 | — |
| | | 700 | 300 | 2 | 1 | 86.6 | 37.0 | 150.0[b] | 131.9[b] | 34.6 | — |
| | | | 800 | 2 | 1 | 94.9 | 44.1 | 150.0[b] | 157.4[b] | 34.1 | — |
| | | 1,200 | 300 | 2 | 2 | 87.6 | 39.7 | 150.0[b] | 181.2[b] | 31.3 | — |
| | | | 800 | 2 | 1 | 139.7 | 58.8 | 150.0[b] | 192.4[b] | 49.2 | — |
| | 800 | 200 | 300 | 1 | 1 | 106.6 | 42.4 | 150.0[b] | 128.9[b] | 33.4 | — |
| | | | 800 | 2 | 1 | 111.4 | 48.7 | 150.0[b] | 149.9[b] | 38.8 | — |
| | | 700 | 300 | 1 | 1 | 106.6 | 45.7 | 150.0[b] | 129.4[b] | 36.2 | — |
| | | 1,200 | 300 | 1 | 2 | 139.7 | 57.8 | 150.0[b] | 192.4[b] | 49.2 | — |
| | 1,300 | 200 | 300 | 1 | 1 | 106.6 | 41.8 | 150.0[b] | 123.0[b] | 35.4 | — |
| | | | 800 | 1 | 0 | 115.8 | 50.2 | 150.0[b] | 139.0[b] | 40.8 | — |
| | | 700 | 300 | 1 | 2 | 139.7 | 58.0 | 150.0[b] | 131.8[b] | 67.5 | — |

NOTE: — = no results were obtained.
[a]Fixed lane use means that all VALs are fixed as through lanes.
[b]Suboptimal solution for which certain constraints in the model are not satisfied.

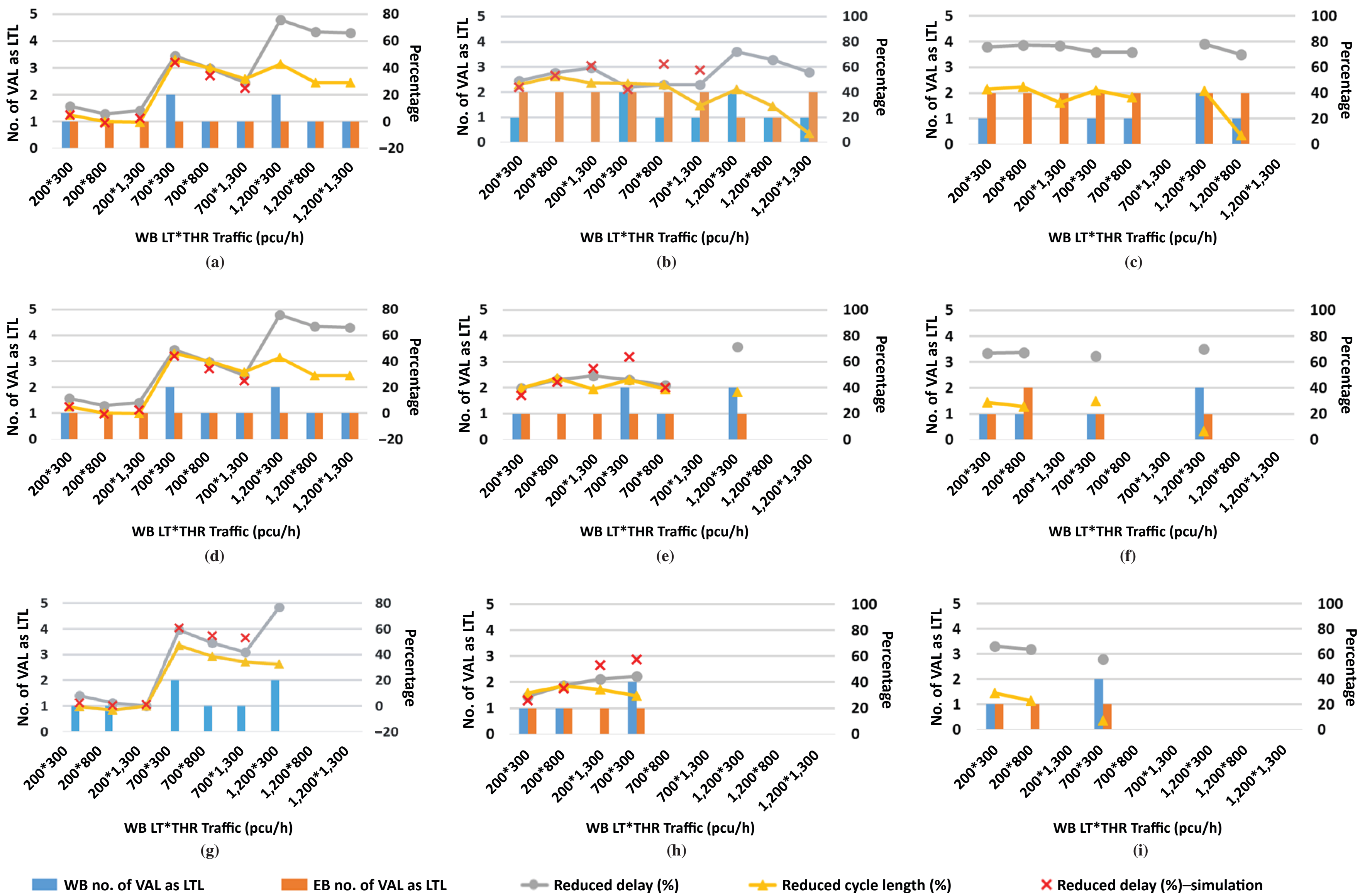


FIGURE 4 Number of VALs as LT lanes and percentages of reduction in cycle length and average delay: (*a*) EB 200 pcu/h ∗ 300 pcu/h, (*b*) EB 700 pcu/h ∗ 300 pcu/h, (*c*) EB 1,200 pcu/h ∗ 300 pcu/h, (*d*) EB 200 pcu/h ∗ 300 pcu/h, (*e*) EB 700 pcu/h ∗ 800 pcu/h, (*f*) EB 1,200 pcu/h ∗ 800 pcu/h, (*g*) EB 200 pcu/h ∗ 1,300 pcu/h, (*h*) EB 700 pcu/h ∗ 1,300 pcu/h, and (*i*) EB 1,200 pcu/h ∗ 1,300 pcu/h (EB 200 pcu/h ∗ 300 pcu/h indicates that left-turn and through traffic demands on eastbound approach = 200 and 300 pcu/h, respectively; LTL = left-turn lane; no. = number).

The algorithm in its current form is not yet ready for field testing. The limitations and recommendations are summarized in the following list:

1. When a VAL changes the function, there will be a transition period during which normal traffic operations may be affected, incurring excess delay. This effect was not studied, but will be included in future research.
2. To evaluate the effectiveness of VALs in practical application, the whole process of VAL operations should be covered, including the transition period. The benefits gained by changing the VAL and the possible loss caused by the transition should be taken into account. Then validation of the model can be conducted with observed demand profiles from locations that experience variation.
3. The objective function in the model was simplified by assuming no initial queue delay from the previous analysis period. Although the proposed model is able to optimize traffic operations and reduce the queue, under heavy traffic conditions the impact of residual queues from the previous analysis period may become a critical issue. Further analysis of the impacts of initial queues on the optimization model should be conducted.
4. The effects of different vehicle arrival types at the intersection were not considered in the model. Considering a variety of vehicle arrival types would provide a more accurate estimate of the intersection delay. The present model may be improved by accounting for such effects.

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