Development of a Signal Optimization Model for Diverging Diamond Interchange

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Abstract: As one of the most popular unconventional interchange designs, diverging diamond intersection (DDI) has received increased attention over the past decade. Through a reverse operation of traffic movements between its two crossover intersections, DDI can accommodate more traffic movements within each phase. To design an effective signal plan for DDIs, one needs to address the following two critical issues: (1) how to select the common cycle length and green splits at each crossover intersection under different geometric conditions, and (2) how to coordinate a DDI's two crossover intersections with its adjacent conventional intersections. To contend with these issues, this paper presents an optimization model with the objective of maximizing intersection capacity to yield the optimal green splits and cycle length. Also, in view of the potentially large left-turn traffic volumes from the freeway off-ramps, this study has further modified a model to provide progressions to both left-turn and through traffic paths. Using simulation software as an unbiased tool, this study has conducted extensive simulation comparisons between the optimized signal plans and the results from signal optimization software under various traffic scenarios. The experimental results confirm the promising properties of the proposed signal models for DDI, especially if the traffic progression between two crossover intersections is the major concern. **DOI:** 10.1061/(ASCE)TE.1943-5436.0000657.

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Introduction

Diverging diamond interchange (or DDI), one of the unconventional intersection/interchange designs, has received increasing attentions in recent years due to its cost-effectiveness over a traditional diamond interchange design. The key logic of DDI is to provide efficient navigation for both left-turn and through movements between highway ramps and to accommodate left-turn movements onto the arterial without using a left-turn bay. As shown in Fig. 1, due to the reversed operation of two through traffic movements between its two crossover intersections, a DDI design can eliminate the conflict between the left-turn and the opposing through flows. With such an assignment of flow movements, a DDI design can significantly reduce the number of traffic conflict points and thus provide a more safe and cost-effective environment.

Since the early 2000s, a large body of studies related to DDI has been reported in the literature. For example, Chlewicki (2003, 2011) used *Synchro* and *SimTraffic* to analyze the delays in a DDI design and compared its performance with a conventional interchange under various demand levels. His study concluded that a properly designed DDI can reduce about 60% of the total intersection delay and 50% of the total number of stops. Applying the same simulation tools to DDI and conventional interchange, Siromaskul and Speth (2008) also reached similar conclusions, especially regarding the average delay and the average number of stops per vehicle. Bared et al. (2005) extensively investigated the performance of DDI at five volume levels and under two geometric conditions. Their research results, based on simulation experiments, indicated that a DDI can outperform a conventional diamond interchange, especially at a high volume level. The general conclusion is that a DDI design can accommodate higher volumes for all movements, especially for left-turn flows, than a conventional diamond interchange. They also concluded that converting an interchange into a six-lane DDI is financially more beneficial than a design of widening the bridge. To investigate the strengths and deficiencies of DDI, Hughes et al. (2010) and Chang et al. (2011) conducted extensive performance comparisons between DDI and conventional interchanges. Also, considering the possible internal queue spillback, Xu et al. (2011) developed an analytical method to estimate the control delay of a DDI on its internal and external movements.

Despite the increasing popularity of DDI, many critical tasks associated with its effective operations remain to be investigated. For example, development of an effective signal control method, a critical task for DDI applications, has not been addressed adequately in the existing literature. By eliminating the conflicts between left-turn and opposite through movements, DDI allows the use of a simple two-phase signal control to guide its traffic movements. The decreased number of phases in DDI can significantly reduce the average travel delay over the entire interchange. Yet such a desirable operational efficiency can be achieved only if the green splits, cycle length, and offsets at each crossover intersection of a DDI have been properly optimized. In response to such needs, this study proposes a two-stage solution approach for the DDI's signal optimization. In the first stage, a linear programming model with an objective of maximizing traffic throughput is proposed to optimize the green splits. To coordinate flows between two crossover intersections, the second stage offers a modified *Maxband* model to optimize the offsets. A summary

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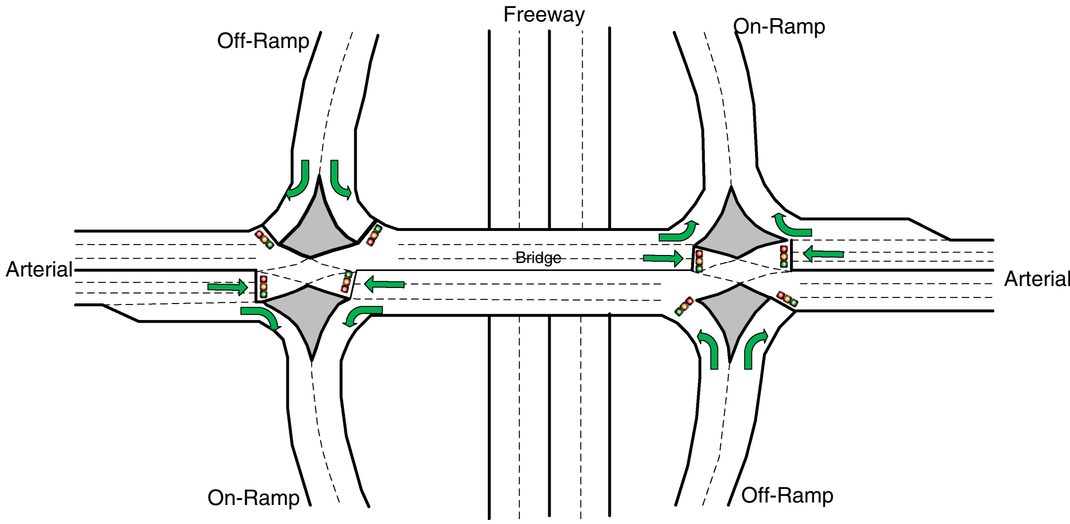


Fig. 1. Geometric layout of DDI design

of critical issues associated with DDI signal optimization will be provided in the following section.

Research Background

Over the past decades, many researchers have been devoted to signal optimization for conventional intersections. Aiming to maximize the green bandwidth and intersection throughput, or to minimize the total delay, traffic researchers have developed various mixed integer linear programming models in the literature (Gartner et al. 1975; Little et al. 1981; Cohen and Liu 1986; Wong and Wong 2003). Also, to represent the complex interactions between traffic state evolution and key control parameters, some studies have reported the use of simulation-based approaches. Among the existing traffic models for signal optimization, various versions of *Transyt* (Robertson 1969) and *Transyt-7F* (Wallace et al. 1988) are perhaps the most widely used programs. Over the past two decades, traffic researchers have also explored various methods to produce the optimal signal plan. Examples of such methods include the use of mesocopic or microscopic simulation-based optimizers (Park et al. 1999; Yun and Park 2006; Stevanovic et al. 2007), store-and-forward models (D'Ans and Gazis 1976; Papageorgiou 1995), queue-and-dispersion models (Kashani and Saridis 1983; Wu and Chang 1999), and discrete-time kinematic models (Lo et al. 2001).

Despite the promising developments in signal optimization in recent decades, those models may not be applicable to a typical DDI design due to the DDI's unique geometric characteristics. Most existing DDIs deployed by different states share the following two common features: (1) the left-turn volumes are allowed to use an exclusive lane to move continuously without stops on the bridge, as shown in Fig. 2(a), or (2) without the exclusive lane, the volumes to ramps are often delayed by through traffic, as indicated in Fig. 2(b). For example, DDIs with left-turn lanes have been operated on Dorsett Rd. in Maryland Heights, Missouri and on National Avenue in Springfield, Missouri; DDIs in the second category were constructed at MO-13 and I-44 in Missouri and at Bessemer Street and US 129 in Tennessee. Both design types need an optimized signal plan to ensure their operational efficiency.

Note that DDI can be operated as an isolated interchange or as a section of local arterial that needs to coordinate with its neighboring intersections. Some potentially applicable programs, such as the *Maxband* model, mainly focus on providing signal progression

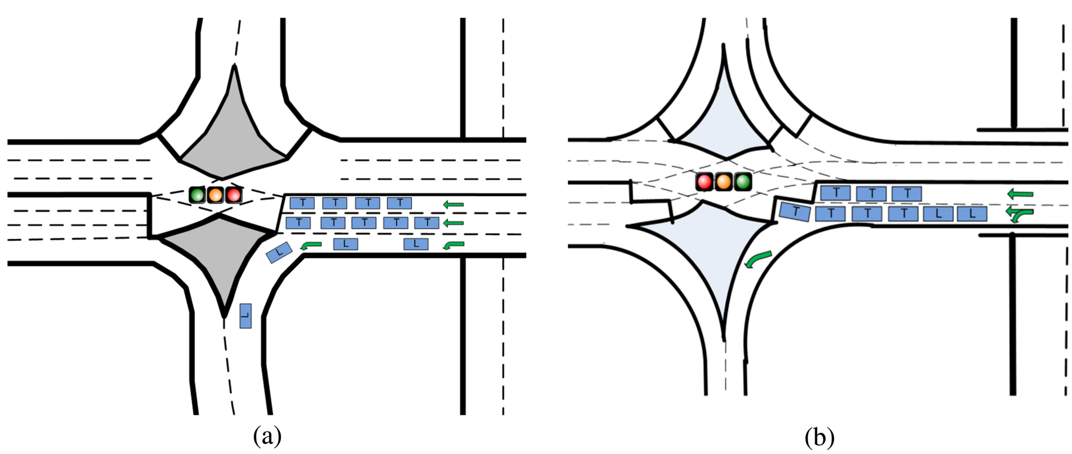


Fig. 2. Illustration of DDIs with different geometric design: (a) DDI with left-turn only lane; (b) DDI without left-turn only lane

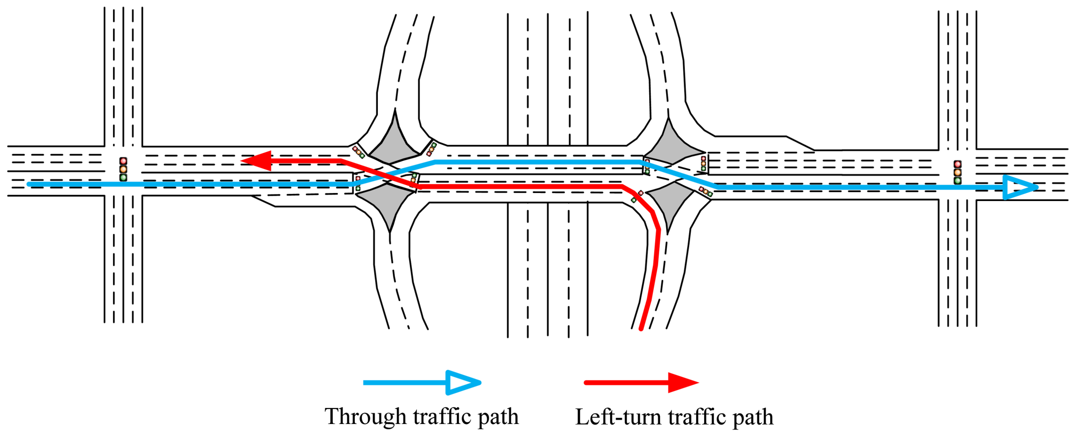


Fig. 3. Two types of critical paths for DDI within a corridor segment

for through movements. However, DDIs are implemented mainly for interchanges having high off-ramp volumes. Hence, as shown in Fig. 3, accommodating traffic via the left-turn path is the core task in DDI's signal design because (1) without proper signal progression, the left-turn movement may encounter the red phase at the downstream crossover intersection and consequently lead to a long traffic queue on the bridge, (2) the left-turn volume is generally high in DDI, so the reduction in left-turn delay can directly improve the efficiency of the entire network, and (3) coordination of signals will enable the off-ramp volumes to pass the intersection quickly and to prevent the formation of a queue spillback to the freeway mainline.

Signal Timing Optimization

As noted previously, a typical DDI design with reduced conflict points can significantly improve the entire interchange's operational efficiency. A report published by Hughes et al. (2010) has recommended two kinds of signal control strategy, as shown in Figs. 4(a and b). Due to the sharp turning feature, it should be noted that the right-turn volumes from the off-ramps are preferably operated under signal control if no long merge areas are provided.

Compared with conventional interchanges, a DDI allows for a relatively shorter cycle length at its crossover intersections. Hence, when a DDI is operated within an arterial segment, it mostly adopts the common cycle length at the adjacent intersections to facilitate the progression. For an isolated DDI, one can estimate its cycle length with Webster's formula (1958):

$$C = \frac{1.5 \times L + 5}{1.0 - \Psi/s} \tag{1}$$

where L is the total lost per cycle; Ψ is the critical lane volume (CLV) at the most congested intersection; and s is the saturation flow rate.

Note that a well-designed signal needs to be able to maximize the capacity of an intersection under the given geometric layout (Allsop 1972; Yagar 1975; Xuan et al. 2011; Wong and Heydecker 2011). Based on the assumption that the traffic demand matrix can be multiplied with a common flow multiplier μ to represent the maximum amount of increased volume that would still allow the intersection to perform reasonably well (Wong and Wong 2003), the optimization problem can be converted to an issue of determining the maximum multiplier, $\mu_{\max}$, with flow conservation constraints:

$$q_j = \sum_i \mu \beta_{ij} Q_i \quad \forall\ i, j \tag{2}$$

where $Q = \{Q_i, i \in N_T\}$ denotes the traffic demand to the entire DDI; q_j is the assigned traffic flow (multiplied by μ) on lane group j; and a set of binary variables $\{\beta_{ij}\}$ are used to indicate the resulting traffic assignment

$$\beta_{ij} = \begin{cases} 1 & \text{if flow } i \text{ is assigned to lane group } j \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

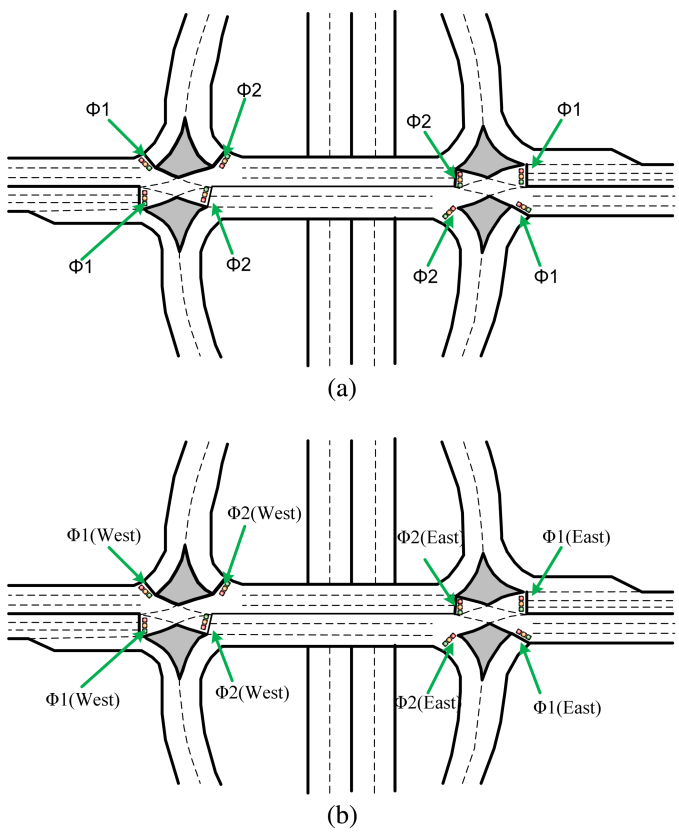


Fig. 4. Signal phasing designs for DDI: (a) signal phasing operating under single controllers; (b) signal phasing operating under separate controllers (west and east)

The following constraints should be satisfied to ensure that the degree of saturation in each movement is below the acceptable limit:

$$q_j \leq s_j \sum_m \sum_n \alpha_{\text{mnj}} g_{mn} \quad \forall\ j \tag{4}$$

where s_j is the saturation flow rate at lane group j; and g_{mn} denotes the assigned g/c ratio for phase m at intersection n while vehicles in lane group j have the right of way. The parameter $\{\alpha_{mnj}\}$, is adopted to represent the phase plan:

$$\alpha_{\text{mnj}} = \begin{cases} 1 & \text{if lane group } j \text{ obtains its right of way in phase} \\ & m \text{ at intersection } n \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

Considering the different types of DDI, for those with left-turn exclusive lanes, the corresponding turning flows will not be controlled with the downstream signal. In contrast, for those designs without exclusive lanes, the left-turn flows to the on-ramps shall be controlled with the through flows.

The green duration for each traffic group is subjected to a minimum value, and these constraints are set as follows:

$$g_{\min} \leq g_{mn} \leq 1 \quad \forall\ m, n \tag{6}$$

Also, for each intersection n

$$\sum_m g_{mn} = 1 \quad \forall\ n \tag{7}$$

Thus, for each intersection, one can present the optimization model as follows:

$$\text{Maximize } \mu \qquad \text{subjectto } q_j = \sum_i \mu \beta_{ij} Q_i \quad \forall\ i, j$$
$$q_j \leq s_j \sum_m \sum_n \alpha_{\text{mnj}} g_{mn} \quad \forall\ j$$
$$g_{\min} \leq g_{mn} \leq 1 \quad \forall\ m, n$$
$$\sum_m g_{mn} = 1 \quad \forall\ n$$

In this optimization model, the green splits $\{g_{mn}\}$ are the control variables; and $\{\alpha_{mnj}\}$ and $\{\beta_{ij}\}$ are the given parameters, determined by the phasing designs and DDI geometric features. Note that the entire interchange is under an over-saturation traffic condition if the optimal result indicates $\mu_{\max} < 1$.

Synchronization of Intersections

Another issue for the DDI signal's design is to design the offsets between its two crossover intersections and neighboring conventional intersections (if any). The signal coordination between intersections has been discussed extensively in the literature, and the *Maxband* (Little 1966; Little et al. 1981) model is viewed as one of the most efficient models for such a purpose. Hence, this study employs the core logic of *Maxband* to design the signal coordination. As shown in Fig. 3, to accommodate both through and left-turn traffic paths, their green bands are taken into account concurrently in the optimization process, and the objective function is to maximize the sum of weighted green bands for all critical paths:

$$\text{Max:} \sum_{i \in V} \varphi_i b_i \tag{8}$$

where φ_i is the weight factor.

Since DDI can be operated as an isolate or as a part of an arterial, the proposed model needs to be applicable under both control scenarios. Using the phase sequence given by Fig. 4, the green band of each path in an isolated DDI is presented in Fig. 5.

Let the direction from east to west be defined as the inbound direction, and denote θ_k as the offset of intersection k. The interference constraints for the left-turn paths can then be specified as follows:

$$0 \leq w_{l,k} + b_l \leq g_{l,k} \quad \forall\ k \tag{9}$$

$$0 \leq \overline{w}_{l,k} + \overline{b}_l \leq \overline{g}_{l,k} \quad \forall\ k \tag{10}$$

$$0 \leq \theta_k \leq C \quad \forall\ k \tag{11}$$

where $w_{l,k}$ ($\overline{w}_{l,k}$) is the time from the right (left) side of the phase signal to the boundary of the left-turn green band; and $g_{l,k}$ ($\overline{g}_{l,k}$) is its received green time at intersection k.

The loop integer constraints for the left-turn path are listed as follows:

$$\theta_1 + (C - g_{l,1}) + w_{l,1} + t_{1,2} + n_{l,1}C = \theta_2 + (C - g_{l,2}) + w_{l,2} + n_{l,2}C \tag{12}$$

$$-\theta_1 + \overline{w}_{l,1} + \overline{t}_{1,2} + \overline{n}_{l,1}C = -\theta_2 + \overline{w}_{l,2} + \overline{n}_{l,2}C \tag{13}$$

where $t_{k,k+1}$ ($\overline{t}_{k,k+1}$) is the inbound (outbound) travel time of the left-turn path between intersection k and $k+1$; and $n_{l,k}$ is an integer variable.

Similarly, for the through paths, the corresponding constraints are given as

$$0 \leq w_{t,k} + b_t \leq g_{t,k} \quad \forall\ k \tag{14}$$

$$0 \leq \overline{w}_{t,k} + \overline{b}_t \leq \overline{g}_{t,k} \quad \forall\ k \tag{15}$$

$$\theta_1 + w_{t,1} + t_{1,2} + n_{t,1}C = \theta_2 + (C - g_{t,2}) + w_{t,2} + n_{t,2}C \tag{16}$$

$$-\theta_1 + (C - \overline{g}_{t,1}) + \overline{w}_{l,1} + \overline{t}_{1,2} + \overline{n}_{l,1}C = -\theta_2 + \overline{w}_{t,2} + \overline{n}_{l,2}C \tag{17}$$

where $w_{t,k}$ ($\overline{w}_{t,k}$) is the time from the right (left) side of the red phase to the boundary of the through green band.

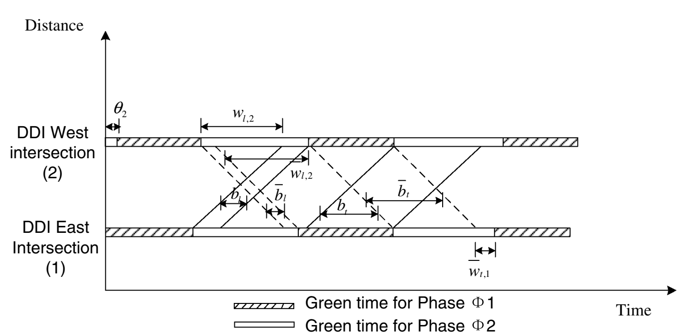


Fig. 5. The green band of each movement in an isolated DDI

Therefore, the optimization model can be summarized as follows:

$$
\begin{aligned}
\text{Max: } \sum_{i\in V}\varphi_i b_i \quad \text{s.t. } & 0 \le w_{l,k} + b_l \le g_{l,k} \quad \forall\ k \\
& 0 \le \overline{w}_{l,k} + \overline{b}_l \le \overline{g}_{l,k} \quad \forall\ k \\
& 0 \le w_{t,k} + b_t \le g_{t,k} \quad \forall\ k \\
& 0 \le \overline{w}_{t,k} + \overline{b}_t \le \overline{g}_{t,k} \quad \forall\ k \\
& 0 \le \theta_k \le C \quad \forall\ k \\
& \theta_1 + (C - g_{l,1}) + w_{l,1} + t_{1,2} + n_{l,1}C = \theta_2 \\
& + (C - g_{l,2}) + w_{l,2} + n_{l,2}C \\
& - \theta_1 + \overline{w}_{l,1} + \overline{t}_{1,2} + \overline{n}_{l,1}C = -\theta_2 + \overline{w}_{l,2} \\
& + \overline{n}_{l,2}C \qquad \theta_1 + w_{t,1} + t_{1,2} + n_{t,1}C = \theta_2 \\
& + (C - g_{t,2}) + w_{t,2} + n_{t,2}C \\
& - \theta_1 + (C - \overline{g}_{t,1}) + \overline{w}_{l,1} + \overline{t}_{1,2} \\
& + \overline{n}_{l,1}C = -\theta_2 + \overline{w}_{t,2} + \overline{n}_{l,2}C \\
& w_{l,k}, \overline{w}_{l,k}, w_{t,k}, \overline{w}_{t,k}, n_{l,k}, \overline{n}_{l,k}, n_{t,k}, \overline{n}_{l,k} >= 0 \\
& \forall\ k \quad n_{l,k}, \overline{n}_{l,k}, n_{t,k}, \overline{n}_{l,k} \text{ are intergers} \quad \forall\ k
\end{aligned}
$$

If the DDI is operated as a section of an arterial, its impact on adjacent intersections should be taken into account. Considering two additional conventional intersections in the progression design, the green band for each path is shown in Fig. 6.

Note that taking adjacent intersections into account naturally generates some additional constraints. As shown in Fig. 6, for the green band between intersections 0 and 1, it has the following loop integer constraints:

$$\theta_0 + w_{t,0} + t_{0,1} + n_{t,0}C = \theta_1 + w_{t,1} + n_{t,1}C \tag{18}$$

$$-\theta_0 + (C - g_{t,0}) + \overline{w}_{t,0} + \overline{t}_{0,1} + \overline{n}_{t,0}C = -\theta_1 + \overline{w}_{t,1} + \overline{n}_{t,1}C \tag{19}$$

By the same token, the green band between intersections 2 and 3 has the similar loop integer constraints shown below:

$$\theta_2 + (C - g_{t,2}) + w_{t,2} + t_{2,3} + n_{t,2}C = \theta_3 + w_{t,3} + n_{t,3}C \tag{20}$$

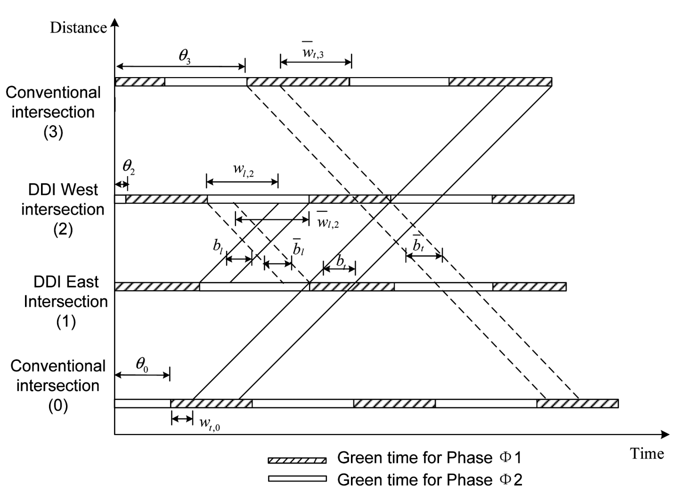


Fig. 6. The green band of each movement along an arterial

$$
\begin{aligned}
& -\theta_2 + (C - g_{t,2}) + \overline{t}_{2,3} + \overline{w}_{t,2} + \overline{n}_{t,2}C \\
& \quad = -\theta_3 + (C - g_{t,3}) + \overline{w}_{t,3} + \overline{n}_{t,3}C
\end{aligned} \tag{21}
$$

The above optimization models are mixed integer linear programming formulations and could thus be solved efficiently with existing methods.

Numerical Examples

Due to both operational efficiency and potential safety improvements, highway agencies are increasingly interested in constructing DDIs. Some DDIs are implemented in rural areas and function as isolated interchanges, and the others are operated in main highway segments where their efficiencies could be impacted by neighboring intersections. Hence, to test the performance of the proposed models under different volume and geometric conditions, the numerical experiments include the following four DDI design cases:

1. Isolated DDI (one left-turn exclusive lane in each direction),
2. Isolated DDI (no left-turn exclusive lane),
3. DDI (one left-turn exclusive lane in each direction) with two adjacent intersections, and
4. DDI (no left-turn exclusive lane) with two adjacent intersections.

The geometric features of each case are presented in Fig. 7. Also, the distance between two DDI subintersections is 183 m 600 ft, and the distance between DDI and either conventional intersection is set as 305 m (1,000 ft).

Optimization Results

In design of the signal progression for DDI, there exists a trade-off between left-turn and through traffic paths. To investigate the efficiency of the proposed models in optimizing such trade-off relations under different traffic conditions, this study selects the following two types of demand patterns for each case, where Type-A has higher through traffic volumes from local arterials and Type-B exhibits higher left-turn volumes from the freeway

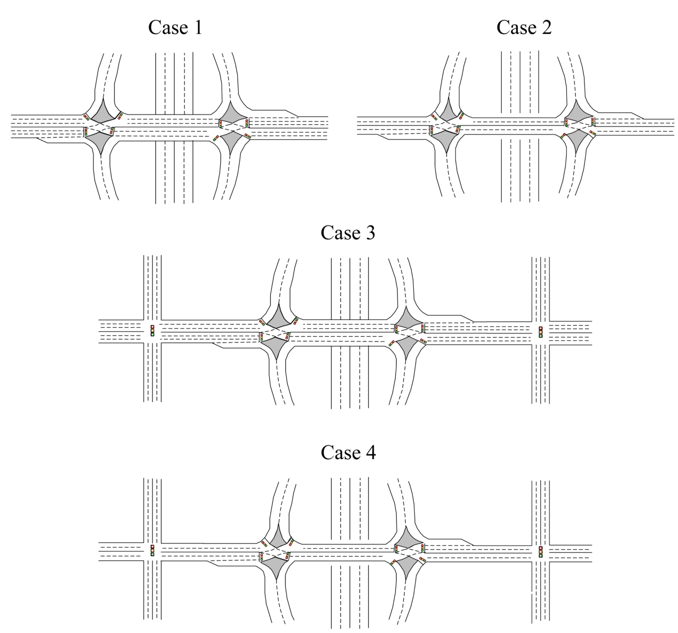


Fig. 7. Geometric features of four cases to be tested

Table 1. Traffic Demand Pattern for Each Case

Scenarios	Northbound (vehs/h) L	R	Southbound (vehs/h) L	R	Westbound (vehs/h) L	T	R	Eastbound (vehs/h) L	T	R
Case 1,3										
A	400	250	380	210	450	1,600	450	340	1,100	400
B	900	250	880	210	450	1,100	400	340	1,000	350
Case 2,4										
A	350	250	330	210	380	1,000	320	380	900	330
B	900	250	850	210	280	750	310	240	750	300

Note: vehs/h = vehicles per hour.

Table 2. Signal Optimization Result from the Proposed Models

Scenarios	Intersection	Cycle length (s)	Offset (s)	$\varphi 1$ green (s)	$\varphi 2$ green (s)
Case 1					
A	East DDI intersection	95[a] (120[b])	0[a] (73[b])	45[a] (58[b])	50[a] (62[b])
	West DDI intersection		55[a] (0[b])	32[a] (43[b])	63[a] (77[b])
B	East DDI intersection	85[a] (120[b])	0[a] (62[b])	31[a] (45[b])	54[a] (75[b])
	West DDI intersection		78[a] (0[b])	28[a] (40[b])	57[a] (80[b])
Case 2					
A	East DDI intersection	100[a] (150[b])	0[a] (80[b])	46[a] (71[b])	54[a] (79[b])
	West DDI intersection		56[a] (0[b])	43[a] (66[b])	57[a] (84[b])
B	East DDI intersection	90[a] (110[b])	0[a] (56[b])	41[a] (6[b])	69[a] (6[b])
	West DDI intersection		0[a] (0[b])	40[a] (6[b])	70[a] (6[b])
Case 3					
A	East DDI intersection	120[a] (120[b])	0[a] (72[b])	57[a] (58[b])	63[a] (62[b])
	West DDI intersection		69[a] (4[b])	41[a] (41[b])	79[a] (79[b])
	East con-intersection	—	82[a] (36[b])	78[a] (78[b])	42[a] (42[b])
	West con-intersection	—	15[a] (70[b])	78[a] (78[b])	42[a] (42[b])
B	East DDI intersection	120[a] (120[b])	0[a] (68[b])	44[a] (46[b])	76[a] (74[b])
	West DDI intersection		56[a] (8[b])	39[a] (39[b])	81[a] (81[b])
	East con-intersection	—	83[a] (20[b])	78[a] (78[b])	42[a] (42[b])
	West con-intersection	—	0[a] (70[b])	78[a] (78[b])	42[a] (42[b])
Case 4					
A	East DDI intersection	120[a] (120[b])	0[a] (68[b])	55[a] (57[b])	65[a] (63[b])
	West DDI intersection		65[a] (2[b])	51[a] (53[b])	69[a] (67[b])
	East con-intersection	—	80[a] (30[b])	78[a] (78[b])	42[a] (42[b])
	West con-intersection	—	15[a] (80[b])	78[a] (78[b])	42[a] (42[b])
B	East DDI intersection	120[a] (120[b])	0[a] (66[b])	44[a] (46[b])	76[a] (74[b])
	West DDI intersection		68[a] (8[b])	42[a] (44[b])	78[a] (76[b])
	East con-intersection	—	69[a] (13[b])	78[a] (78[b])	42[a] (42[b])
	West con-intersection	—	27[a] (70[b])	78[a] (78[b])	42[a] (42[b])

[a]Proposed model.
[b]*Synchro 7.1*.

off-ramps. Table 1 shows related demand information for experimental analyses.

Some key parameters used in the proposed models are

- The free-flow speeds are set to be 18 m/s (40 mph);
- The lost time per cycle is given by 8 s;
- The minimal green time for each phase is 10 s;
- The yellow time and all-red time are set to be 3 s;
- The saturation flow rate is 1,800 vehicles per hour per land (vehs/h/lane) for all traffic movements;
- The weight factor φi of left-turn and through paths are 1 for Case 1-B and 2-B; and
- The weight factor φi of left-turn and through paths are 1 and 2, respectively, for all the cases except Case 1-B and 2-B.

The cycle lengths in Cases 1 and 2 are computed with Eq. (1). For Cases 3 and 4, the cycle lengths are selected to be consistent with the common cycle at adjacent conventional intersections. In this study, the common cycle length is assumed to be 120 s, and the green ratio for the through traffic at conventional intersections is set to 0.65. The optimization results are summarized in Table 2.

Simulation Calibration

To evaluate the performance of the proposed two-stage model, *VISSIM 5.2* is used as an unbiased tool to estimate the measure

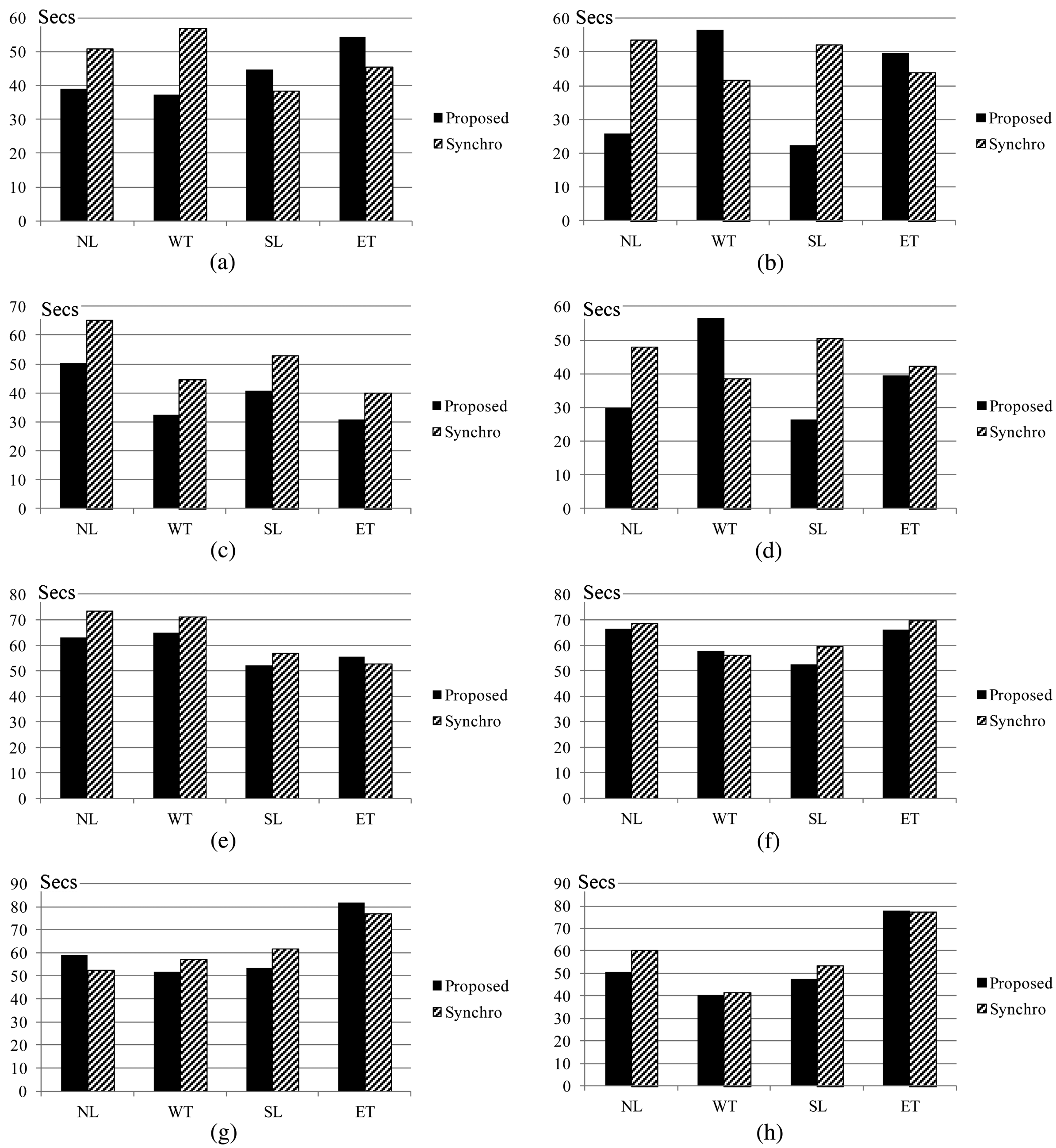
Table 3. List of Calibrated Parameters in *VISSIM*

Parameters	Value
Desired speed distribution (car)	16.7 m/s (60 km/h) (36.0, 42.3)
Desired speed distribution (truck)	13.9 m/s (50 km/h) (29.8, 36.0)
Look ahead distance	0 ~ 304.8 m (0 ~ 1,000 ft)
Probability of temporary lack of attention	5%
Duration of temporary lack of attention	0.2 s
Average stand still distance	2.19 m (7.19 ft)

Table 4. Operational Analysis Result of the Four DDI Cases

Scenarios`	MOEs	Simulation results from *VISSIM*		Improvement (%)	
		A	B	A	B
Case 1	Average delay (s)	33.591[a] (39.533[b])	37.547[a] (45.667[b])	15.03	17.78
	Average number of stops	0.855[a] (0.889 [b])	1.074[a] (1.092[b])	3.82	1.65
Case 2	Average delay (s)	36.454[a] (45.136[b])	38.604[a] (43.454)	19.24	11.16
	Average number of stops	0.938[a] (0.971[b])	1.136[a] (1.174 [b])	3.40	3.24
Case 3	Average delay (s)	60.569[a] (62.410 [b])	57.812[a] (60.158[b])	2.95	3.90
	Average number of stops	1.579[a] (1.638 [b])	1.567[a] (1.611[b])	3.60	2.73
Case 4	Average delay (s)	58.262 [a] (60.602 [b])	53.210[a] (55.682[b])	3.86	4.44
	Average number of stops	1.319[a] (1.348 [b])	1.404[a] (1.459 [b])	2.15	3.77

Note: 3600 s (2 h) time frame.
[a]Proposed model.
[b]*Synchro 7.1*.



*Note: NL = Northbound Left; WT = Westbound Through; SL = Southbound Left; ET = Eastbound Through

Fig. 8. Delays of left-turn and through traffic paths: (a) Case 1-A; (b) Case 1-B; (c) Case 2-A; (d) Case 2-B; (e) Case 3-A; (f) Case 3-B; (g) Case 4-A; (h) Case 4-B

of effectiveness (MOEs) under different signal plans and traffic conditions. Recognizing that a simulated system is useful only if it has been calibrated with field data, this study has taken the following typical steps to calibrate the experimental DDI system: (1) data collection, (2) selection of the calibration objective function, (3) selection of key parameters to be calibrated, and (4) searching for the optimal values of those parameters.

Using the field data collected from MD 295 and Arundel Mills Blvd. in Maryland, this study has performed the parameter calibration task by minimizing the following objective function:

$$\min \frac{1}{N} \sum_{i=1}^{N} (Q_{bi} - Q_{si})^2$$

where Q_{bi} is the observed maximum queue length at cycle i; Q_{si} denotes the simulated maximum queue length at cycle i; and N is the number of cycles observed.

The search of optimal parameters was conducted with a standard GA algorithm. Table 3 summarizes the primary driving behavior parameters in *VISSIM* for the target DDI after being calibrated with the field data.

Performance Analysis for Simulation Experiments

To evaluate the model effectiveness, the signal timing plans obtained from the proposed model are also compared with the one provided by *Synchro 7.1*, using the calibrated *VISSIM* networks. The implementation of *Synchro* to optimize the signals has five major steps:

1. Network construction: based on the geometric parameters shown in Fig. 7, four separate DDI networks with respect to four cases are constructed in Synchro;
2. Settings of key parameters: some parameters in Synchro are reset to ensure its consistence to the proposed model, including saturation flow rate, link travel speed, minimum green time, minimum/maximum cycle length, yellow time, and all-red time;
3. Cycle length optimization: for Cases 1 and 2, the Network Cycle Length Optimization function is used to explore the common cycle length of the two crossover intersections; for Cases 3 and 4, the common cycle length is preset as 120 s;
4. Green split optimization: at each crossover intersection, the green splits are optimized using the input demand patterns; and
5. Offset optimization: the Network Offset Optimization function is used to search the optimal offset of each intersection.

Two major MOEs selected for comparison are the average delay and the average number of stops. Note that each MOE was taken from the average over the results of ten simulation replications to overcome the stochastic nature of a microscopic simulation system. The simulation results with respect to each scenario are summarized in Table 4.

Based on the results provided in Table 4, one can observe that the proposed optimization model can outperform *Synchro* in most cases with respect to the average delay and average number of stops. Particularly, for those isolated DDI cases (Cases 1 and 2), the proposed model can significantly outperform *Synchro*, and the reduction in delay can reach nearly 20%. However, when DDIs are operated with adjacent intersections (Cases 3 and 4), the proposed model and *Synchro* can generate comparable results, and the differences in the resulting MOEs are insignificant (less than 5%).

To analyze the results presented in Table 4 and to investigate the potential reasons, this study has further evaluated the operational performance of critical traffic paths shown in Fig. 3. The corresponding delays of left-turn and through paths are presented in Fig. 8, and several key findings are summarized as follows:

- In Case 1-A, the proposed model has reduced the delays of northbound left and westbound through paths but increased the delays of southbound left and eastbound through paths. However, the overall delay comparison can reflect its effectiveness in design of signal progression for multiple paths;
- In Case 2-A, the proposed model can produce fewer delays for all critical paths. One possible reason is that the cycle length generated by Synchro is longer than the optimal value;
- In Cases 1-B and 1-C, the proposed model clearly outperforms Synchro due to the proposed model's strengths in synchronizing traffic for the left-turn paths, as evidenced by the much fewer delays over the left-turn paths; and
- In Cases 3 and 4, the proposed model and Synchro can generate comparable results for most other paths. Since the through-traffic paths, which have to pass four intersections, are the major contributors to the overall delays, both models will give the through-traffic paths the highest priority in the signal coordination.

Conclusions

This study has produced a two-stage optimization model for the signal design of DDI. Given the phasing plan, the proposed model employs a linear programming model with an objective function of maximizing the intersection capacity to optimize the green splits, which is applicable to both types of geometric designs. Also, to accommodate both left-turn and through traffic volumes, this study has developed a modified *Maxband* optimization model for use in design of signal coordination between two crossover intersections. To evaluate the performance of the proposed models, this study has adopted *VISSIM* as an unbiased simulation tool and the optimized signal plans from *Synchro* as the base line. The results of extensive simulation experiments reveal that the proposed model and *Synchro* can yield comparable performance for those cases where DDI is part of the arterial control system. However, due to the proposed model's strengths in synchronizing traffic flows in the left-turn paths, it significantly outperforms *Synchro* for those cases where DDI functions as an isolated interchange and has a high left-turn demand. Overall, although the proposed models for DDI signal design remain exploratory in nature, the performance comparison with existing methods seems to show their promising properties and the potential for use in practice.

In response to the increasing requests of constructing DDI in different states, future research extension of this line shall include the following tasks: (1) development of operational tools that allows engineers to analyze the resulting delays, required bay length, and the distance between two crossovers, (2) evaluation of a DDI's impact on the adjacent intersections and roadways, and (3) design of signal control guidelines to assist engineers in selecting the proper control objective and phase plan under different time-varying traffic conditions.

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