Operational Analysis and Signal Design for Asymmetric Two-Leg Continuous Flow Intersections

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ABSTRACT

Despite the increasing implementation of Continuous Flow Intersection (CFI) in practice, the development of reliable guidelines for its operational analysis and signal design remains at the infancy stage, especially for the popular two-leg asymmetric CFI design due to its relative low cost and desirable efficiency. To best utilize the capacity of such a CFI design, this paper presents a signal optimization model that can serve as an effective tool for engineers to design the cycle length, phase duration and sequences, and offsets for both its primary and sub intersections. By accounting for the commonly-encountered constraints of short bay length for turning movements and the interrelations between critical flow movements, the proposed model can prevent the queue spillover on left turn bays, and offer concurrent progression for both the through and left-turn flows.

To ensure the applicability and effectiveness of the proposed model, this study has further used the data from a proposed asymmetric CFI in Maryland for performance evaluation. The results of extensive simulation with field data confirm that the proposed signal optimization with its capability to account for all physical constraints and flow conflicts can indeed perform as expected, that is, offering concurrent progression to both through and left-turning flows and preventing any queue from spilling over its designated bay.

INTRODUCTION

As is well recognized, the main feature of CFI is to eliminate the conflict between the left-turn and opposing through traffic by relocating the left-turn bay to several hundred feet upstream of the primary intersection so that the through and left-turn flows can move concurrently. Due to the increasing applications of CFI, some fundamental issues associated with its operational efficiency have emerged as the priority subjects in the traffic community. For instance, Goldblatt et al. *(1)* showed that the efficiency of CFI is particularly pronounced when the traffic volumes in some approaches exceed the capacity of a conventional intersection. Based on simulation results, Reid and Hummer *(2-3)* indicated that CFIs offer the potential to accommodate heavy left-turn volumes.

Along the same line, some researchers devote considerable efforts on analyzing the operational benefits of a CFI design, compared with conventional intersection *(4-5)*. In a later study, Cheong et al. *(6)* compared the performance of CFIs under balanced and unbalanced volume conditions, and reported that switching a conventional intersection to CFI can reduce the total delay by approximately 60% ~ 85% percent. Kim et al. *(7)* addressed the initiative works in the state of Maryland to provide a clearing house for unconventional arterial intersections, and also applied their concepts to selected locations. Mohamed and Sayed *(8)* reported similar results and further argued that the capacity improvement from a CFI design is insensitive to an increase in the left-turn volume. Yang et al. *(9)* developed a set of planning models to evaluate the geometric features of a CFI design, and identify the potential queue spillback locations, based on the estimated queue length and the available link length.

It is noticeable from the literature that there are four types of CFI designs being implemented in practice *(10)*: Full CFI (each of the four approaches contains a CFI leg), CFI-T (T-intersection contains one CFI leg), Symmetric two-leg CFI (contains two CFI legs in opposite directions), and Asymmetric two-leg CFI (contains two neighboring CFI legs). To best utilize the intersection capacity, some researchers focused on another category of studies, that is, developing signal plans for CFIs. For example, Hughes et al. *(11)* analyzed the geometric features of each type of CFI, and suggested the corresponding signal phase design. Hilderbrand *(12)* proposed an actuated signal control system for Full CFI, and demonstrated its operational benefits by comparing the resulting delays with a conventional intersection. Also targeting on the Full CFI, You et al. *(13)* developed a pre-timed signal optimization model to design the cycle length, phase duration, and offsets for its sub-intersections. For the same purpose but with different simulations, Sun et al. *(14)* and Chang et al. *(15)* developed signal optimization models to minimize the total delay at a Full CFI intersection.

In brief, most existing studies have focused on critical issues associated with Full CFI. However, due to the high construction cost and required right-of-way, Full CFI is not commonly implemented in US (only a few Full CFIs are under-construction in Louisiana). In contrast, most states, such as Utah, Ohio, New York, Louisiana, Colorado, and Mississippi, have constructed and operated two-leg CFIs which only place CFI legs in the two major approaches with heavy left-turning volumes. Hence, design of an optimized signal plan for such intersections, which differs from the one for Full CFI, is a vital issue.

By relocating the left-turn bay on the left-side of the opposite through lanes, a Full CFI allows a simple two-phase signal control plan for its primary intersection and four sub-intersections *(8)*. On the primary intersection of a symmetric two-leg CFI, only one additional signal phase shall be used to accommodate the left-turning flows from the two conventional approaches. Hence, a well-developed Full CFI signal optimization model is potentially implementable to a symmetric two-leg CFI with minor modifications. However, due to the unique geometric features of asymmetric two-leg CFI, it has the potential for best utilizing the intersection capacity with an optimized signal plan.

OPERATIONAL ANALYSIS

Figure 1 presents the geometric layout of its three sub-intersections and the conflict traffic movements. Compared with the conventional intersections, the total number of conflict points has been reduced from 24 to 16 due to the two CFI legs. For example, the conflict between the left-turn flows from a CFI leg and its opposing through flows has been successfully eliminated. In addition, by placing the two CFI legs in mutual perpendicular directions, no conflict would exist between their left-turn flows.

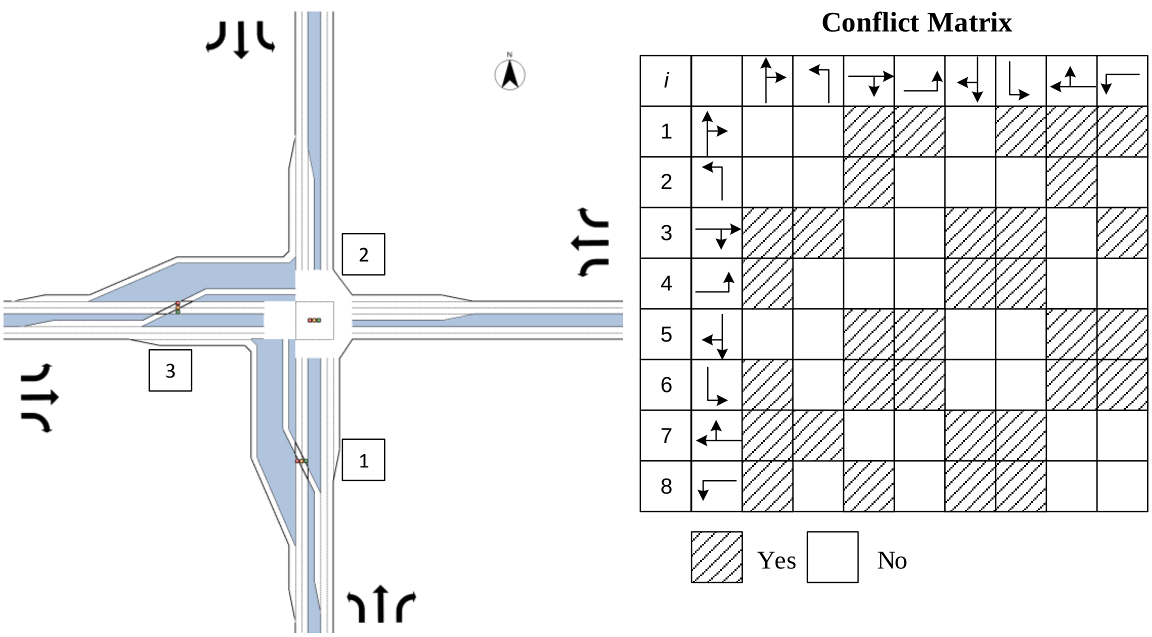

FIGURE 1. Geometry and conflict matrix of an asymmetric CFI

Due to the high construction cost and its large footprint, the distance between sub intersections in CFI is inevitably shorter than the intersection spacing on conventional arterials. Hence, the heavy volume on a CFI leg may cause queue spillovers on some short links and consequently block neighboring intersections. Figure 2 shows three possible blockage scenarios in a typical asymmetric two-leg CFI: 1) the left-turn bay is insufficient to accommodate the intended left-turn volumes, and thus spill back to partially block the through traffic; 2) the overflowed queues from the through lane groups may block the entry of the left-turn bay, and thus completely block the left-turn traffic; and 3) the queuing vehicles may reach the downstream link and block the upstream traffic. Hence, an optimal signal design model for such CFI shall effectively account for all above potential blockage issues.

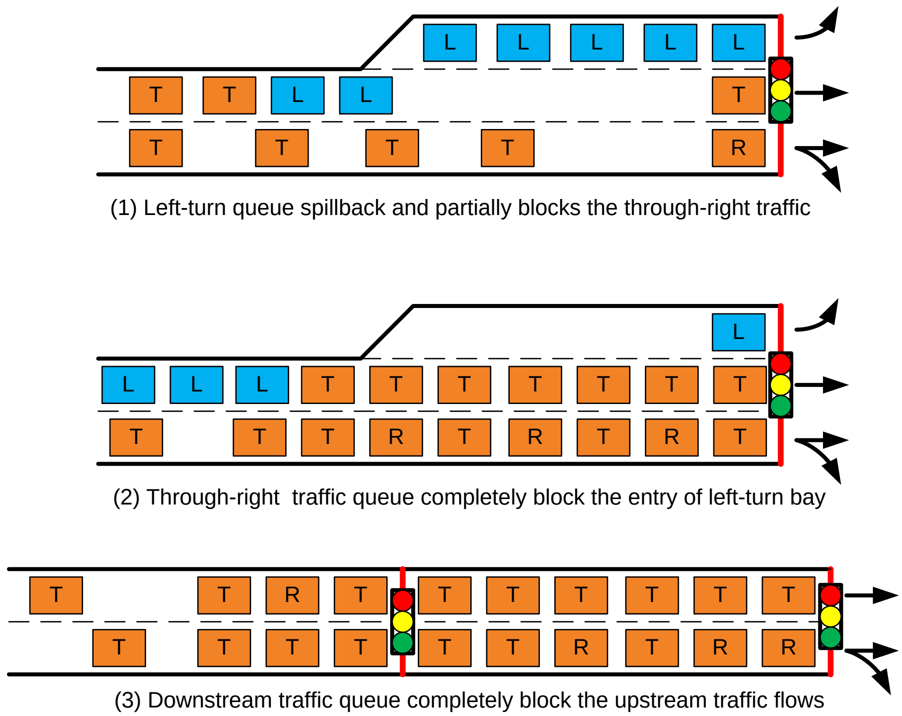

FIGURE 2 Blockage scenarios in a CFI

In brief, a model signed to optimize the signal design for such a CFI shall have the following functions: 1) optimizing the signal plan and phase sequences to best utilize the intersection capacity; 2) preventing the potential queue spillover with the optimized cycle length, green split, and offset for each sub-intersection; 3) accommodating both through and heavy turning flows with concurrent progression bands.

SIGNAL OPTIMIZATION MODEL

Objective Function

As reported in the literature *(17-18)*, a well-designed signal needs to be able to maximize the capacity of an intersection under the given geometric layout. As reported in the literature, the traffic demand matrix can be multiplied with a common flow multiplier μ to represent the maximum amount of the increased volume that would still allow the intersection to perform reasonably well (*19*). Hence, one can convert such a signal optimization problem to an issue of determining the maximal multiplier:

$$Maxmize \sum_{l} \mu_l \tag{1}$$

Note that such an objective function can be used to optimize the signal timings for each sub-intersection of CFI. In addition, when designing the signal progression plan to coordinate those sub-intersections, a commonly used objective function is to maximize the total green bandwidth for those critical movements, which is given as follows:

$$Maxmize \sum_{p \in P} \eta_p b_p \tag{2}$$

where η_p and b_p denote the weighting factor and green bandwidth of critical movement *p*, respectively.

Due to the unique geometric features of an asymmetric two-leg CFI, a simple two-phase signal plan can be used on its two crossover intersections. However, the phase plan on its primary intersection can concurrently affect the intersection capacity and signal progression efficiency. In responds to such issues, the proposed model is designed to maximize the pre-defined Performance Index (PI) shown below:

$$Maxmize\ \ PI = \eta' \sum_{l\in L} \mu_l + \sum_{p\in P} \eta_p b_p \tag{3}$$

where μ_l denotes the flow multiplier for intersection *l*; η' is a weighting factor; *L* and *P* are sets of intersections and critical paths, respectively. To ensure that each traffic movement has a sufficient green duration to pass the sub-intersections, one shall note that the weighting factor η' needs to be significantly greater than η_p in the objective function.

Constraints

Given the phasing plan and traffic demand pattern at each intersection, the following constraints should be satisfied to ensure that the degree of saturation at each lane group is below the acceptable limit:

$$\mu_l \alpha_{l,i} q_{l,i} \le s_{l,i} (\phi_{l,i} - \delta \times \xi) \quad \forall l,i \tag{4}$$

where, $\alpha_{l,i}$ denotes the lane use factor for lane group *i* at the intersection *l*, which is a function of the number of lanes (e.g., 0.55 for two lanes); $q_{l,i}$ is the traffic volume in lane group *i* at the intersection *l*, and $s_{l,i}$ is the corresponding saturation flow rate (unit: veh/hour/lane); ξ is the reciprocal of the common cycle length; $\Phi_{l,i}$ is the duration of the green phase for lane group *i* at the intersection *l*; δ denotes the duration of lost time due to the transition between consecutive signal phases. The index of intersections and definitions of lane groups at the main intersection are listed in Figure 1. Note that there are only two movements, through (*i*=1) and left turn (*i*=2), for these two sub-intersections.

The common cycle length and each phase duration shall be subjected to the constraints of a minimum and a maximum as follows:

$$\frac{1}{C_{\max}} \le \xi \le \frac{1}{C_{\min}} \tag{5}$$

$$\xi \times g_{\min} \le \phi_{l,i} \le \xi \times g_{\max} \qquad \forall l,i \tag{6}$$

where, $C_{\min}$ and $C_{\max}$ are the minimal and maximal cycle lengths; and $g_{\min}$ and $g_{\max}$ are the minimal and maximal phase durations. Also, the sum of phase durations at the main intersection should equal the cycle length:

$$\sum_i \phi_{l,i} = 1 \qquad \forall l \tag{7}$$

Since these two sub intersections have only two phases, it is not necessary to discuss their phase sequences. However, the phasing plan and phase sequence should be optimized at the main intersection so that all critical movements may benefit from signal progression. To design the optimal phase plan and phase sequence for the main-intersection, this study has proposed the following constraints to determine the sequence of green times allocated to different movements:

$$x_{i,j} - 1 \le \theta_i + \phi_i - \theta_j \le x_{i,j} \ , \ i, j \in I \quad if \quad f_{i,j} = 1 \tag{8}$$

where θ_i denotes the start of a green time of movement *i* at the main intersection in a signal cycle; $x_{i,j}$ and $f_{i,j}$ are binary variable and parameter, respectively:

$$x_{i,j} = \begin{cases} 0; & \text{if the green time for movement i is ahead of the one for j} \\ 1; & \text{otherwise} \end{cases}$$

$$f_{i,j} = \begin{cases} 0; & \text{no conflict between movement i and j can be observed at the main intersection} \\ 1; & \text{otherwise} \end{cases}$$

Also to ensure the feasibility of the produced phase plan, the proposed model adopts the following two constraints:

$$x_{i,j} + x_{j,i} = 1 \ , \ i, j \in I \quad if \quad f_{i,j} = 1 \tag{9}$$

$$x_{i,k} + x_{k,j} - 1 \le x_{i,j} \le x_{i,k} + x_{k,j} \ , \ i, j, k \in I \quad if \quad f_{i,j} = f_{i,k} = f_{k,j} = 1 \tag{10}$$

These two sets of constraints are set to make sure that $x_{i,j}$ is able to represent the sequence of phases for two lane groups.

As discussed above, the queue spillover on a short link can may result in the intersection blockage and consequently affect the operational efficiency of a CFI. Hence, under such conditions, one shall control the traffic queue on these links to be below the storage capacity. Figure 3 shows an approximate queueing formation process under such conditions.

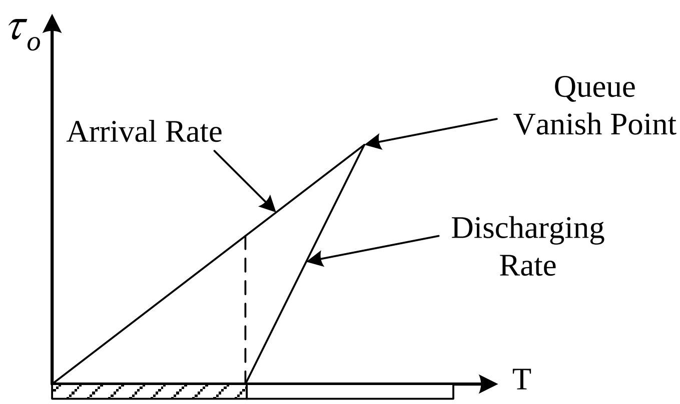

FIGURE 3 the deterministic queuing formation process

Based on the signal timings and coming flows, one can estimate the queue length on lane group *i* with the following equation:

$$\tau_i = \frac{(1 - \phi_i + \delta \times \xi) \cdot \alpha_i q_i \cdot s}{(s - \alpha_i q_i)\xi} \tag{11}$$

Then, one shall set the following queue length constraints to prevent the queue from exceeding the bay length:

$$\left(\phi_{1,1} + \xi\delta\right)\alpha_2 q_2 s \le \tau_2 \left(s - \alpha_2 q_2\right)\xi \tag{12}$$

$$\left(\phi_{3,1}+\xi\delta\right)\alpha_4 q_4 s \le \tau_4\left(s-\alpha_4 q_4\right)\xi \tag{13}$$

$$\left(1-\phi_{2,6}+\xi\delta\right)\alpha_6 q_6 s \le \tau_6\left(s-\alpha_6 q_6\right)\xi \tag{14}$$

$$\left(1-\phi_{2,8}+\xi\delta\right)\alpha_8 q_8 s \le \tau_8\left(s-\alpha_8 q_8\right)\xi \tag{15}$$

Based on the geometric features of an asymmetric two-leg CFI, Figure 4 presets five critical movements which need to be coordinated in a progression design:

- Movement 1, northbound left turn, which passes all three intersections.
- Movement 2, eastbound left turn, which passes two intersections.
- Movement 3, westbound left through, which passes two intersections.
- Movement 4, southbound through, which passes two intersections.
- Movement 5, westbound left turn, which passes two intersections.

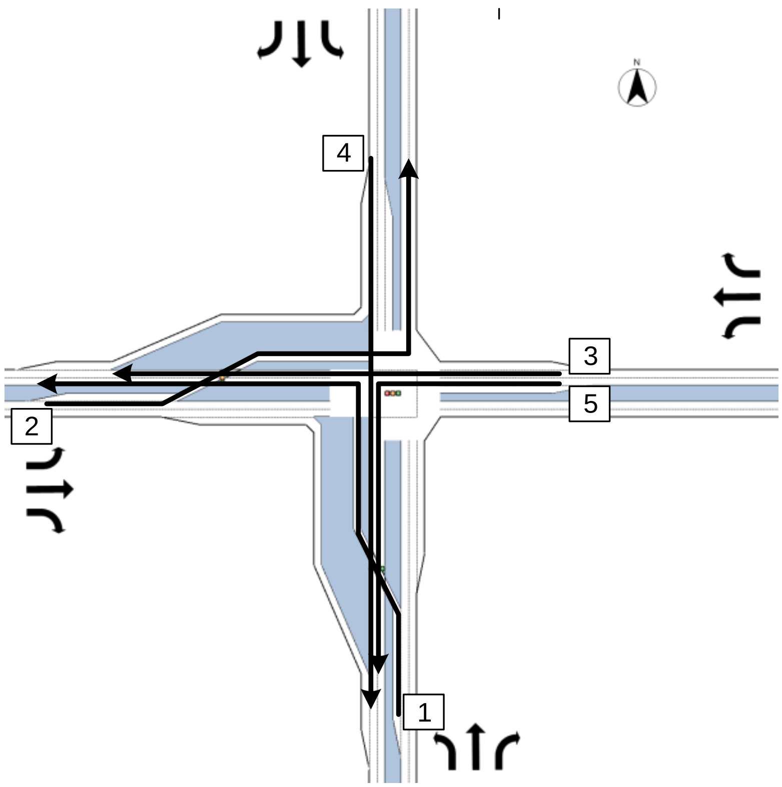

FIGURE 4 Critical movements in a CFI passing at least two intersections

Similar to most existing progression models, such as MAXBAND (20), the interference constraints, based on the notations in Figure 5, for progression of movement 1 are given as follows:

$$w_{1,1} \ge \phi_{1,1} \tag{16}$$

$$w_{1,1} + b_1 \le 1 \tag{17}$$

$$w_{1,3} \ge 0 \tag{18}$$

$$w_{1,3} + b_1 \le \phi_{3,1} \tag{19}$$

$$w_{1,2} \ge \theta_2 \tag{20}$$

$$w_{1,2} + b_1 \le \theta_2 + \phi_{2,2} \tag{21}$$

where, $w_{p,l}$ denotes the difference between the start of a green phase and the start of the band for critical movement p at intersection l.

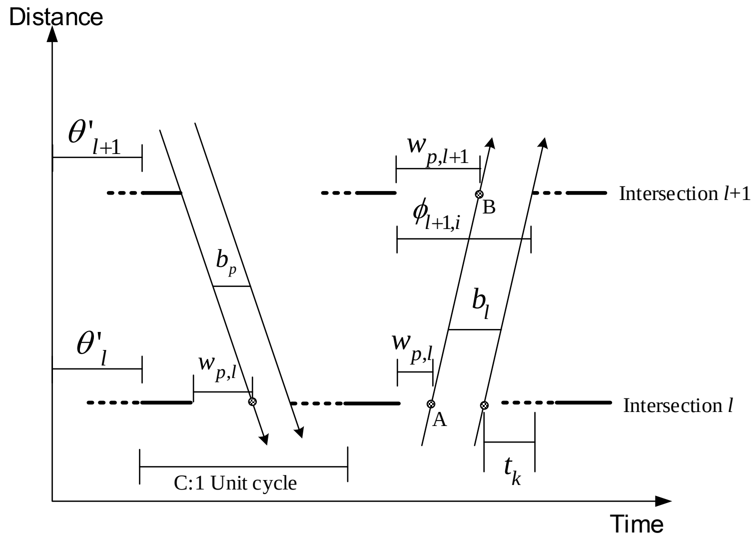

FIGURE 5 Key notations in the progression model

Also, the following progression constraints are specified to represent the progression band for such a movement.

$$\theta'_l + w_{1,l} + t_k\xi + n_{1,l}C = \theta'_{l+1} + w_{1,l+1} + n_{1,l+1}C\ ,\ i=1,2 \tag{22}$$

where, θ'_l denotes the offset at intersection l; t_k is the corresponding travel time between two intersections; $n_{p,l}$ is an integer variable.

Similar to the design for movement 1, the interference and progression constraints for other movements are summarized in Table 1:

TABLE 1. Constraints for Movement 2-5

	Interference Constraints	Progression Constraints
Movement 2	$w_{2,3} \ge \phi_{3,1}$, $w_{2,3} + b_2 \le 1$ $w_{2,2} \ge \theta_4$, $w_{2,2} + b_2 \le \theta_4 + \phi_{2,4}$	$\theta'_3 + w_{2,3} + t_3\xi + n_{2,3}C = \theta'_2 + w_{2,2} + n_{2,2}C$
Movement 3	$w_{3,3} \ge 0$, $w_{3,3} + b_1 \le \phi_{3,1}$ $w_{3,2} \ge \theta_7$, $w_{3,2} + b_3 \le \theta_7 + \phi_{2,7}$	$\theta'_2 + w_{3,2} + t_4\xi + n_{3,2}C = \theta'_3 + w_{3,3} + n_{3,3}C$
Movement 4	$w_{4,2} \ge \theta_5$, $w_{4,2} + b_4 \le \theta_5 + \phi_{2,5}$ $w_{4,1} \ge 0$, $w_{4,1} + b_4 \le \phi_{1,1}$	$\theta'_2 + w_{4,2} + t_5\xi + n_{4,2}C = \theta'_1 + w_{4,1} + n_{4,1}C$
Movement 5	$w_{5,2} \ge \theta_8$, $w_{5,2} + b_5 \le \theta_8 + \phi_{2,8}$ $w_{5,1} \ge 0$, $w_{5,1} + b_5 \le \phi_{1,1}$	$\theta'_2 + w_{5,1} + t_6\xi + n_{5,2}C = \theta'_1 + w_{5,1} + n_{5,1}C$

CASE STUDY

Site Description and Optimization Results

To illustrate the applicability and efficiency of the proposed signal optimization model, this study has taken the intersection of MD4 and MD255 for case study. Due to the high left-turning volumes in both the eastbound and northbound approaches, an asymmetric two-leg CFI is proposed by Maryland SHA for construction. Figure 6 shows the lane configuration and geometric features of the proposed design.

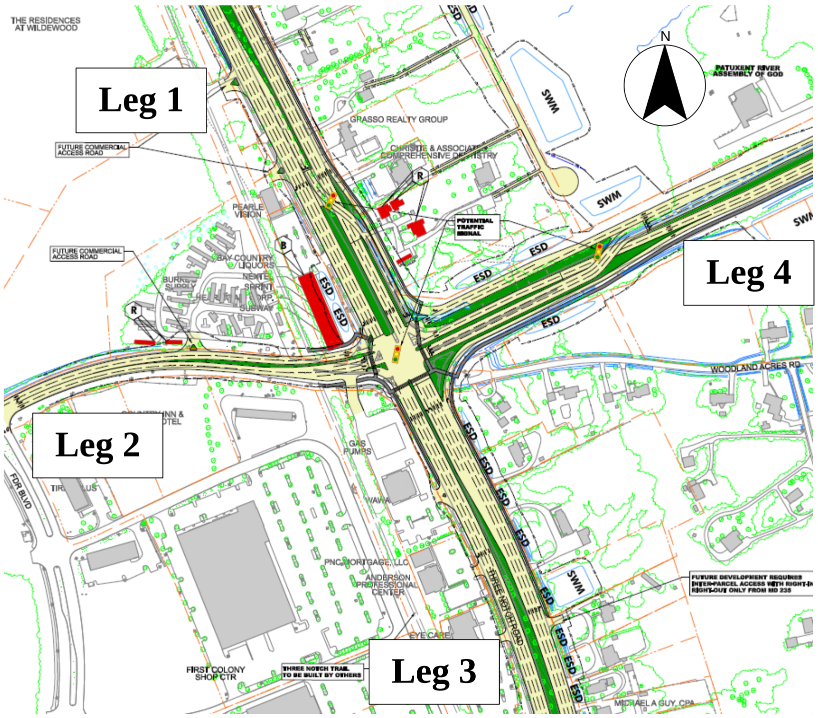

FIGURE 6. Proposed design of partial CFI for intersection MD 4 and MD 235

The proposed unconventional intersection contains two CFI legs which are installed in eastbound and northbound approaches. Such a design is proposed to contend with the heavy traffic volume during the peak hours. Table 2 and Table 3 summarize the key geometric parameters for the proposed design.

TABLE 2: Proposed Link Lengths for the Two-leg CFI

	CFI arms (feet)		
	Left-turn crossover spacing	Left-turn bay	Right-turn bay
Arm 1	350	300	500
Arm 4	350	300	500
	Conventional arms (feet)		
	Left-turn bay	Right-turn bay	
Arm 2	300	300	
Arm 3	300	300	

TABLE 3. Proposed Number of Lanes for the Two-Leg CFI

Arms	Proposed Geometry Type	Left-turn	Through	Right-turn
Arm 1	CFI	2 lanes	3 lanes	1 lanes
Arm 2	Conventional	1 lanes	2 lanes	1 lanes
Arm 3	Conventional	2 lanes	3 lanes	2 lanes
Arm 4	CFI	3 lanes	2 lanes	1 lanes

Table 4 summarizes the PM peak-hour demand patterns from field observation for signal optimizations.

TABLE 4. PM Peak Hour Demands for Intersection MD 4 and MD 235

Arms	Direction	Left-turn volume (vph)	Through volume (vph)	Right-turn volume (vph)
Arm 1	Southbound	575	1675	125
Arm 2	Eastbound	125	425	200
Arm 3	Northbound	400	2325	1375
Arm 4	Westbound	825	400	375

Also, to evaluate the effectiveness of the proposed signal optimization model, this study has compared its performance with the other two models:

- Model-1: The proposed signal optimization model;
- Model-2: The proposed model without setting queue length constraints;
- Model-3: The proposed model which only accounts for progression of the selected movements.

Under the demand shown in Table 1, the signal plans produced from each of these three models are applied for simulation evaluation. In Model 2, the queue length constraints are removed in order to verify whether or not these constraints are effective in preventing potential queue spillovers. In addition, to evaluate the effectiveness of the progression design, Model 3 will consider only the left-turn movement from Leg 1 and through movements from Leg 2 & 3 for progression. The phase plan, phase sequence, cycle length, and offsets for each signal plan are shown in Figure 7. Based on the optimization results, it is noticeable that Model 1 and Model 2 have produced an identical phase plan but different phase sequences and signal cycle lengths, indicating the effectiveness of the queue constraints in optimizing signal plans. A further comparison between Model 1 and Model 3 reveals that different leading-and-lagging signal plans for the major approaches may be used when different numbers of critical movements are accounted for progression.

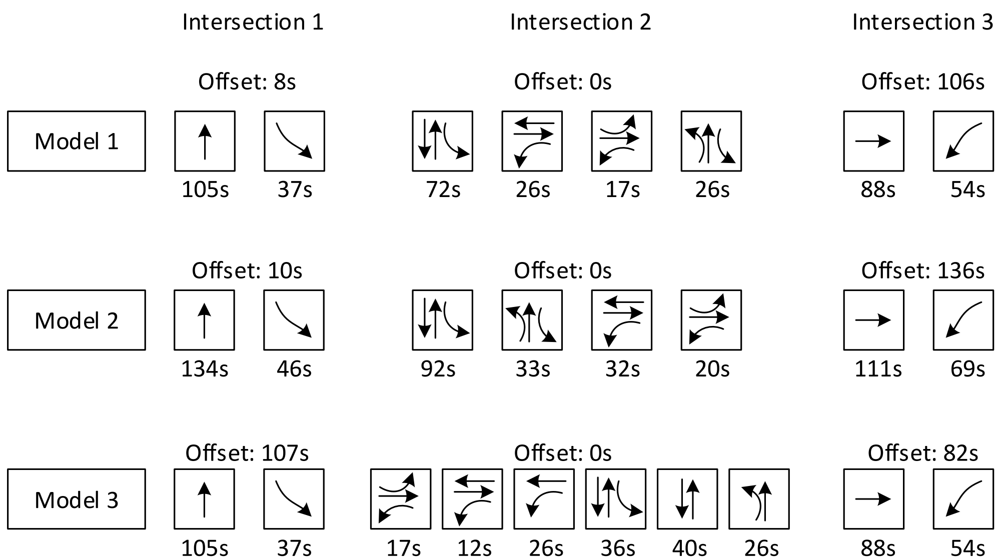

FIGURE 7. Signal Plans Produced by the Three Models

Experimental results

Based on the results shown in Figure 7, this study has further simulated the network with VISSIM for evaluation. To assess the effectiveness of the queue length constraints, Figures 8(A) and 8(B) present the resulting average queue length on the left-turn bays of these two CFI legs. Based on the simulation results, it is noticeable that both Model 1 and Model 3 can yield a much shorter queue length on these left-turn bays, compared with the results by Model 2. In addition, the simulation results also indicate the occurrence of queue spillovers in most cycles with the signal plan generated by Model 2. This is due to the fact that Model 2 has not considered the queue constraints in producing the signal timing plans. Hence, this evidences the need to properly specify such constraints to reduce the queue length on those short turning bays.

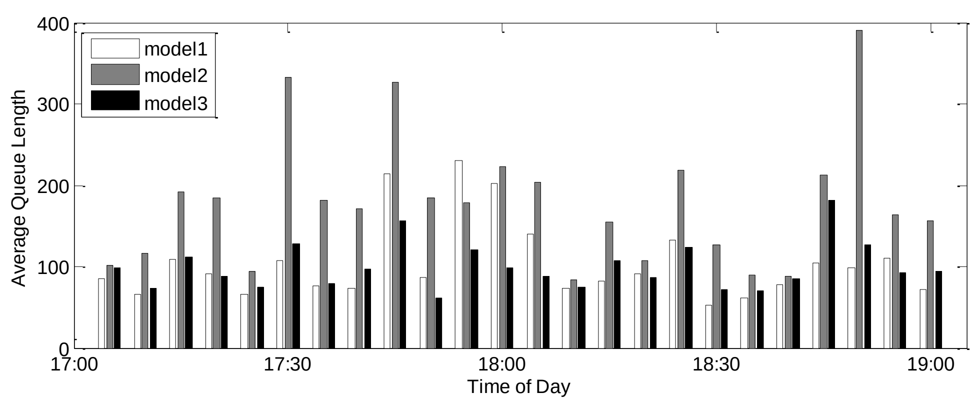

FIGURE 8. (A) Queue Length for the Left-turn Bay at Arm 1 of the Intersection

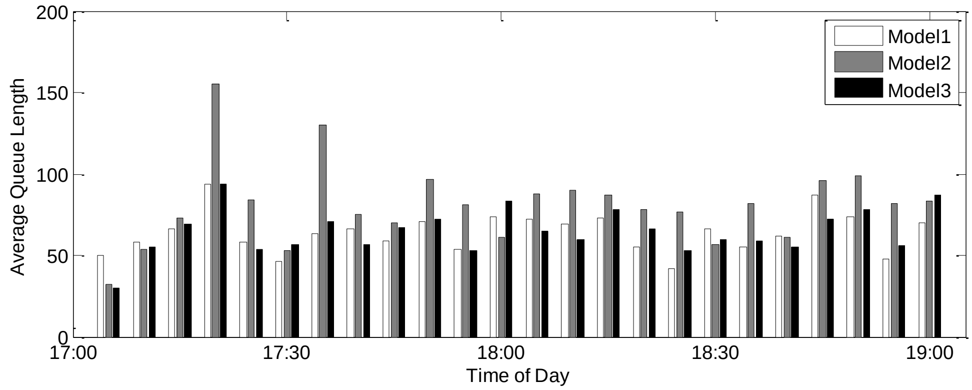

FIGURE 8. (B) Queue Length for the Left-turn Bay at Arm 4 of the Intersection

Figure 9 (A)-(E) shows the time-dependent travel time for critical movements passing at least two intersections in the target CFI. Based on the simulation result, the proposed model (Model 1) and Model 3 yields approximately the same travel times for the left-turn flows from Arm 1, while the proposed model outperforms the other two for other left-turn movements. As expected, although the overall performance of Model 3 is inferior to Model 1, it yields shorter travel times for the through movements. Also, Model 3 may yield a shorter queue length due to the adoption of a shorter cycle length than in model 2, its resulting travel times for left-turn movements are higher than those produced by other models, because this model does not offer signal progression for all critical movements.

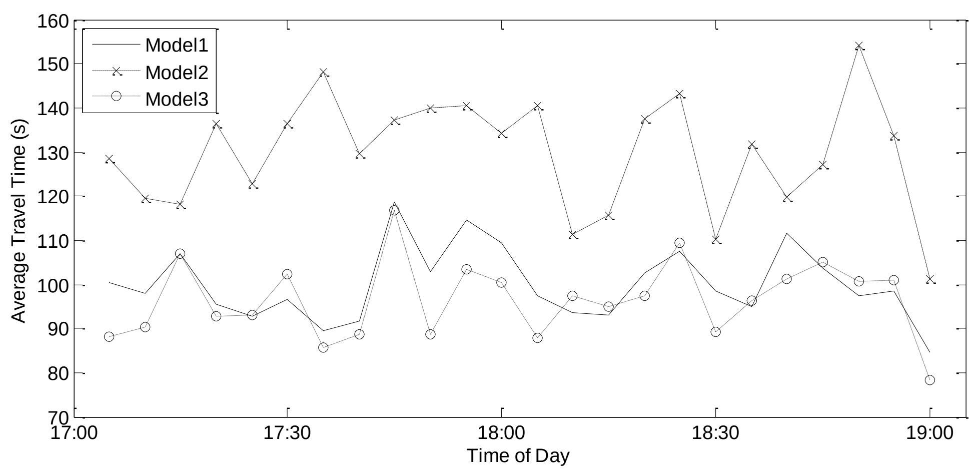

FIGURE 9(A). Time-dependent Travel Times for Left-turn Movement from Arm 1

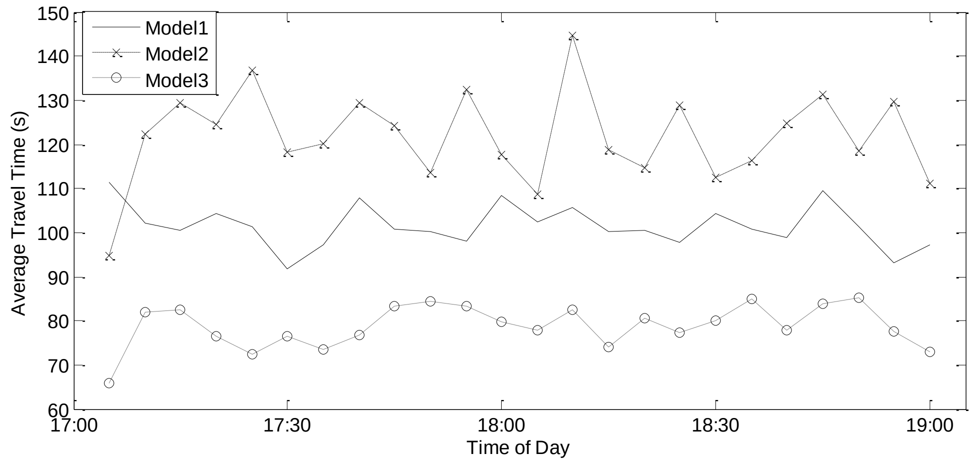

FIGURE 9(B). Time-dependent Travel Times for Left-turn Movement from Arm 4

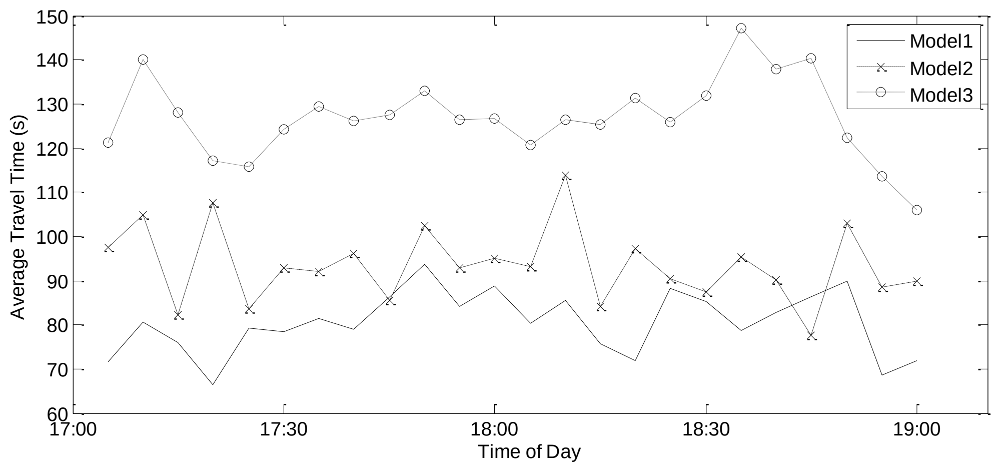

FIGURE 9(C). Time-dependent Travel Times for Through Movement from Arm 2

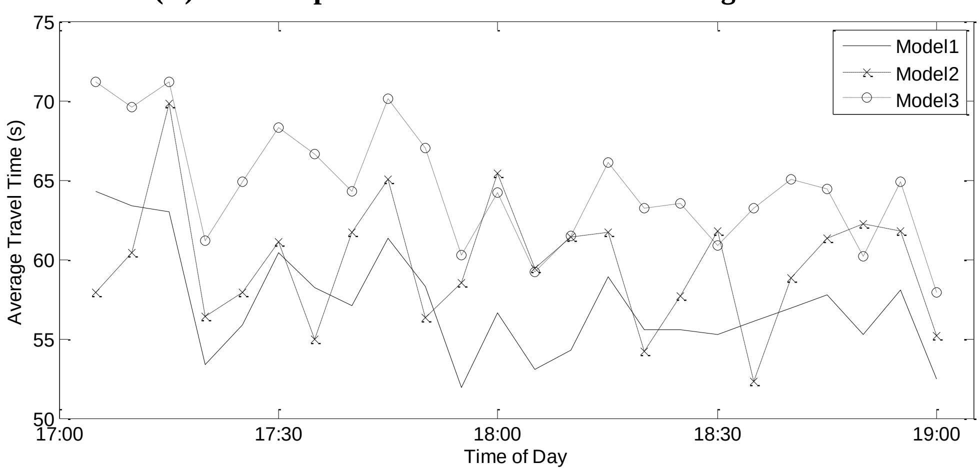

FIGURE 9(D) Time-dependent Travel Times for Through Movement from Arm 3

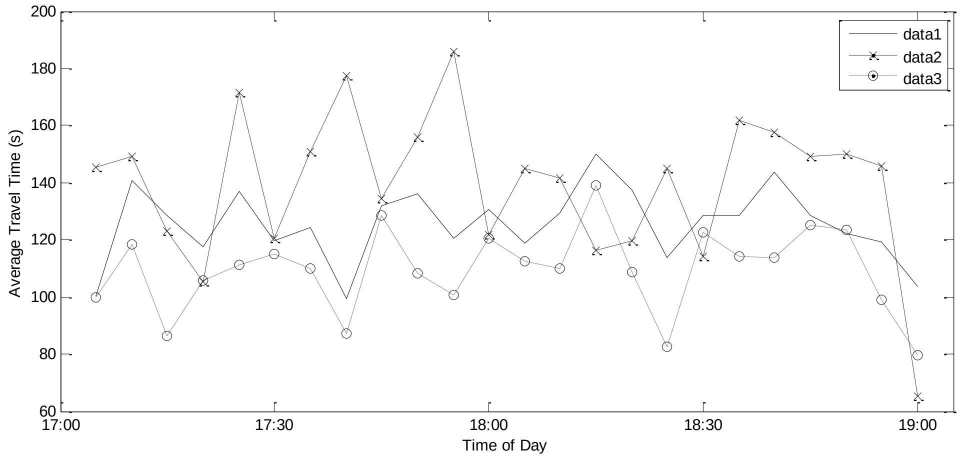

FIGURE 9(E) Time-dependent Travel Times for Left-turn Movement from Arm 2

From Figures 8 and 9, one can observe that the proposed model clearly outperforms the other two models with respect to reduction in travel time for these critical traffic movements and prevention of potential queue spillovers on short left-turn bays. To evaluate the average network performance under different models, Table 5 further presents the experimental results of average intersection delay and average number of stops. In brief, one can summarize the key findings from the experimental results as follows:

- The proposed model yields the best performance with respect to the average delay and average number of stops.
- The queue length constraints are effective in shortening the cycle length, and consequently prevent the queues on the left-turn bays to spill over.
- The progression constraints are effective in smoothing traffic movements for the designed paths that pass two or more intersections.
- The proposed model is sufficiently flexible to yield the phase plan that can effectively accommodate the need for progression. When the progression is not considered in the model, some phase may be not fully used by the designated movements.

TABLE 5. Performance Evaluation of the Whole Intersection

Performance Index	Model 1 (proposed)	Model 2 (w/o queue constraint)	Model 3 (w/ only one movement)	Model 1 Improvement with Model 2	Model 1 Improvement with Model 3
Ave. intersection Delay (s)	30.527	38.886	32.213	-21.50%	-5.23%
Ave. Number of Stops	0.669	0.709	0.704	-5.64%	-4.97%

CONCLUSIONS

By analyzing the conflicting traffic movements in an asymmetric two-leg CFI, this study has identified multiple ways to design its phase plan. To fully utilize such an intersection's capacity, this study has further developed a signal optimization model, based on the mixed-integer-linear-programming technique, to design the common cycle length, phase sequence, green split, and the offsets for all intersections in an asymmetric two-leg CFI. The proposed model is capable of concurrently providing signal progression to both the heavy through and left-turning flows. In addition, to prevent the potential arterial blockage caused by the queue spillback, this study has specified a set of constraints to reduce the queue length on the short left-turn bays.

Using the field data from a CFI site in Maryland, this study has conducted extensive simulation experiments to evaluate the performance of the proposed model. The experimental results indicate that the proposed model can successfully offer sufficient green bands to both the through and heavy turning flows. Also, the proposed model with specified queue constraints can prevent the queues to spill over short left-turning bays. Future research directions along this study will focus on the enhancement of the proposed signal design model for coordination with neighboring intersections and consideration of pedestrians. The concept of concurrently optimizing the green split and progression can also be employed to other types of CFI design.

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