Signal timing optimization of shifted left-turn intersections

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Abstract. A signal timing optimization method based on shifted left turn lane intersections is proposed to increase the efficiency of shifted left turn lane junctions. In previous studies, vehicle delays were often the only concern but vehicle exhaust emissions were ignored, which could easily aggravate environmental pollution. A multi-objective optimization model was developed in this paper for intersection signal timing from a vehicle and environmental perspective, using vehicle delay, capacity and exhaust emissions as indicators. A modified particle swarm algorithm was used to resolve the impact of a shifted left turn lane on vehicles at a selected junction in Shanghai. The proposed scheme can reduce vehicle delay by 24.58%, increase traffic capacity by 17.09% and reduce tail gas emission by 34.68% in peak period compared with before improvement. In low peak period, the delay, exhaust emission and traffic capacity are reduced by 49.04%, 41.68% and 17.09% compared with those before improvement. Using this optimization scheme can improve vehicle delay to a certain extent, improve vehicle traffic capacity and reduce pollution caused by exhaust emission to the environment. It also verifies the validity of the model and provides some theoretical basis for setting the signal timing for shifted left-turn lane intersections.

1. Introduction
In China, the passage of left-turning vehicles is a major conflict point for traffic at intersections, which complicates crossover signal timing. The way to balance the efficiency of vehicle traffic and the accident rate within the space-limited intersection is a popular issue discussed by many scholars world wide.

Ma [1] et al. put forward a layered multi-objective optimization framework suitable for low-resolution trajectory data. Based on the optimization of traffic signals at fixed times, both cycle length and green bifurcation were optimized in the under-saturation state; Song [2] et al. built a dynamic lane and traffic signal optimization model by combining dynamic lane alternative scheme, lane optimization and signal optimization scheme, aiming at minimizing average delay; An [3] et al. analyzed and predicted unconventional intersections, and pointed out that the reverse variable lane left turn and U-turn have good application prospects in China. However, continuous flow intersections and parallel flow intersections are not suitable for rapid and large-scale promotion in China due to their complex operation; Ren [4] et al. used the simulated annealing algorithm to select the minimum average delay and maximum capacity as targets. Reverse variable lane length and cycle length were used as constraint conditions to optimize signal timing.
Shifting the left-turn intersection can make full use of the idle resources of the intersection space, reduce the phase sequence and vehicle waiting time, and improve the overall efficiency of vehicles. But previous studies often are the studies of the single index such as vehicle delay, without considering the environmental impact of vehicle emissions, today is in advocate green development, pay attention to the benefits to ignore the green development is one-sided. Therefore, this paper chooses the vehicle delay, capacity, vehicle exhaust emissions as indicators, comprehensive analysis on the signal timing optimization of shifted left-turn intersections.

2. Shifting Traffic Flow Rules at Left-turn Intersections

The left-turning traffic entering the intersection is controlled by a pre-signal into the shifted left-turn lane and is then released at the main intersection with the straight traffic by the main signal. With such a mechanism, the number of conflict points in the traffic flow is greatly reduced and the traffic flow efficiency is improved, while at the same time the number of signal phases is reduced, thus reducing the total average traffic delays. This design is more suitable for large intersections with high direct traffic flow and low left-turn traffic. Figure 1 shows the west import set shift left turn lane, assuming that the phase sequence of the intersection is: north-south left turn, north-south straight and east-west straight left, the rules of passage are: when the north-south left turn phase starts, the pre-signal of the west import is closed to prevent traffic conflicts; when the north-south straight phase starts, the pre-signal of the west import opens, and the vehicles slowly drive into the shift left turn lane; When the north-south straight phase ends, the pre-signal also ends accordingly, at which point the left-turning traffic stops driving into the shift left lane, the east-west straight left phase opens and the left-turning traffic leaves the intersection together with the straight traffic. As there is a real possibility of vehicles being stranded in the shift left lane, the shift left lane here does not allow vehicles from other phases to drive into it.

3. Optimization Model for Signal Timing of Shifted Left-turn Intersections

3.1. The optimization goal

The traffic state of the intersection is changing all the time, so we should focus on the index selectively in different situations. For example, when traffic volumes are low and the degree of environmental pollution is light, the main consideration for signal control is to minimise delays at the intersection; When traffic volumes are high, the main consideration for signal control is to maximise the capacity of the intersection; When the degree of environmental pollution is heavy, the first consideration is to reduce vehicle exhaust emissions. Combined with the original research, it can be seen that the ratio of the weighting coefficient of the two factors, vehicle capacity and vehicle delay, increases with the decrease of vehicle flow. Based on the existing research, this paper made some modifications to the vehicle weight coefficient, and established the following index weight coefficient and objective function with the goal of minimizing vehicle delay, exhaust emissions and maximum vehicle capacity.

$$\min f(C,g_i) = \min \sum_{i=1}^{3} (k_i^1D(C,g_i) + k_i^2E(C,g_i) - k_i^3Q(C,g_i))$$

Figure 1. Traffic flow rules at a shifted left-turn intersection
\[
\begin{aligned}
    k_1^i &= 2\sqrt{S_i(1 - Y)} \\
    k_2^i &= 2Y\sqrt{S_i} \\
    k_3^i &= 2Y \frac{C}{3600}
\end{aligned}
\]  

Where, \( S_i \) represents the saturation flow of the lane for phase \( i \); \( g_i \) represents the validity of the first phase \( i \); \( Y \) represents the total volume of the max. flow ratio of each phase; \( C \) represents the signal cycle; \( T \) represents the delay time for vehicles crossing the intersection; \( D \) represents the exhaust emissions of vehicles passing through intersections; \( Q \) represents the capacity of vehicles to pass through the intersection.

### 3.2. Phase sequence design

In this paper, the east-west section is chosen to set up a shift left turn as an example, with the left turn and east-west straight being released at the same time. Assuming that the north-south straight is phase 1 and the north-south left turn is phase 2, the north and south left turn vehicles through can make things turn left into the shift extend the time of the left lane, so choose to the left as phase 1, the north and the south straight behavior phase 2, in the second phase is open at this time, things left turn vehicles release into the shift left lane, things go straight and turn left to the third phase. It is assumed that there is a time difference \( \Delta t_1 \) between the opening time of the green light for phase 2 and the opening time of the green light for the left turn phase of the roadway, and that there is a time difference \( \Delta t_2 \) between the ending time of the green light for phase 2 and the ending time of the green light for the left turn phase of the roadway. The signal timing of the shifted left turn lane intersection is shown in Figure 2.
3.3. Intersection delay model

Intersection delay formula adopts Webster average delay formula as follows:

\[ D_i = \frac{C(1-\lambda_i)^2}{2(1-y_i)} + \frac{x_i^2}{2q_i(1-x_i)} - 0.65\left(\frac{C}{q_i}\right)x_i^{(i-1)} \]  \hspace{1cm} (3)

Where: \( D_i \) represents the intersection phase \( i \) volume delay time, 1, 2, 3, 4, where 1 represents the north-south left-turn phase; 2 represents the north-south straight ahead phase; 3 represents the east-west straight ahead phase; 4 represents the east-west left-turn phase; \( \lambda_i \) is the green signal ratio of phase 1; \( y_i \) represents the flow ratio of the phase; \( x_i \) represents the saturation of the first phase; \( q_i \) represents the rate of vehicle arrival in phase 1; \( C \) represents the duration of the signal period.

For an intersection inlet lane with a shift left turn, the vehicle delay is made up of two components: delay for straight ahead traffic and delay for shift left turn traffic. The east-west inlet is set here, and the shift left turn is set. Because the straight-going vehicles are not affected by the shift left turn lane, the delay formula can be obtained by Webster's average delay formula:

\[ D_3 = \frac{C(1-\lambda_3)^2}{2(1-y_3)} + \frac{x_3^2}{2q_3(1-x_3)} - 0.65\left(\frac{C}{q_3}\right)x_3^{(i-1)} \]  \hspace{1cm} (4)

Where: \( D_3 \) represents the average east-west direct phase vehicle delay.

\[ D_4 = \frac{C(1-\lambda_4)^2}{2(1-y_4)} + \frac{x_4^2}{2q_4(1-x_4)} - 0.65\left(\frac{C}{q_4}\right)x_4^{(i-1)} \]  \hspace{1cm} (5)

Where: \( D_4 \) represents the delay caused by the east-west shift of vehicles turning left.

According to the calculation, there is a time difference between the time when the shifted left turn phase starts to pass and the time when the straight east-west phase starts to pass, with a difference of \( \Delta t_1 \), and left-turning vehicles still need to wait when they arrive at the intersection, so the delay generated here is \( \Delta t_1 \); In addition to this, the time taken for the left-turning vehicle to travel normally from the first stop line to the second stop line needs to be subtracted; because of the left-turn lane, left-turning vehicles have an additional stop compared to left-turning vehicles at regular intersections, and the increased delay equivalent is set as \( k \). The average delay formula for shifting left-turn vehicles is as follows:

\[ D_4 = D_3 + g_{\text{avg}} + I - \Delta t_1 - \left(l_i + l_j\right)v_s + k \]  \hspace{1cm} (6)

Where: \( D_4 \) represents the average delay of vehicles turning left in the east-west direction; \( g_{\text{avg}} \) represents the length of green light in the north-south phase; \( I \) represents the value of interval time between green lights; \( k \) represents the non-uniformity coefficient of the arrival of left-turn vehicles within a period, which is generally 1.5~2.

From the above, the total delay time for total vehicles in the east-west direction is:

\[ D_T = \frac{C}{3600}(D_3Q_3 + D_4Q_4) \]  \hspace{1cm} (7)

Where: \( D_T \) represents the total delay time of vehicles in the east-west direction; \( Q_3 \) represents the value taken from the straight east-west traffic flow; \( Q_4 \) represents the value of the traffic flow in the east-west direction.
3.4. Capacity model
In this paper, the traffic capacity is calculated according to the principle of stop line method. According to traffic rules, vehicles are only allowed to cross the stop line during the valid green light time. The formula is as follows:

\[ B_i = S_i \left( \frac{g_i}{C_g} \right) \tag{8} \]

Where: \( B_i \) represents the capacity of vehicles in phase \( i \); \( S_i \) represents the saturation flow of the lane in phase \( i \); \( g_i \) represents the effective greening time for phase \( i \).

3.5. Exhaust emission model
When the vehicle is near the intersection, its motion state is in the state of frequent acceleration, deceleration and idling. This driving behavior is also an important source of exhaust gas. Vehicle exhaust emission formula is as below:

\[ E = \sum_{i=1}^{3} \left( E_1 + E_2 + E_3 \right) \tag{9} \]

Where: \( e \) represents the idle speed factor. For convenience of calculation, value is 5 here.

3.6. Model constraint

3.6.1. General constraint

\[ \begin{align*}
C_g &= g_1 + g_2 + g_3 \\
&\ s.t. \quad g_{1_{\min}} \leq g_1 \leq g_{1_{\max}} \\
&\ s.t. \quad g_{2_{\min}} \leq g_2 \leq g_{2_{\max}} \\
&\ s.t. \quad g_{3_{\min}} \leq g_3 \leq g_{3_{\max}}
\end{align*} \tag{10} \]

Where: \( g_1 \) represents the green light duration for the north-south left turn phase; \( g_2 \) represents the green light duration in north-south straight phase; \( g_3 \) represents the green light duration of east-west straight and left-turn phases; \( g_{1_{\min}} \), \( g_{2_{\min}} \) and \( g_{3_{\min}} \) are respectively the shortest green time in each phase; \( g_{1_{\max}} \), \( g_{2_{\max}} \) and \( g_{3_{\max}} \) are respectively the longest green time in each phase; \( t \) is the duration of signal cycle loss.

3.6.2. Length of vehicle lane change
The vehicle needs to cross the lane change section from the first stop line to the shifted left turn lane. The length of the section passed during the lane change is related to the turning radius of the vehicle and therefore the length of the lane change should meet the following requirements:

\[ l_1 \geq 2\sqrt{r^2 - (r - s)^2}, \quad s = \frac{W_1 + W_c}{2} \tag{11} \]

Where: \( r \) represents the minimum turning radius; \( s \) represents the intermediate variable in geometric calculation; \( W_1 \) represents the width of one lane; \( W_c \) represents double yellow line width.

3.6.3. Shift the length of the left turn lane
Relocation of left-turn lane \( l_2 \) in relation to hourly traffic volumes of left-turning vehicles and lane saturation flow rates, and should meet the following requirements:

\[ l_2 \geq \frac{3600Q_{h1}}{mnS_{cl}} \tag{12} \]
Where: \( m \) represents the number of left-turn lanes on the road; \( n \) represents the number of signal cycles in an hour; \( S_{el} \) represents the value of saturation flow rate in the left-turn lane; \( h_i \) represents the space headway.

### 3.6.4. Shift storage lane

The vehicles of the storage lane should drive into the shifted left-turn lane as much as possible within A cycle to prevent the waste of capacity. Since the shift storage lane is set in the first lane, it can be used as an overtaking lane at conventional intersections, and the set disrespect will affect the driving of vehicles on the road and increase safety risks, so it should meet the following requirements:

\[
l_i \geq \frac{Q_i k h_i}{nm}
\]

### 3.6.5. The relationship between main signal and pre-signal

Before the left-turning vehicles change lanes, it should be ensured that the shifted left-turn lane is cleared, so as to reduce the parking rate of vehicles leaving the junctions. Meanwhile, the duration of the north-south straight line should not be less than the duration of the vehicles entering the shifted left-turn lane, and the phase duration of the east-west straight line and left-turn should not be less than the maximum value of the clearing duration of the straight line and left-turn vehicles, so as to ensure the efficiency of the traffic. The end of the north-south straight ahead phase can be earlier than the end of the left turn phase. Therefore, be satisfied with:

\[
\begin{align*}
g_4 - g_1 & \geq \frac{l_i + l_j}{v_{sl}} \\
g_2 & \geq \frac{3600 Q'_e}{mn S_{el}} \\
g_3 & \geq \max \left\{ \frac{3600 Q'_s}{mn S_{el}}, \frac{3600 Q'_e}{mn S_{es}} \right\} \\
g_4 - g_1 & \geq \frac{l_i + l_j}{v_{en}}
\end{align*}
\]

Where: \( l_j \) represents the length of the section through the intersection for vehicles turning left north-south; \( v_{sl} \) represents the average speed taken for vehicles turning left north-south; \( Q'_e \) represents the volume of traffic in the shifted left turn lane; \( S'_{el} \) represents the saturation flow rate of the shifted left turn lane; \( S_{es} \) represents the saturation flow rate of the straight ahead lane; \( l_i \) represents the length of the section through which east-west straight ahead traffic crosses the intersection; \( v_{en} \) represents the average speed of east-west straight ahead traffic taken.

### 4. Case Analysis

#### 4.1. The traffic situation

The intersection of Huamu Road and Jinxiu Road in Shanghai was chosen as the experimental site of the multi-objective optimization model. The intersection is a crossover, with the east and west inlet lanes being 4 lanes; the south and north inlet lanes being 5 lanes, with 3 east and west straight lanes and 1 left turn lane; and 3 south and north straight lanes and 2 left turn lanes. The control phase of the intersection is 4 phase. The relevant intersection data dynamics are shown in Table 1:
Table 1. Intersection traffic flow

|                | East import/pcu | West import/pcu | South import/pcu | North import/pcu |
|----------------|-----------------|-----------------|------------------|------------------|
| Peak traffic   | 1221/156        | 1101/243        | 1307/227         | 1652/249         |
| Low peak flow  | 610/69          | 551/88          | 676/138          | 1152/176         |

Note: Taking the east import as an example, the numbers 1221/156 represent the flow of traffic going straight ahead and turning left at the east import respectively.

Table 2. Signal Phase At Intersection

| Phase sequence | Phase                        | Green time/s | Yellow light time/s | Cycle |
|----------------|------------------------------|--------------|---------------------|-------|
| One            | North and south straight (Nss)| 21           | 3                   |       |
| Two            | North and south left (Nsl)   | 69           | 3                   | 172   |
| Three          | East and west straight (Ews) | 46           | 3                   |       |
| Four           | East and west left (Ewl)     | 24           | 3                   |       |

4.2. Results analysis

Comparison results of conventional channelized intersections and intersections with shifted left-turn lanes are shown in Figure 3.

Table 3. Signal timing optimization scheme

| Phase sequence | Phase                        | Green time/s | Yellow light time/s | Cycle |
|----------------|------------------------------|--------------|---------------------|-------|
| One            | North and south left         | 15           | 3                   |       |
| Two            | All red                      | 2            |                     |       |
| Three          | North and south straight     | 49           | 3                   |       |
| Four           | All red                      | 2            |                     |       |
| Five           | Go straight east-west and turn left | 39    | 3                   | 113   |
| Six            | All red                      | 2            |                     |       |
A comparison of the results shows that vehicle delays, capacity and exhaust emissions for left-turning vehicles in the east-west direction are increased after the specified shift of left-turn lane in that direction, while the straight and left turn of other inlet lanes are all decreased, which promotes the overall optimization of the intersection. In this experiment, the total vehicle delay decreased by 24.58%, the total capacity increased by 17.09% and the total exhaust emission decreased by 34.68% at the intersection with high traffic flow. According to the traffic capacity model used in this paper, the signal timing scheme remains the same as the traffic capacity remains the same, and the total tail gas emissions are reduced by 41.68%. The results show that this experiment has a good improvement effect on vehicle delay and tail gas emissions, while the traffic capacity improvement effect is relatively not obvious. And the improvement effect is better in the period of low peak traffic flow.

5. Conclusion
In this paper, an optimization model of signal timing for shifted left-turn lanes is conjured up with the objectives of minimizing delay, emissions and capacity. A case study has been conducted to confirm that the installation of shifted left-turn lanes can significantly improve vehicle delays and exhaust emissions, while the improvement in capacity is less significant. However, this paper does not take pedestrian, non-motor vehicle and other factors into comprehensive consideration, and also does not take into account the situation that all the four inlet roads are set to shift left, so it is not perfect. In the following research, the shift left turn lane can be set in all the four entrance lanes as the research background, and the travel characteristics and benefits of pedestrians and non-motor vehicles can be taken into comprehensive consideration, so as to better fit the situation of intersections in real life.

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