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CAPACITY MATCHING BASED MODEL FOR PROTECTED LEFT TURN PHASES DESIGN OF ADJACENT SIGNALIZED INTERSECTIONS ALONG ARTERIAL ROADS

ABSTRACT

A protected left turn phase is often used at intersections with heavy left turns. This may induce a capacity gap between adjacent intersections along the arterial road among which only parts of intersection are with protected left turn phase. A model for integrated optimization of protected left turn phases for adjacent intersections along the arterial road is developed to solve this problem. Two objectives are considered: capacity gap minimization and capacity maximization. The problems are formulated as Binary-Integer-Linear-Programs, which are solvable by standard branch-and-bound routine. A set of constraints have been set up to ensure the feasibility of the resulting optimal left turn phase type and signal settings. A field intersections group of the Wei-er Road of Ji'nan city is used to test the proposed model. The results show that the method can decrease the capacity gap between adjacent intersections, reduce the delay as well as increase the capacity in comparison with the field signal plan and signal plan optimized by Synchro. The sensitivity analysis has further demonstrated the potential of the proposed approach to be applied in coordinated design of left turn phases between adjacent intersections along the arterial road under different traffic demand patterns.

KEY WORDS

capacity gap; protected left turn phase; signal optimization; signalized arterial intersection;

1. INTRODUCTION

Left turns can be a significant hindrance to the smooth flow of traffic in networks involving at-grade intersections. If left turn traffic volume is too heavy, separate left turn phases are typically introduced at signalized intersections to handle the flow. The problem with left turns is also indirectly addressed by optimization models of signal timings for intersections [1-5]. In summary, those optimization control models can be classified into two categories: mathematical programming approach and simulation-based approach [6].

Left turns in large numbers contribute to the oversaturation, because they require separate green phase allocations and these sub-phases reduce intersection capacity. Many studies have been conducted on methods which can be used to improve the traffic capacity with unconventional intersection schemes such as left turn bay or shared with the through lane [7-8]. However, in order to alleviate traffic congestion and avoid spill back at high-density signalized intersections due to high traffic demand, left turn forbidden has been viewed as an efficient method. Prohibiting the offending left turn can be done in different ways; e.g., with median U-turns [9-10], jughandles [11], superstreets [12], split intersection, quadrant roadways, and bowties [13]. To some extent, these strategies can be effective because they eliminate the conflicts between the left turn and through movement, decrease the lost time, and add the number of through lanes, thereby solving the problem.

Despite mathematical models or simulation-based models, most existing models for traffic signal control have been developed based on the assumption that the number of signal phases (e.g. a protected left turn phase existing or not) is given as exogenous input. Based on the number of signal phases, traffic engineers usually start with grouping the traffic lanes into traffic streams, and then the signal settings are determined [14]. However, the impacts of the number of signal phases on the capacity of the intersection and the capacity gap between two adjacent intersections have not been discussed in detail. Moreover, both left turn forbidden and protected left turn phase may induce a redistribution of traffic flow as well as changes in capacity and capacity gap between adjacent intersections along the arterial road.

Despite their significant contribution in left turn signal operations, most of the literatures and guidelines have focused on the optimization of appropriate left turn signal control mode for an isolated signalized intersection only based on left turn traffic demand of the target isolated intersection [15-21]. These strategies may not always be effective when the total capacity of the arterial road which consists of several adjacent intersections is taken into consideration. To forbid or permit a separate phase at one intersection may easily change the capacity of the target intersection and result in capacity gap between adjacent intersections which will induce the transfer of bottleneck from one intersection to another, and the capacity of the arterial road cannot be improved accordingly.

In response to aforementioned concern, a capacity matching problem for design of left turn phases of adjacent intersections are developed. Two objectives are considered; capacity gap minimization and capacity maximization. These problems are formulated as Binary-Integer-Linear-Programs (BILP). The main advantage of the model is that the left phasing design of adjacent intersections along the arterial road are integrated to produce the best operational strategy, minimize capacity gap and increase the total capacity for adjacent intersections along an arterial road.

In the next section, the notation and terminology adopted in this paper are described. The set of constraints for the BILP are discussed subsequently. Then the formulations of capacity matching problems are given. Numerical examples are shown at the end to demonstrate the effectiveness of the proposed method.

2. BASIC CONCEPT

The basic concept of capacity matching of adjacent interactions is shown in *Figure 1*. Intersection *j* (with protected left turn phase) and *I* (without protected left turn phase) are two adjacent intersections of an artery as shown in *Figure 1*. Taking traffic flows from east to west as an example, the straight traffic volume along the arterial road is usually very heavy. The movements on approaches of intersection *j* along the arterial road, especially westbound through movements will be allocated less green split and fewer lanes than those of intersection *i* as long as total number of lanes on approaches along the arterial road and cycle length are the same. That means the capacity of through movements of two intersections do not match with each other, and through capacity of intersection *i* is larger than that of intersection *j*. This capacity gap will lead to serious traffic issues such as oversaturation, excessive delay at intersection *j* and spillover from intersection *j* to intersection *i*.

Therefore, the design of left turn phase should consider the impacts on capacity gap between relative movements of adjacent intersections along the arteri-

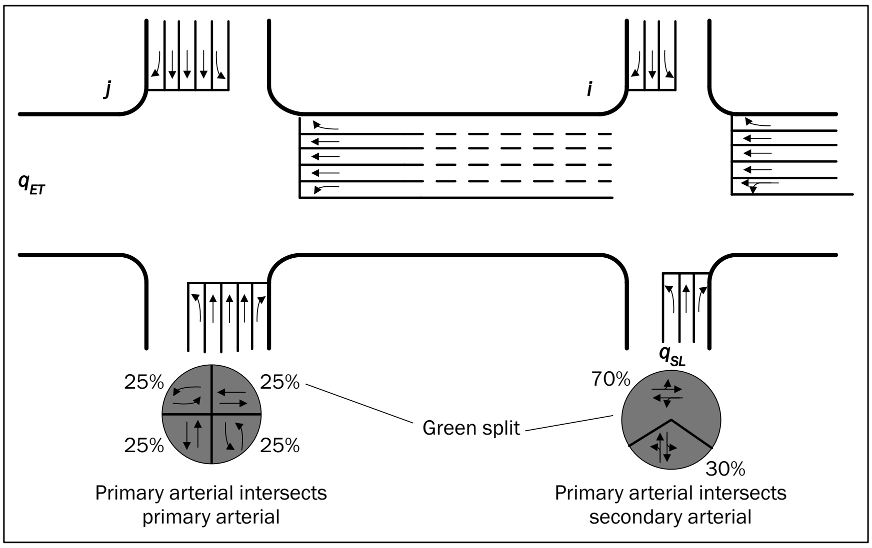

Figure 1 - Left turn phases design and concept of capacity matching

al road. Improper design of left turn phase may induce capacity gaps between intersections and reduce the total capacity of the arterial road.

In order to solve the aforementioned problem, a capacity matching based optimization model for integrated design of protected left turn phases for adjacent signalized intersections was developed in the following sections.

3. GENERAL NOTATION AND TERMINOLOGY

Considering two adjacent intersections *i* and *j*, as shown in *Figure 2*, the notations used hereafter are summarized in *Table 1*.

4. ASSUMPTIONS

- If left turn is prohibited at intersection *i* along the arterial road, the left turn traffic flow will go to intersection *j* to make a left turn and vice versa.
- Exclusive left turn lane will be provided for left turn movement if protected left turn phase is used. Otherwise, all lanes will be used by through movement and right turn movement.
- A protected left turn phase should be provided at one of the two intersections at least.

Table - 1 List of key variables used in the formulations

(i,j)	Intersection *i* or intersection *j*.
m	Traffic movement of intersection *i*. $m \in [1,12]$
n	Traffic movement of intersection *j*. $n \in [1,12]$
$q_m^i\,(Q_m^i)$	Traffic volume of movement *m* at intersection *i* before optimization(after optimization)
$q_{mn}^{ij}\,(q_{nm}^{ji})$	Traffic volume from movement $m(n)$ to $n(m)$.
$\theta_{mn}^{ij}\,(\theta_{nm}^{ji})$	Relative turning proportion of traffic from movement $m(n)$ to $n(m)$, $\theta_{mn}^{ij} = q_{mn}^{ij}/q_m^i$
$k, k = (1,2,3,4)$	Identification number of approaches before optimization (after optimization)
l_k^i/L_k^i	Lane number at approach *k* of intersection *i*
$c_i\,(c_j)$	Cycle time of intersection $i(j)$.
c_{min}, c_{max}	Minimum and maximum cycle length
$s_m^i\,(s_n^j)$	Saturation flow of $m(n)$ at intersection $i(j)$
λ_m^i	Green split of movement *m* of intersection *i*
t_m^i	Capacity of movement *m* of intersection *i*
$\sigma_i, \sigma_j = (0,1)$	Binary variable, the value 0 denotes left-turn forbidden, 1 denotes protected left-turn.
g_m^i	Green time of movement *m* of intersection *i*
g_{min}, g, g_{max}	Minimum green time, duration of green time, maximum green time
L	Whole phase lost time in one cycle
d_m^i	Degree of saturation of movement *m* at intersection *i*
p_m^{in}	Input capacity of movement *m* from upstream
p_m^{out}	Output capacity of movement *m* at downstream
P_m^i	Variable for capacity optimization

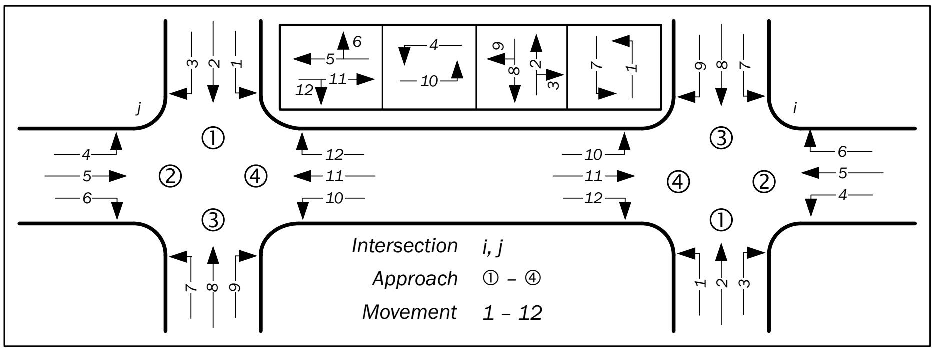

Figure 2 - Intersection layout, basic notation and phase sequence

5. THE CONSTRAINTS

5.1 Flow conservation

It is assumed that the traffic volume (q_m^i) and relative turning proportion (q_{mn}^{ij}) of each movement at approaches 1, 2 and 3 are given, then the traffic volume for approach 4 (including movements 10, 11 and 12) at each intersection can be set as

$$q_m^i = \sum_n q_n^j \theta_{nm}^{ji} \quad \forall m = 10, 11, 12. \tag{1}$$

$$q_n^j = \sum_m q_m^i \theta_{mn}^{ij} \quad \forall n = 10, 11, 12. \tag{2}$$

If left turn is prohibited along the arterial road at one intersection, the left turn traffic volume will transfer to another intersection. The formulations of flow conservation for left turn movements along the arterial road (movements 4 and 10) can be specified as:

$$Q_4^i = q_4^i \sigma_i + q_{10}^j (1 - \sigma_j) \tag{3}$$

$$Q_4^j = q_4^j \sigma_j + q_{10}^i (1 - \sigma_i) \tag{4}$$

$$Q_{10}^i = q_{10}^i \sigma_i + q_4^j (1 - \sigma_j) \tag{5}$$

$$Q_{10}^j = q_{10}^j \sigma_j + q_4^i (1 - \sigma_i) \tag{6}$$

Take formulation (3) for example, Q_4^i represents left turn volume for movement 4 at intersection *i* after optimization, and $q_4^i \sigma_i$ denotes if left turn is prohibited at intersection *i*, it will equal zero, otherwise it will equal q_4^i; $q_{10}^j (1 - \sigma_j)$ means if left turn is prohibited at intersection *j*, the traffic volume of q_{10}^j will turn to intersection *i* for left turn.

5.2 Lane number conservation

When left turn is prohibited at any approach, the lane for left turn will be replaced by through movement. The lane number conservation can be set as follows.

$$\boldsymbol{L_k^t} = \boldsymbol{l_k^t} \quad \forall k, t = i, j \tag{7}$$

where $\boldsymbol{L_k^t}$ denotes the number of lanes at approach *k* after optimization.

5.3 Turning proportion of each movement

The sum of turning fractions of each movement (left turn, through and right turn, U-turn is not considered) for each flow should equal 100%. The constraints can be set as

$$\sum_n \boldsymbol{\theta_{mn}^{ij}} = \mathbf{1} \quad \forall m \tag{8}$$

$$\sum_m \boldsymbol{\theta_{nm}^{ji}} = \mathbf{1} \quad \forall n \tag{9}$$

5.4 Duration of the green phase

In this paper, the critical degree of saturation equality is adopted to allocate the green time. Taking movement 4 at intersection *i* as an example, the green time g_4^i can be computed by

$$g_4^i = \max(q_4^i/s_4^i, q_{10}^i/s_{10}^i)/[\max(q_1^i/s_1^i, q_7^i/s_7^i) + \\ + \max(q_2^i/s_2^i, q_8^i/s_8^i) + \max(q_4^i/s_4^i, q_{10}^i/s_{10}^i) + \\ + \max(q_5^i/s_5^i, q_{11}^i/s_{11}^i)] * (c_i - L) \tag{10}$$

The duration of green for a traffic lane is subject to a minimum value and a maximum value. The constraint can be set as

$$g_{\min} \le g \le g_{\max} \tag{11}$$

where $(c_i - L)$ denotes the total effective green time in one cycle.

5.5 Cycle length

The constraints on the cycle length can be specified as

$$c_{\min} \le c_i = c_j \le c_{\max} \tag{12}$$

This ensures that the cycle length at each intersection is the same and that they will fall within the feasible range.

5.6 Left turn phase settings

The constraints on the left turn phase can be set as

$$\boldsymbol{\sigma_i} + \boldsymbol{\sigma_j} \ge \mathbf{1} \tag{13}$$

This constraint ensures that traffic flow can make a left turn at least at one intersection.

5.7 Degree of saturation

Take intersection *i* for example, the constraints on the degree of saturation can be set as

$$\boldsymbol{d_m^i} = \boldsymbol{q_m^i}/\boldsymbol{s_m^i} \tag{14}$$

$$\boldsymbol{d_m^i} < \mathbf{1} \quad \forall m \tag{15}$$

This ensures that the degree of saturation will fall within the feasible range.

5.8 Capacity

Each single traffic flow at downstream intersection comes from the three movements at upstream intersection, which have been shown in *Figure 3*.

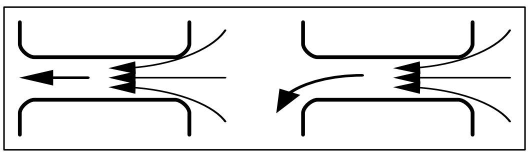

Figure 3 - Traffic streams outflow from upstream intersection then merge into through flow at downstream intersection

In this paper, it is assumed that it would be best if the capacity-merge-in from upstream equalled the capacity-merge-out at downstream. The constraint on the capacity can be set as

$$p_m^{out} = s_m^i \lambda_m^i L_m^i \quad (16)$$

$$p_n^{out} = s_n^i \lambda_n^i L_n^i \quad (17)$$

where s_m^i denotes saturation flow per lane; λ_m^i means green split, $\lambda_m^i = g_m^i / c_m^i$; L_m^i represents the number of lanes for the movement.

$$p_m^{in} = \sum_n p_n^{out} \theta_{nm}^{ji} \quad \forall m = 10, 11, 12. \quad (18)$$

$$p_n^{in} = \sum_n p_m^{out} \theta_{mn}^{ij} \quad \forall m = 10, 11, 12. \quad (19)$$

where p_m^{out} and p_n^{out} denote the output capacity at downstream; p_m^{in} and p_n^{in} represent the input capacity from upstream.

6. OBJECTIVE FUNCTIONS

With the above formulations, the following model can be developed to optimize design of protected left turn phase for the target intersections along an arterial road. In this study, it is assumed that these intersections share the same cycle length which is necessary for coordination of adjacent signals.

Control variables:

Binary variable which denotes whether left turn is forbidden: σ_i, σ_j

Common cycle length: c.

Green split : λ

In this paper, two criteria are considered for the optimization: capacity maximization and capacity gap minimization between the intersections.

6.1 Capacity maximization

One objective of traffic signal design is to maximize the capacity of intersections given the geometric layout. The interaction of relative traffic flows between intersections are considered; that is, the capacity of each movement will be the one which is lower between input capacity from upstream and output capacity downstream. The formulations can be set as

$$P_m^i = \min(p_m^{in}, p_m^{out}) \quad \forall m = 10, 11, 12. \quad (20)$$

$$P_n^j = \min(p_n^{in}, p_n^{out}) \quad \forall n = 10, 11, 12. \quad (21)$$

Then the objective function can be constructed as follows,

$$\max\left[\sum_{m,n} P_m^i + aP_n^j\right]$$

Subject to constraints in (1) - (21)

6.2 Capacity gap minimization

Another criterion arisen for optimization in this paper is how to create the smallest capacity gap between intersections along the arterial road to decrease the chances of spillover. The formulations of capacity gap can be set as

$$P_m^i = (p_m^{in} - p_m^{out})^2 \quad \forall m = 10, 11, 12. \quad (22)$$

$$P_n^j = (p_n^{in} - p_n^{out})^2 \quad \forall n = 10, 11, 12. \quad (23)$$

Then the objective function can be constructed as follows,

$$\min[\max(P_m^i, P_n^j)]$$

Subject to constraints in (1) - (19), (22), (23).

7. NUMERICAL EXAMPLES

To validate the efficiency and illustrate the applicability of the proposed model, this study employs an arterial road consisting of two intersections in Jinan city, China (Wei-er Road intersects with Jing-san Road, and Wei-er Road intersects with Jing-si Road) to evaluate the proposed model. Both Wei-er Road and Jing-si Road are primary arterial roads. Jing-san Road is a collector road.

The basic layouts of the intersections, traffic volume (peak hour volume from 8:00 a.m. to 9:00 a.m. measured by researchers in the field) for each movement and phase configurations are given in *Figure 4*. Turning ratios of each movement are given in *Table 2*. The spacing between intersections in the arterial road is 450 m (1,476 ft), $g_{min} = 15$, $g_{max} = 120$, $C_{min} = 60$ and $C_{max} = 180$ are used in the case study.

(O denotes originate, D denotes destination, i1 denotes approach 1 at intersection i)

To evaluate the performance of the proposed model, four different cases of signal plans are developed and compared in the following:

- *Case 1: Field signal plan; implementation of fixed signal timing plans optimized offline by local agency based on the Webster model.*

Table 2 - Turning fractions of each movement

D \ O	i1	i2	i3	j1	j2	j3
i1				20%	10%	20%
i2				70%	80%	70%
i3				10%	10%	10%
j1	5%	4%	5%			
j2	65%	76%	85%			
j3	30%	20%	10%			

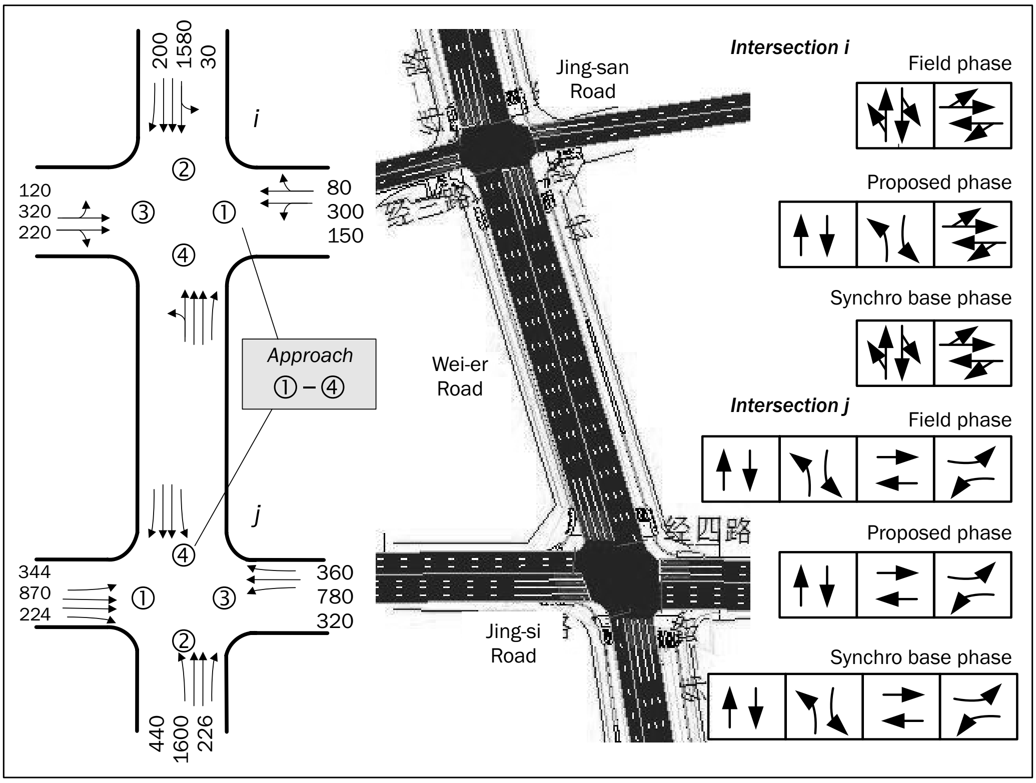

Figure 4 - Experimental intersection layout, traffic volume and phase settings

- *Case 2: Signal plan optimized by Synchro.*
- *Case 3: Signal plan optimized by proposed model with capacity gap minimization.*
- *Case 4: Signal plan optimized by proposed model with capacity maximization.*

Table 3 shows the optimization and comparison results of different scenarios.

As indicated in *Table 3*, one can reach the following findings:

- Both Case 1 and Case 2 generate two phases signal plans at intersection *i* and four phases signal plans at intersection *j* , while Case 3 and Case 4 generate three phases signal plans at these two intersections (see phase setting in *Figure 4*).
- For Case 3, with the objective of capacity gap minimization, a shorter cycle length was obtained from the proposed model, which is 92 seconds and much less than field signal program of 160 seconds and Synchro based signal program of 150 seconds. Moreover, the analysis of degree of saturation further demonstrated that the proposed model for Case 3 can handle the same traffic demand with smaller cycle duration at nearly the same constraint of degree of saturation.
- For Case 4, with the objective of capacity maximization, the optimal cycle lengths are bound to the maximum limit of 180 s, and a lower degree of saturation was achieved compared to Case 3.
- For Cases 1 and 2, the degree of saturation of movements at intersection *j* is much higher than those at intersection *i*; while the degree of saturation of movements at both intersection *j* and intersection *i* are very similar with each other under Case 3 and Case 4.

The delay and throughput of the two intersections in different cases are shown in *Figure 5* and *Figure 6*. The following conclusions can be reached by comparing the performance measures under different cases.

- For Case 3 and Case 4, the average delay has been increased at intersection *i* and decreased even more at intersection *j* compared with Cases 1 and 2. And the average delay at each intersection gets closer to each other, which means the traffic flows are well-distributed by the proposed control model.
- Taking the total network into consideration, for Case 3, with a smaller cycle time, the signal plan can provide the lowest total average delay which is decreased by 49.6% compared to Case 1 and 49.8% compared to Case 2. For Case 4, the total average delay is decreased by 43.0% and 43.2% compared with Cases 1 and 2, respectively.
- In *Figure 6*, for Case 3, even with smaller cycle time, the total throughput of the total network is larger than that in Case 1 and Case 2 (9.2% and 9.8%, respectively). For Case 4, the throughput per hour at these two intersections increases by 14.1% and 14.7% compared with Cases 1 and 2, respectively. This verified that the proposed method, by either maximum capacity or minimum capacity gap, can always improve the traffic efficiency of the intersections.

Table 3 - Comparison of results at different signal plans

Intersection	Scenarios	Number of phases	Cycle length	Wei-er Road Green time (degree of saturation)		Crossing road Green time (degree of saturation)	
				Through	Left-turn	Through	Left-turn
Intersection i	Case 1	2	160	101 (0.51)		53(0.48)	
	Case 2	2	150	95(0.50)		49(0.48)	
	Case 3	3	92	40(0.96)	28(0.96)	15(0.97)	
	Case 4	3	180	82(0.91)	58(0.91)	31(0.92)	
Intersection j	Case 1	4	160	74(0.91)	28(1.32)	36(1.82)	10(2.21)
	Case 2	4	150	52(1.21)	26(1.33)	43(1.43)	17(1.48)
	Case 3	3	92	27(0.95)	/	40(0.95)	16(0.96)
	Case 4	3	180	57(0.91)		81(0.91)	33(0.92)

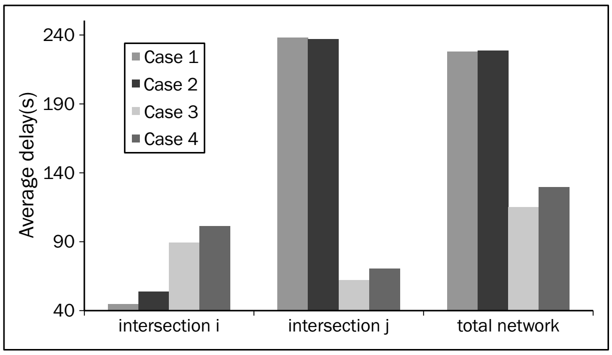

Figure 5 - Comparisons of the average delay for different signal plans

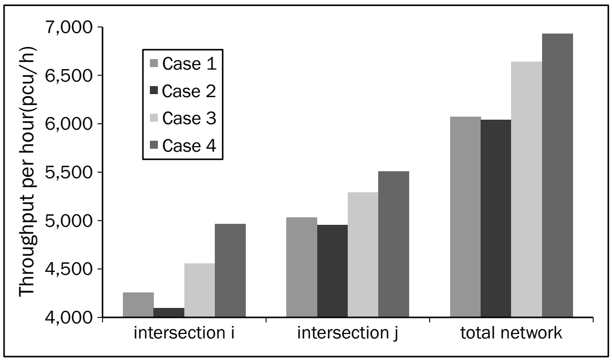

Figure 6 - Comparisons of throughput for different signal plans

To investigate the performance of the proposed model under different through volume along the arterial road, this study analyses the impacts of through movement ratio. Let $\boldsymbol{Y_T^A}$ denotes the ratio of the arterial road through flows over total flow of intersection $A(\boldsymbol{A} \in (\boldsymbol{i},\boldsymbol{j}))$, where

$$\boldsymbol{Y_T^A} = \max(q_4^i/s_4^i, q_{10}^i/s_{10}^i)/[\max(q_1^i/s_1^i, q_7^i/s_7^i) + \max(q_2^i/s_2^i, q_8^i/s_8^i) + \max(q_4^i/s_4^i, q_{10}^i/s_{10}^i) + \max(q_5^i/s_5^i, q_{11}^i/s_{11}^i)] \quad (24)$$

Then let $\boldsymbol{Y_T^i}$ and $\boldsymbol{Y_T^j}$ vary in the range of 0.1 to 0.5, then compare the capacity gap and capacity under different scenarios. Let PM denote the proposed model; IP represents left turn prohibited at intersection *i* only; JP represents left turn prohibited at intersection *j* only; and BP denotes protected left turn adopted at both intersections. The results are shown in *Figure 7*

The capacity gap varies with the increase of the volume ratio of the arterial through flows at intersection $j(\boldsymbol{Y_T^j})$ under all kinds of control model while the proposed model can always generate the minimum capacity gap signal plan at different conditions (figures on the left side). When $\boldsymbol{Y_T^j} < 0.4$, the signal plan of left turn prohibited at intersection *j* only is the best one, which testifies that despite the left turn volumes are large at principal intersection along the arterial road, left turn should be prohibited to alleviate heavy traffic demand on the crossing road. When $\boldsymbol{Y_T^j} > 0.4$, the plan of the protected left turn phase adopted at both intersections (BP) will be better.

With respect to capacity (figures on the right side), *Figure 7* also shows that the proposed model always generates left turn prohibited signal plan at intersection *j* only (JP), which illustrates left turn prohibited at primary intersection while the protected left turn phase at the secondary intersection along the arterial road can provide maximum capacity.

8. CONCLUSION

An optimization method for the integrated design of protected left turn phase and signal settings for the adjacent intersections along the arterial road has been presented. Two criteria for signal optimization have been considered: the capacity gap minimization and capacity maximization. A set of constraints has been set up to ensure the feasibility of the resulting optimal left turn phase and signal settings. The proposed model can adapt to different traffic demand patterns with the most suitable left turn phases design and signal settings. Numerical examples have been given to demonstrate the effectiveness of the proposed method in comparison with the field and Synchro based. Both capacity gaps of relative movements between adjacent intersections and average delay can be decreased and the throughput of the two intersections can be in-

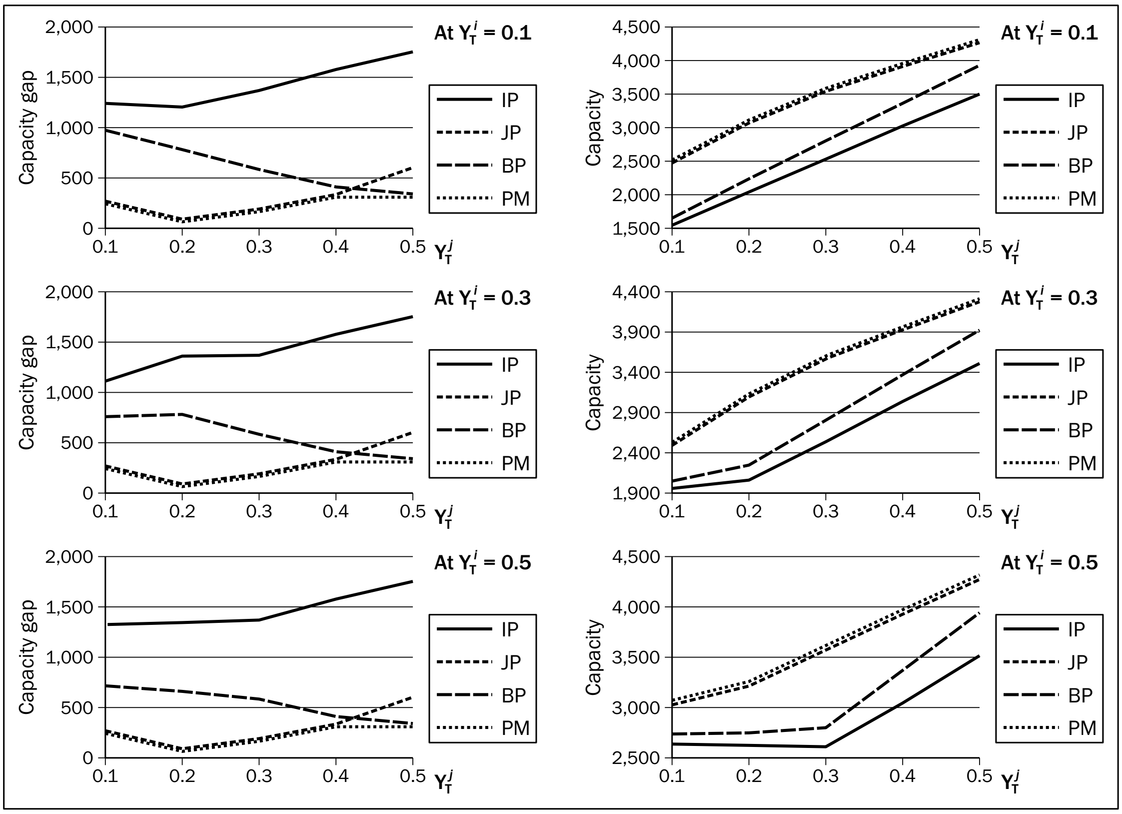

Figure 7 - Compare the capacity gap and capacity at different scenarios (the figures on the left side are optimized by objective function of capacity gap minimization while the capacity maximization is on the right side)

creased by the proposed model. Furthermore, the sensitivity analyses of the flow ratio of through movement along the arterial road further demonstrate that the intersection with heavy flow on the crossing road (e.g. crossing road is another arterial road) shall forbid left turn in order to increase the capacity of other movements.

This paper proposed a very practical model for the protected left turn phase design problem to improve the overall efficiency as well as decrease the probability of spillover by minimizing capacity gap between adjacent intersections. Common practices when designing a protected phase are based on the left turn volume in the field at a single intersection. As result, the main intersections (arterial road intersecting arterial road) always have a protected left turn phase while secondary intersections do not. This usually causes insufficient capacity at the main intersections and surplus capacity at the secondary intersection. In this paper, the proposed model can design the left turn phase at a systematic level that maximizes the capacity of the entire system and minimizes the capacity gap between adjacent intersections simultaneously.

Note that this paper has presented the preliminary evaluation results for the proposed model. More extensive numerical experiments or field tests will be conducted to assess the effectiveness of the proposed model under various traffic demand patterns, intersection and arterial road geometry configurations. Another possible extension to this study is to optimize the protected left turn phase of several intersections along the arterial road and provide smoother and more efficient control of the arterial roads.

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吴伟
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基于通行能力匹配的相邻信号控制交叉口左转保护相位优化设计

左转交通量大时常采用左转保护相位，但在城市干道上，当部分交叉口设置左转保护相位而部分交叉口未设置时，上下游交叉口之间通常会存在通行能力的差，从而造成交通拥堵等问题。本文正是针对上述问题，优化城市干道相邻交叉口间的左转相位设置。建立了0-1整数规划模型，模型分别以通行能力差值最小和干道通行能力最大为

目标，建立了一系列约束条件保证解的可行性，使用分枝定界法进行求解。最后，本文选取济南市纬二路进行模型验证，结果表明：对比实地和Synchro的信号控制方案，本文模型能减少交叉口间的通行能力差值，降低延误。敏感性分析进一步表明即使在不同的交通需求情况下，本文模型也能针对城市干道进行最佳左转相位优化设计。

通行能力差，左转保护相位，信号优化，信号控制交叉口

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