TRAFFIC PERFORMANCE IN MEDIAN U-TURN INTERSECTIONS WITH PROTECTED PRE-SIGNAL AND ITS APPLICATION

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ABSTRACT

The median U-turn with protected pre-signal is proposed in the paper to explore the potential capacity of intersections. The space between the main signal and the pre-signal is isolated as an exclusive waiting area. The relationship between the capacity and the arrival rates in the design is investigated and the sensitivities of length of waiting area, signal timing and arrival rates are presented. The comparison among Continuous Flow Intersection, the method Xuan (2011) proposed and the design in the paper is proposed. The results show that Median U-Turn intersections with protected pre-signal is expected to increase the capacity and decrease the average delay of intersections.

Keywords: Median U-turn, Geometric Design, Protected Pre-signal, Signal Timing.

INTRODUCTION

In urban transportation, proper signal design and operation are critical to the orderly movements and the capacity of intersections. Separate green phases are typically introduced in intersections with high turning movements, hence the capacity of the intersection is limited. One approach to eliminate the negative effects of multi-phases signal timing is by utilizing the unconventional method to reduce the sub-phases without sacrificing the safety concerns. The unconventional designs may include the Roundabout, Median U-Turn, Bowtie, Superstreet, Jughandle, and Continuous Flow Intersection. All the measures above seem effective to maintain the orderly flow and adopt separate turning phases as few as possible. However, most of these designs require additional construction, which may not be available in some local geometric conditions. Besides, these strategies force left-turning vehicles to go through the intersection multiple times, increasing demand there (Xuan, 2011).
To explore the potential capacity of isolated intersections, a new geometric design combined with protected signal control is proposed. The new configuration originates from the

observation of signalized roundabouts, which requires left-turn vehicles to wait in certain areas and to be discharged together with through vehicles from a perpendicular arm. Figure 1 presents a signalized roundabouts design with eight signals established, four of which is utilized by through vehicles and four for left-turns. For example, southbound vehicles from east directions should wait in site A until the through phase for vehicles from north and south direction starts. There are only two phases in the signalized roundabouts, which highly decreased the average delay and increase the capacity of intersections. Although the performance of roundabouts may be inferior to the unsignalized roundabouts in the situation of low arrival rates (Fouladvand M. et al., 2004), the advantage of signalized operation is significant nevertheless. However, compared to the conventional intersections, roundabouts requires large construction and usage of land, which may be unavailable in urban cities.

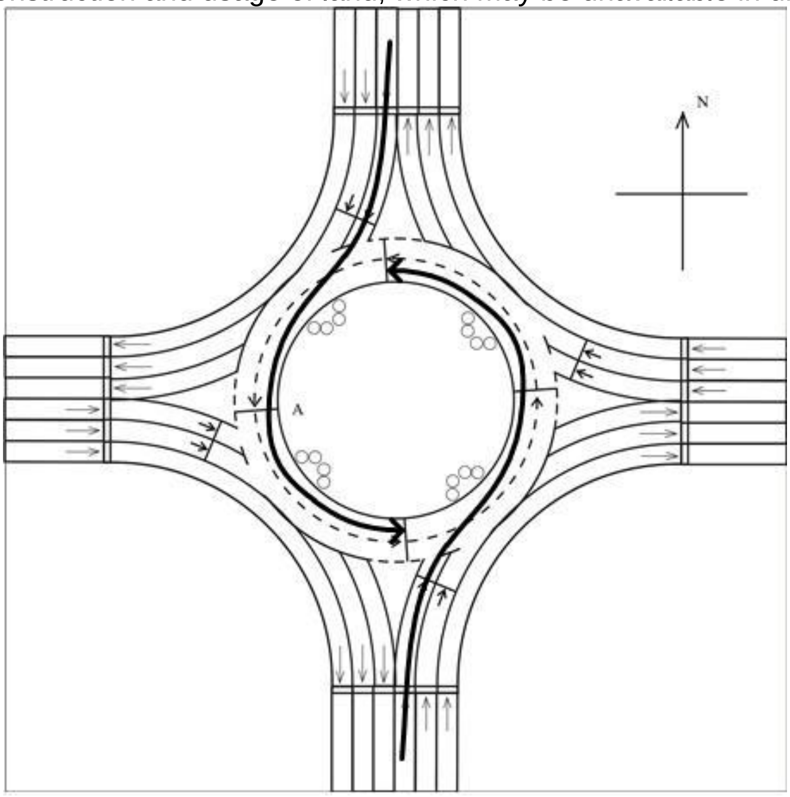

Figure 1 – An example of signalized roundabouts.

The national cooperative highway research program report 524 (NCHRP,2004) on the safety of U-turns at unsignalized median openings presents a detail elaboration on the unsignalized median openings. Similarly, the Highway Capacity Manual (2000) investigate the evaluation of the capacity of unsignalized median openings. The gap acceptance is the main theme of this literatures. However, few research focus on the median openings with protected signal. In this paper, a geometric design originated from the topology of the signalized roundabouts is presented to increase the capacity of intersections. The new design retain the advantage of roundabout whereas the additional construction is removed. Similar to the median U-turn, Figure 2a presents a new geometric design for urban intersections. Left-turns are required to maneuver in the rightmost lane and share lane with the right-turns. Besides, in each approach, main signal and pre-signal are coordinated to regulate the traffic. In each cycle, the through vehicles should wait behind the stop line where pre-signal established until the green phase starts. The left-turns, however, should first make right-turn and then U-turn to wait behind the stop line of main signal. If the minor road is not wide enough, an alternative configuration is available in Figure 2b. The left-turn vehicles are required to first move across the intersection and later make U-turn in the median opening and right turn in the intersection. Regardless of the variant configuration, the paper focuses on the former to investigate the traffic performance in intersections with protected pre-signal established in median opening.

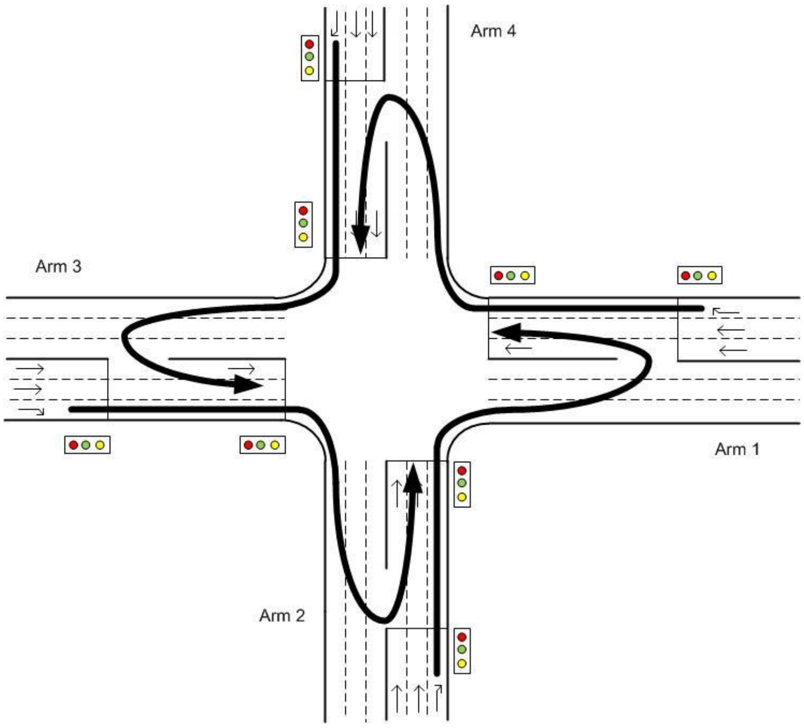

Figure 2a – Geometric design of intersections with protected pre-signal.

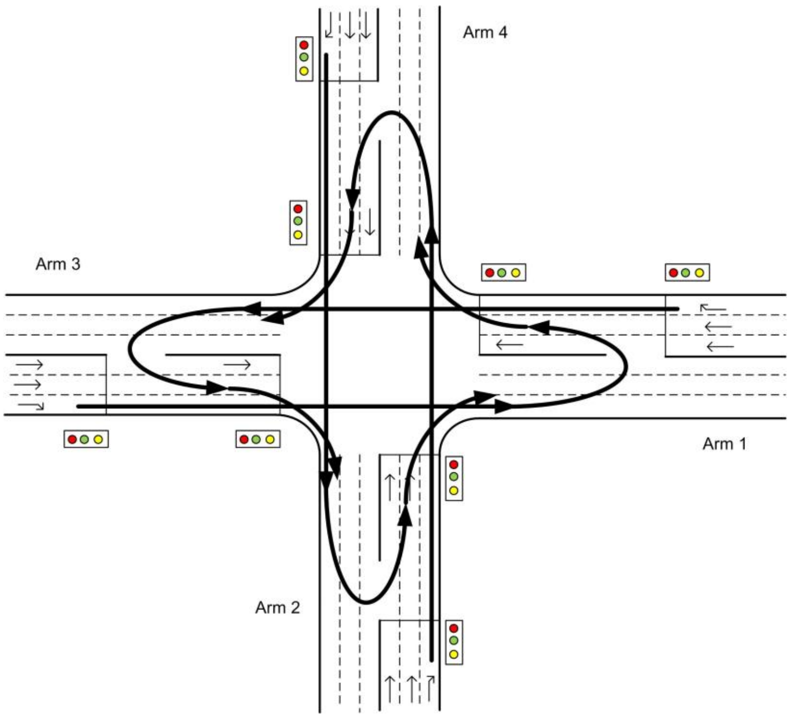

Figure 2b – An alternative configuration of intersections with protected pre-signal.

The operation is to some extent similar to the median U-turn, except that the protected signal timing is operated in the pre-signal. Besides, median U-turn requires wide median to handle the conflict between turning vehicles and through vehicles from main street. Therefore, the capacity of median U-turn is highly affected by the width of median opening (Liu P., et al, 2008). However, in the new configuration, the conflict is eliminated by utilizing the protected signal phases and the median width is not critical to the traffic movements. For through vehicles, drivers are easy to adapt to the configuration, because their behaviours are the same as the conventional operation, except that the stop line for through vehicles is moved to the median opening. For left-turns, drivers will experience the pre-signal and the main signal in the perpendicular arm. Therefore, the through vehicles are organized to follow the left turns in each cycle. To simply the analysis, the intersections with four arms are investigated in the paper.

THE CONSTRAINTS FOR ORDERLY DISCHARGE

To ensure the safety and orderly discharge of vehicles in the intersection with protected pre-signal, several constraints considering the signal timing and geometric design are presented. The constraints are incorporated in the delay minimization.

Label transition function

The configuration is basically operated in the at-grade intersection with four arms and the arms are marked by using clockwise rotation. Since there are only two phases in main signal, a label transition function is defined below.

$$m_T(i) = \text{mod}(i+2,4) + 4\{1 - \text{sgn}[\text{mod}(i+2,4)]\}, \quad i = 1,2,3,4 \tag{1}$$

$$m_L(i) = \text{mod}(i+3,4) + 4\{1 - \text{sgn}[\text{mod}(i+3,4)]\}, \quad i = 1,2,3,4 \tag{2}$$

where $\text{sgn}(\cdot)$ is the sign function, $\text{sgn}(x)=1$ if $x>0$, $\text{sgn}(x)=0$ if $x=0$ and $\text{sgn}(x)=-1$ if $x<0$. $\text{mod}(\cdot)$ is a modulo operation to find the remainder of division of one number by another. Arm $m_T(i)$ is the one located at the opposite direction of arm i and similarly, arm $m_L(i)$ is the one located at the right side of arm i. The first part in equations reflects the label transition and the second part is to prevent zeros in some modulo operation. Besides, the approach in one arm shares the same label with the corresponding arm.

Symmetric green interval and the main signal cycle

To prevent the left-turn vehicles from accumulating in the exits, which will block the opposite through vehicles in the next phase, the symmetric green interval is operated in the main signal, which indicates that the length of green time in one direction and its opposing direction is equal; therefore the number of signal phases is reduced and we have

$$G_{i,m_T(i)} = G_{m_T(i),i}, \quad i = 1,2,3,4 \tag{3}$$

where $G_{i,m_T(i)}$ is the length of green phase in the main signal. Besides, it is obvious that the cycle length of main signal is the sum of all the phases, hence we have

$$C = \frac{1}{2}\sum_i G_{i,m_T(i)} + 2t_{lost}, \qquad i = 1,2,3,4. \tag{4}$$

where C is the cycle length of main signal and t_{lost} is the lost time between consecutive phases and is the sum of clearance lost time plus start-up lost time. It should be realized that the lost time here is a little longer than the conventional operations, because through vehicles have to traverse the whole waiting area. If the length of waiting area is denoted by $l_i,\ i = 1,2,3,4$, the lost time should be added by l_i / v, where v is the average velocity of through vehicles starting from the pre-signal to the main stop line. In practice, the average velocity approximates to the vehicle length divided by headway.

Green length constraint for pre-signal

Since left-turns have to first make right-turn and then U-turn, the excessive left-turns during the clearance time may block the through vehicles from perpendicular arms and the congestion may happen. To prevent the failure, it is critical to require the excessive left-turns stay behind the stop line of the pre-signal, which means the green phase for left-turns should be terminated earlier than the through green length. Therefore the green length for left-turns in the pre-signal should minus the traverse time from main stop line to the stop line of perpendicular arms. Hence we have,

$$g_{i,m_L(i)} = \max\{G_{i,m_L(i)} - \frac{l_{m_L(i)}}{v},\ \ g_{\min}\} \tag{5}$$

where $g_{i,m_L(i)}$ is the green length for left-turns in pre-signal and $g_{\min}$ is the minimum green length.

However, if the length for left-turns is too short whereas the arrival rates of left-turns is not small, an alternative design is available nevertheless. The alternative is that the pre-signal for left-turns retains green during the whole cycle and the left-turns stay behind the main stop line, which is different from the through vehicles. In this compromise, however, the waiting area for left-turns from perpendicular arm will be smaller and the turning radius will be reduced. The tradeoff between the two operations is dependent on the local conditions.

Constraint of the waiting area

If the waiting area is large enough to prevent left-turn queues at the main signal from backing up the pre-signal, the configuration is expected to operate the movements effectively. However, if the left-turns spill over the waiting area, the excessive left-turns would block the through vehicles, which may cause congestion. To prevent the situation, the following equation should be satisfied.

$$n_i^L g_{i,m_L(i)} s_{i,L} \le \frac{(n_{m_L(i)}^L + n_{m_L(i)}^T) l_{m_L(i)}}{u} \tag{6}$$

where n_i^L and n_i^T are the number of left-turn lanes and through lanes in approach i respectively. $g_{i,m_L(i)}$ the green length, $s_{i,L}$ the saturation flow rate of left-turns and u the average length of vehicles. $l_{m_L(i)}$ is the length of waiting area, which is equal to the distance between the main stop line and the pre-signal stop line. The equation states that the number of vehicles discharged from approach i should not surpass the capacity of waiting area of approach $m_L(i)$.

In practice, due to the randomness of headways, the de facto vehicles arrived may be varied in each cycle. Therefore, to ensure the configuration is safely operated, a safety coefficient σ is considered, with $0 \le \sigma \le 1$. Hence we have

$$n_i^L g_{i,m_L(i)} s_{i,L} = \frac{\sigma(n_{m_L(i)}^L + n_{m_L(i)}^T) l_{m_L(i)}}{u} \tag{7}$$

CAPACITY OF THE INTERSECTION

The capacity of the intersection is hence expected to derived by solving the following linear program.

$$\max_{G_{i,m_T(i)}, G_{m_L(i),m_T(m_L(i))}, g_{i,m_L(i)}} \sum_i q_i$$

$$q_{i,L} = q_i p_{i,L} \tag{8}$$

$$q_{i,T} = q_i (1 - p_{i,L}) \tag{9}$$

$$g_{i,m_T(i)} = G_{i,m_T(i)} \tag{10}$$

$$g_{i,m_L(i)} = \max\{\min(G_{i,m_L(i)} - \frac{l_{m_L(i)}}{v}, \frac{\sigma(n_{m_L(i)}^L + n_{m_L(i)}^T) l_{m_L(i)}}{u n_i^L s_{i,L}}),\ g_{\min}\} \tag{11}$$

$$C = G_{i,m_T(i)} + G_{m_L(i),m_T(m_L(i))} + 2t_{lost} \tag{12}$$

$$q_{i,T} = \frac{n_i^T s_{i,T} G_{i,m_T(i)}}{C} \tag{13}$$

$$q_{i,L} = \frac{n_{m_L(i)}^L s_{i,L} g_{i,m_L(i)}}{C} \tag{14}$$

where $p_{i,L}$ is the turning proportion in arm i, $g_{i,m_L(i)}$ is the green length for left-turns in pre-signal and $g_{\min}$ is the minimum green length. $G_{i,m_T(i)}$ is the length of green phase in the main signal. Without loss of generality, if equation (12) is replaced by $g_{i,m_L(i)} = G_{i,m_L(i)} - \frac{l_{m_L(i)}}{v}$, the solution for the linear program is

$$q_i = \frac{C - 2t_{lost} + l_{m_L(i)}/v}{\frac{(1-p_{i,L})C}{n_i^T s_{i,T}} + \frac{p_{i,L} C}{n_{m_L(i)}^L s_{i,L}}} \tag{15}$$

The improvement for typical cases is significant. For example, assume that there are three lane in each approach, two of which is for through vehicle and one for left-turns. The saturation flow rate for each lane is 1800veh/h, the cycle $C = 120s$, $l_{m_L(i)}$ =50m, $t_{lost} = 10s$, $v = 10m/s$, $p_{i,L} = 0.4$, and $G_{i,m_L(i)} = 55s$, the capacity of one approach is 2250veh/h. For conventional operation, if we assume 22s for left-turns and 30s for through lanes, which is proportional to the turning ratio, the capacity is 1230veh/h. Therefore, the capacity improvement is quite large.

COMPARISON AMONG SEVERAL UNCONVENTIONAL INTERSECTIONS

The comparison among the conventional four-phase intersection, the Continuous Flow Intersection and the method Xuan (2011) proposed are presented in this section. Because the proposed method, the Continuous Flow Intersection are all operated with two phases, whereas the Xuan method is with four phases, a critical performance to evaluate the efficiency is the average delay. A four-arm intersection with three lanes is investigated in the paper.

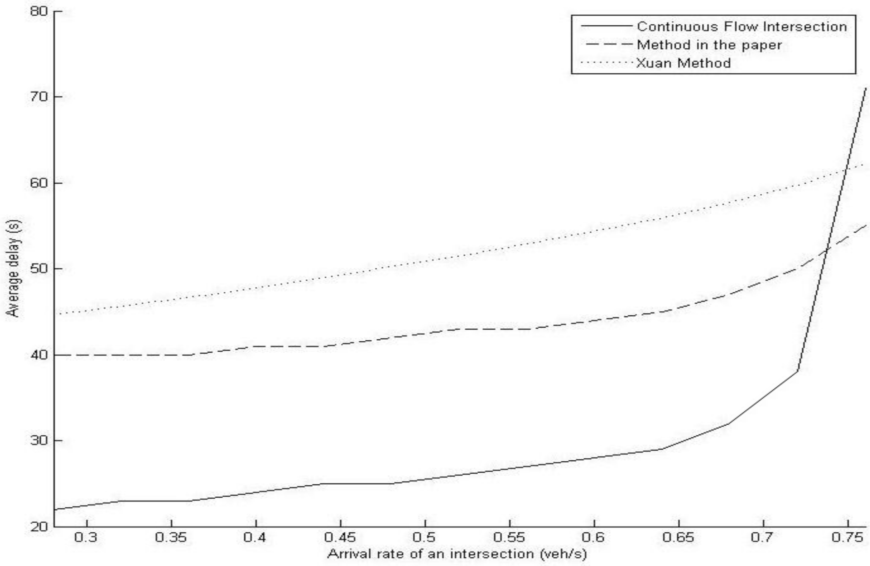

Figure 3 – Comparison of average delay between three unconventional method.

Figure 3 plots the comparison of average delay between the three method. The method in the paper has lower average delay than the Xuan method. With the increase of arrival rate, the increase of delay is steady, which imply that the new method has the potential to handle the situations with high arrivals. If the arrival is low, the average delay of Continuous Flow Intersection is not significant. If the arrival is high, the average delay, however, will increase tremendously. The improvement of the method compared to the conventional four-phase intersection is presented in Figure 4. As is shown, the average delay of conventional intersection is quite large, due to the low capacity of the intersections. The intuitive reason is that the signal phase has been reduced to two phases.

The improvement is significant as shown in Figure 4. However, if the arrival rate is low, the conventional method may be in advantage, which is due to the additional stops experienced by left-turns. The reason is that the capacity is not the critical factors if the arrival rate is low.

Therefore, if the arrival rate in one intersection is low, the method in the paper is not recommended. The turning point of the example with three lanes is around 0.4veh/s, which is 1440veh/h for the whole intersection. The arrival is quite small and not common in urban intersections; hence the method of the paper is applicable to intersections nevertheless.

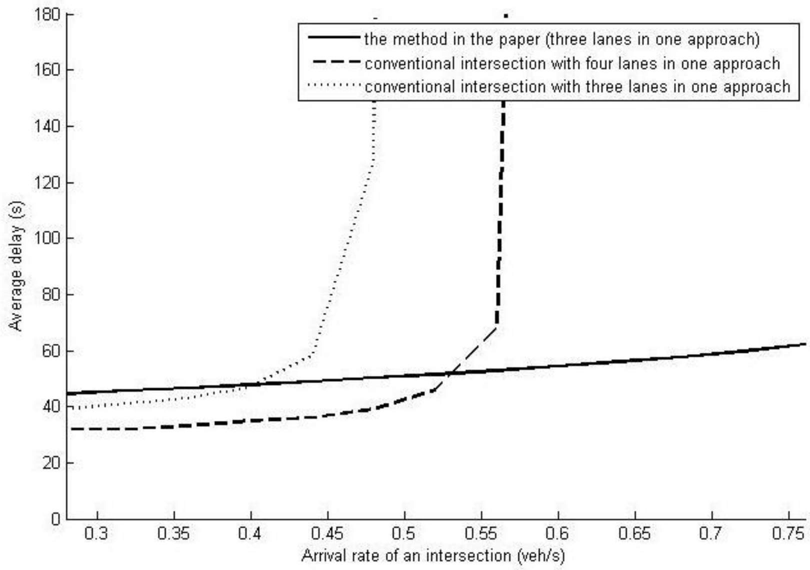

Figure 4 – Comparison between the conventional method and method in the paper.

EMPIRICAL EXAMPLE

As shown in Figure 5 and Figure 6, two intersections in the city Hefei of China are investigated to illustrate the advantage of protected pre-signal operation. The intersection of Jinzhai Road and Furong Road is located in the north side of the other intersection, hence the two intersection are represented as north intersection and south intersection respectively. The number of lanes are presented in Table I and the current signal timing is shown in Figure 7. The signal cycle are 134s and 124s respectively. Currently, the traffic congestion emerging from the two intersections seriously deteriorate the performance of the region since the Jinzhai Road is a vein with high arrival rates. The traffic police occasionally intervene to alleviate the situation.

Table I –The number of lanes in the two intersections

	Jinzhai (north)	Furong (east)	Furong (west)	Jinzhai (south)	Fanhua Avenue
Approach	7	2	5	6	6
Exit	6	2	3	5	4

Since there are only two lanes in the Furong Road, the space cannot support the U-turn in Furong Road. Hence, it is recommended that the left-turns from Jinzhai Road traverse the intersection and then make U-turn at the median opening of Jinzhai Road. The geometric layout of southern intersection, however, can utilize the protected pre-signal as suggested above. The average delay by using the protected pre-signal is lowered to 23.7s in the north intersection and 35.2s in the south intersection. The degree of saturation of each phase is summarized in Table II. Based on the improved operation and the optimized signal timing, the performance of the two signalized intersections significantly outperform the conventional operation.

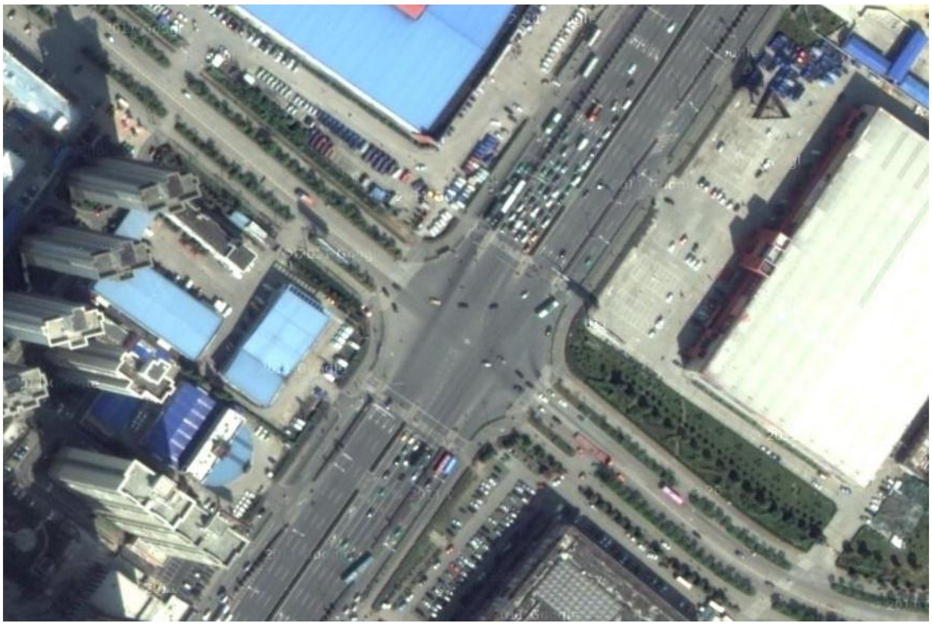

Figure 5 – The Intersection of Jinzhai Road and Furong Road

Figure 6 – The Intersection of Jinzhai Road and Fanhua Avenue

Table II. The degree of saturation in each phase.

	W.B.from east	E.B. from west	S.B. from east	N.B. from west	N.B. from south	S.B. from north	E.B. from south	W.B.from north
North inter.	0.5246	0.2533	0.2895	0.3347	0.5865	0.6171	0.2188	0.3764
South inter.	0.3664	0.7016	0.3720	0.7910	0.4569	0.5831	0.3498	0.4562

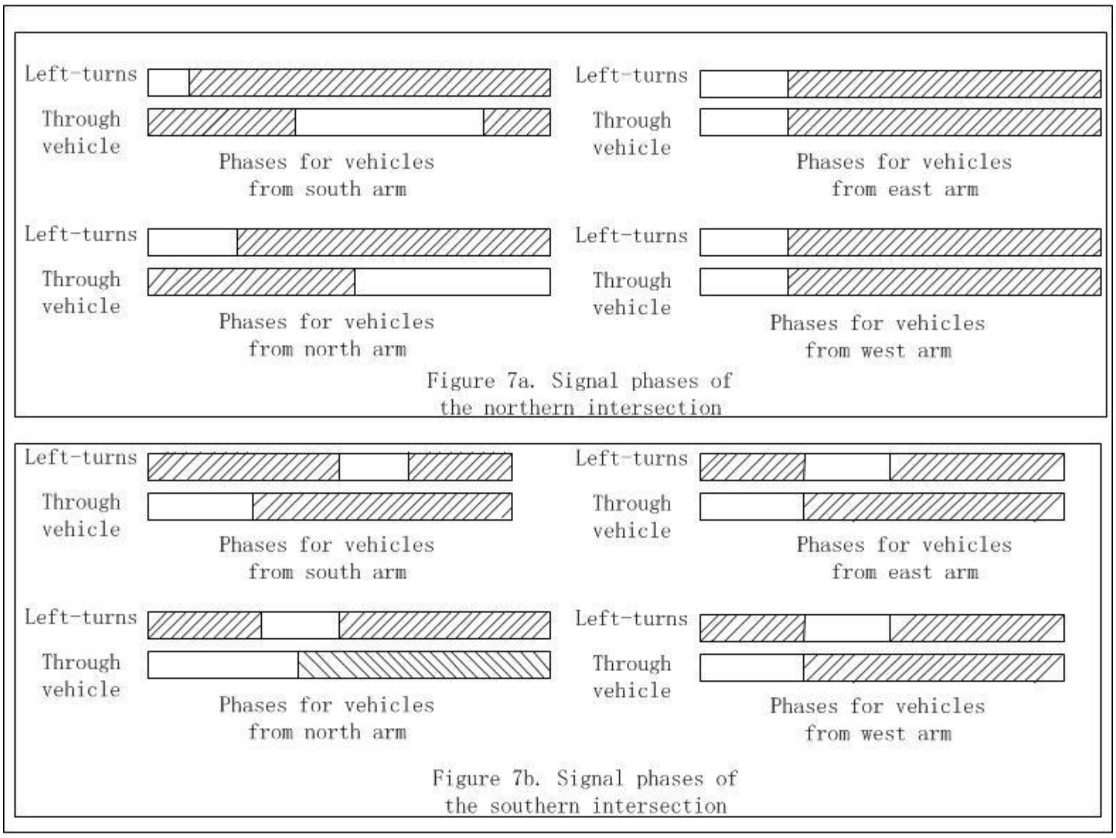

Figure 7 – The current signal timing of the two intersections

CONCLUSION

In this paper, an intersection with protected pre-signal is presented to explore the potential capacity of intersections. The new configuration originates from the observation of signalized roundabouts and is improved to be utilized by conventional intersections without extra construction. The capacity of the configuration is evaluated and the comparison of average delay among three common unconventional intersections is proposed. Compared to the conventional configuration, the result proves that the improvement is significant in urban intersections.

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