Optimization Design and Simulation Evaluation of Signalized Intersection

Zhuanzhuan Shi
Chang'an University
Institute of South Second Ring Road, Xi’an, China
503053556@qq.com

Hong Chen
Chang'an University
Institute of South Second Ring Road, Xi’an, China
534813862@qq.com

ABSTRACT

This paper put forward the optimization design of intersection from three aspects: channelization optimization design, optimal design of signal timing, and simulation evaluation. Through traffic data investigation and data analysis with theoretical method and VISSIM simulation method, two channelization plans were presented, and corresponding signal timing plans were provided by using Webster method and SYNCHRO respectively. Then, the traffic simulation models for optimized plans were established to evaluate the optimization efficiency and to determine the optimum design. By comparing the simulation results of the old and improved plans, the conclusion that the new plan can improve the level of service at the intersection can be concluded.

KEYWORDS: Signalized Intersection Optimization; Channelization Design; Signal Timing Optimization; SYNCHRO; VISSIM; Traffic Simulation.

1 INTRODUCTION

With the development of society, the process of urbanization is advancing, and the urban traffic volume grows rapidly. Due to limited traffic resources, congestion is common. There are a lot of problems: increasing delay and travel time, traffic crash, environment pollution and so on. Relieving congestion is necessary. An urban road network mainly consists of road segments, intersections, and interchanges. The traffic characteristic at the intersection is complex, and traffic disorder and accidents easily happen at the intersection. It has become the bottleneck of the urban road network. Intersection congestion is caused by unbalance of supply and demand. To solve this problem, one is reducing traffic demand and the other is increasing traffic supply. Increasing traffic supply that is improving capacity is can be realized by the optimization design of intersection. A bad intersection design could worsen the traffic congestion and even causes traffic accidents. Therefore, intersection optimization design is vitally important for an urban road network.

2 METHODOLOGY

For intersection capacity calculation, the method in urban road design criteria (1991) adopts a large number of existing road traffic flow ratio and vehicle composition and other measured data, so if the intersection tends to saturation, the calculated results are closest to the measured value. As the traffic load on urban roads is increasing, especially in crowded areas of medium and large cities, most intersections have become saturated, and this capacity calculation method is mostly used (Yuan et al., 2006). The research object of this paper is the intersection tending to saturation, based on this, this paper uses the method in urban road design criteria (1991) to calculate the intersection capacity.
The average parking delay calculation method proposed in HCM (2000) takes into account factors such as signal cycle, split ratio, actual traffic volume and capacity, and divides the delay into uniform delay and additional delay, which can better adapt to the actual traffic condition and play a key role in the evaluation of the intersection service level (Akcelik, 1980). Therefore, this paper uses this method as the basis for determining the traffic capacity evaluation index, so as to obtain reasonable level of service and better analyse and evaluate the intersection capacity.

Channelization optimization design mainly referred to manual of urban traffic design (Yang, 2003) and related researches (Bared et al., 2002; Bai, 2006). For signal timing, the classical signal timing method Webster method (Webster, 1954) is adopted. However, due to the limitation of the traditional method, a signal timing method based on the Synchro is provided, and VISSIM simulation models are developed to evaluate which method is better. Synchro is the software for modelling, optimizing, managing and simulating traffic systems. The Synchro system is dedicated to the signal timing and takes the comprehensive optimization index composed of three performance indicators delay, the number of stops and queue length as the objective function. The micro-traffic simulation package VISSIM is now the most commonly used in our country, developed by the German PTV company. It is a microscopic traffic simulation modelling tool based on the time step and vehicle driving behaviour. It can be used to simulate and analyse the operating conditions of urban road traffic and public transport under various road conditions (Yang and Wang, 2004). Therefore, the analysis of the present situation of intersection and evaluation of improved intersection would be done based on VISSIM.

3 TRAFFIC ANALYSIS AND SIMULATION

3.1 Traffic data survey

The selected intersection is a cross junction which is in Xi’an. There are three approach lanes in south, north and west direction, and only two approach lanes in east direction. The through traffic flows from east and west approaches crossing the intersection by the underground two-way four lanes are not considered for that they are not controlled by traffic light. Peak hour traffic volume had been collected, and the detailed intersection layout and the fixed signal timing plan are as shown in follows.

![Figure 1: Layout and signal timing plan of the intersection](image)
3.2 Traffic data analysis

3.2.1 Peak hour traffic flow direction analysis

From the above figure, it can be found that the through traffic flow from south and north direction is relative heavy, and the left-turn traffic flow is also large in east and west direction.

3.2.2 Capacity calculation and delay analysis

The current intersection capacity is determined by the method in *urban road design criteria* (1991). From these data, we can see that the south approach is oversaturated, and its saturation ratio is large. The reason for this is that the left-turn traffic flow from north approach blocked the straight flow from south approach, so the south approach capacity should get reduction. The v/c ratio larger than 1 means that the signal timing and geometrical design provide the inadequate capacity to the given traffic flows. Improvements should be considered in changing the geometry and signal timing plan.

![Figure 2: Diagram of peak hour traffic volume](image)

<table>
<thead>
<tr>
<th>Items</th>
<th>East approach</th>
<th>West approach</th>
<th>South approach</th>
<th>North approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>Volume (pcu/h)</td>
<td>556</td>
<td>522</td>
<td>397</td>
<td>701</td>
</tr>
<tr>
<td>Capacity (pcu/h)</td>
<td>489</td>
<td>451</td>
<td>489</td>
<td>869</td>
</tr>
<tr>
<td>v/c</td>
<td>1.14</td>
<td>1.16</td>
<td>0.81</td>
<td>0.81</td>
</tr>
<tr>
<td>Approach volume</td>
<td>1078</td>
<td>1099</td>
<td>1749</td>
<td></td>
</tr>
<tr>
<td>Approach capacity (pcu/h)</td>
<td>940</td>
<td>1358</td>
<td>1022</td>
<td></td>
</tr>
<tr>
<td>v/c</td>
<td>1.15</td>
<td>0.81</td>
<td>1.71</td>
<td></td>
</tr>
</tbody>
</table>

There are usually three kinds of delay estimation methods: survey method in site, analysis method (delay calculation in HCM2000) and simulation method. From the delay calculation results, we can find out that when the degree of saturation is larger than 1, the delay value is relatively high. The delay calculation by this method is suitable for the intersection with degree of saturation smaller than 1, and many studies have shown that the error of the calculation result is large when the
saturation ratio is larger than 1. Thus, the analysis method can’t be used to determine the delay of this intersection.

Table 2 Delay calculation result by analysis method

<table>
<thead>
<tr>
<th>Items</th>
<th>East approach</th>
<th>West approach</th>
<th>South approach</th>
<th>North approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>Lane group v/c</td>
<td>1.14</td>
<td>1.16</td>
<td>0.81</td>
<td>0.81</td>
</tr>
<tr>
<td>Delay(s)</td>
<td>138.68</td>
<td>148.36</td>
<td>57.52</td>
<td>52.04</td>
</tr>
<tr>
<td>Approach v/c</td>
<td>1.15</td>
<td>0.81</td>
<td>1.71</td>
<td>0.93</td>
</tr>
</tbody>
</table>

3.3 Simulation evaluation

Since analysis method for delay determination can’t be applied, therefore, the simulation model of current status of the intersection is developed as the following figure shows.

![Simulation model of current intersection](image)

Figure 3: Simulation model of current intersection

3.3.1 Model verification by checking traffic volume

Here, the average error rate is defined to determine the degree of compliance between the simulation situation and the actual traffic situation. Set a critical value 5%, as long as the average error rate is less than the critical value, it can be considered that the simulation status is consistent with the actual situation.

After adjustment, use the peak hour traffic volume to simulate the current intersection, and the comparison between the simulation status and the actual situation is shown in the table. Simulation period is one hour. From the table, it can be seen that the average error rate of cycle release is 4.12% which is less than the critical value 5%. Therefore, we can say that the simulation model can describe the actual traffic conditions of this intersection well, and it can be optimized further.

Table 3 Traffic volume comparison of simulation status and actual situation
3.3.2 Level of service determination

The level of service is the main indicator to evaluate the intersection efficiency, and level of service is determined according to the intersection delay. The delay can be estimated by the traffic simulation. The established simulation model has been proved reliable. The simulation data produced in the warm up stage of simulation model is been excluded by recording the data starting from the 900s. Due to the randomness of the simulation results, it needs to simulate the simulation model a certain time to eliminate the effect of the randomness. The current intersection is simulated 10 times here, and the average value is taken as the final simulation result.

Table 4 Delay at Southeast Corner Intersection

<table>
<thead>
<tr>
<th>Methods</th>
<th>Item</th>
<th>East approach</th>
<th>West approach</th>
<th>South approach</th>
<th>North approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>v/c</td>
<td>1.15</td>
<td>0.81</td>
<td>1.71</td>
<td>0.93</td>
</tr>
<tr>
<td>HCM2000</td>
<td>Delay/s</td>
<td>143.37</td>
<td>54.02</td>
<td>83.62</td>
<td>28.46</td>
</tr>
<tr>
<td>VISSIM</td>
<td>Delay/s</td>
<td>86.16</td>
<td>47.61</td>
<td>35.3</td>
<td>27.93</td>
</tr>
</tbody>
</table>

Notes: Delay/15min

By comparing the delay calculation results by analysis method and simulation method separately, it can be found that the two sets of results are closer for the lane group with v/c value less than 1, and for the lane group with v/c value larger than 1, the delay values calculated by analysis method are far greater than by the simulation method. It is also proved the simulation model is accurate.

Control delay per vehicle at the intersection is 46.64s per vehicle, so it can be determined that the level of service of current intersection is D. The level of service of this intersection indicates that the traffic flow is unsteady, large delay within toleration. The main reasons for the low level of service: indefinite division of lane functions, unreasonable phase sequence and green time assignment.

3.3.3 Simulation results and evaluation

Table 5 Simulation result of current status

<table>
<thead>
<tr>
<th>Evaluation</th>
<th>East approach</th>
<th>West approach</th>
<th>South approach</th>
<th>North approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>index</td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>Delay(s/veh)</td>
<td>89.65</td>
<td>82.45</td>
<td>42.74</td>
<td>50.37</td>
</tr>
<tr>
<td>Queue length(m)</td>
<td>26</td>
<td>70.5</td>
<td>57.5</td>
<td>22.9</td>
</tr>
<tr>
<td>Stops</td>
<td>66.6</td>
<td>137.5</td>
<td>119.2</td>
<td>69.6</td>
</tr>
</tbody>
</table>
From the above simulation results, we can find that the delays in east and west approach lanes are relatively high; the main reason for this is that assigned green time is inadequate to release the arriving vehicles. From the queue length data, it is obvious that the queue length of through traffic flow in south and north approach is great except for the left turn traffic flows in east and west direction. Large through traffic volume in south and north approach results in the oversaturated straight lanes. For further, due to unreasonable phase sequence which leads to serious conflict between through traffic flow and left turn flow, the capacity of through lanes is reduced. At the same time, mixed traffic phenomenon is serious at this intersection, which also can reduce the capacity of the intersection.

- **Existing problems**
  - The road marking of west approach is not clear, and there is a mistake, which can’t play the role of indicating lane function.
  - The capacity of north and south straight approach lanes is insufficient, resulting in longer queuing.
  - The capacity of north exit lanes is insufficient, which the multiple flows crowd into the north exit lanes, causing congestion.
  - Unreasonable signal phase setting, uneven distribution of green time, traffic conflicts are serious, large vehicle delays in east and west approach.
  - Mixed traffic phenomenon is serious.

### 4 INTERSECTION CHANNELIZATION DESIGN

According to the intersection problems have been analysed, two channelization design plans are provided.

#### 4.1 Channelization Plan A

![Figure 4: Channelization plan A](image)

Figure 4: Channelization plan A
Widen the north and south approach lanes and set exclusive left-turn lane in south approach. The width of south approach lanes is 3.25m and north approach is 3m after improvement, which satisfies the requirements of specification. The length of widen section and gradual widen section is 30m.

Widen the north exit lanes by compressing the separation strip, and the length of widen section and gradual widen section is 30m.

Set straight and left turn waiting area in front of the north and south approach lanes.

For non-motorized traffic, the idea of slow traffic integration design is used. The left turn non-motor vehicles cross the intersection with two steps. The width of non-motor vehicle lane and crosswalk is 3m respectively. Move up the stop lines of east and west approach. In order to avoid the interference on pedestrians from the U-turn vehicles in east and west approach, the removable separation bar is used.

Improve the relevant markings and signs.

### 4.2 Channelization Plan B

Due to the large straight traffic volume and relatively low left turn volume in north and south direction, if an exclusive left turn phase is set, the cycle length will be extended, which will cause larger delay for left turn vehicles although the delay of other flows is reduced. Hence, in order to optimize the design further, the measure of prohibiting left turn traffic flow is used. The left turn traffic flows from north-south approach turn right first, then turn around and go straight to cross the intersection. It is noticed that the straight flows in east and west direction go through the intersection underground without signal control. This kind of traffic organization method makes effective use of the layout resources near the intersection, not only can effectively alleviate the intersection conflict, but also greatly reduces the delay of the intersection and improve the intersection efficiency.

![Figure 5: Channelization plan B](image)

**Figure 5: Channelization plan B**

### 5 SIGNAL TIMING OPTIMIZATION DESIGN

Signal timing plans corresponding to each channelization plan were developed based on Webster method and SYNCHRO. Signal timing optimization model was established based on SYNCHRO is as follows.
5.1 Signal Timing Plan for Channelization Plan A

Here, the average control delay and the queue length are chosen as the evaluation indicators. To make a quantitative contrast of evaluation indicators, the concept of evaluation index promotion rate is introduced, and it can be calculated by the following formula.

\[
p = \frac{1 - \frac{H}{I}}{H} \times 100\%
\]

- \( p \) — promotion rate of evaluation index;
- \( I \) — the value of original evaluation index (unit: m or s);
- \( H \) — the value of improved evaluation index (unit: m or s).

With consideration of the randomness of traffic flow, it is assumed that there is no obvious difference between two design plans when \(-5\% \leq p \leq 5\%\); when \( p > 5\% \), it indicates that the operation efficiency of improved plan is greater than the original plan, and the greater the value, the greater the efficiency of the improved plan.

Table 6 Comparison of simulation result for plan A

<table>
<thead>
<tr>
<th>Items</th>
<th>Methods</th>
<th>East</th>
<th>West</th>
<th>South</th>
<th>North</th>
<th>Intersection</th>
</tr>
</thead>
</table>
By comparing the simulation results, we can see that the improved design plan is efficient. For intersection delay, the promotion rate by Webster timing method is 43%, and by Synchro is 15%; for intersection queue length, the promotion rate by Webster method is 36.95%, and by Synchro is 36.53%, therefore, it can be concluded that the signal timing plan determined by Webster method is superior for channelization plan A.

5.2 Signal Timing Plan for Channelization Plan B

For channelization plan, the left turn traffic flow in south and north approach through the intersection by detouring, that is turn right first, then go straight through the intersection. So, there are two phases for the intersection. The phase sequence is shown below.
<table>
<thead>
<tr>
<th>Average queue length (m)</th>
<th>Promotion rate</th>
<th>95%</th>
<th>90%</th>
<th>55%</th>
<th>23%</th>
<th>73%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original plan</td>
<td>48.25</td>
<td>40.2</td>
<td>30.25</td>
<td>15.17</td>
<td>33.47</td>
<td></td>
</tr>
<tr>
<td>Webster</td>
<td>16.45</td>
<td>8.9</td>
<td>5.4</td>
<td>2.95</td>
<td>8.425</td>
<td></td>
</tr>
<tr>
<td>Promotion rate</td>
<td>65.91%</td>
<td>77.86%</td>
<td>82.15%</td>
<td>80.55%</td>
<td>74.83%</td>
<td></td>
</tr>
<tr>
<td>Synchro</td>
<td>3.05</td>
<td>0.85</td>
<td>9.75</td>
<td>9.55</td>
<td>5.80</td>
<td></td>
</tr>
<tr>
<td>Promotion rate</td>
<td>93.68%</td>
<td>97.89%</td>
<td>67.77%</td>
<td>37.05%</td>
<td>82.67%</td>
<td></td>
</tr>
</tbody>
</table>

For channelization plan B, the delay and queue length of each approach lanes are significantly reduced. For delay, the promotion rate determined by Webster method is up to 77% and by Synchro is up to 74.83%. It shows that the optimization effect of channelization plan B is remarkable.

For average queue length determined by Synchro, its promotion rate is up to 82.67%, and by Webster method is up to 74.83%. This indicates that the average queue length of improved channelization plan B is shortened obviously. By comprehensive comparison of these two schemes, the channelization plan B which the signal timing plan is determined by Synchro is superior.

### 5.3 Final plan determination

Through the above analysis, for channelization plan A, the signal timing scheme determined by the Webster method is more effective. For plan B, the signal timing plan determined by Synchro is better. Next, the optimal solution is determined by further analysis.

![Figure 9: Comparison of delay (s/veh)](image1)

![Figure 10: Comparison of queue length (m)](image2)

According to the Fig. 6-31, we can see that the delay value determined by plan B is minimal. For queue length, plan B is also the optimal. At the same time, the total delays at the intersection of scenario A is 26.37 (s/veh); according to the table of LOS criteria, it can be determined that the level of service of the intersection is class C. The total delay of scenario B is 12.53 (s/veh), so the level of service of the intersection is class B.

Comprehensive analysis of the above, although the two optimization schemes have a significant improvement in the intersection, the plan B is more superior. Thus, plan B is recommended for traffic peak period of this intersection.

### 6 CONCLUSIONS AND DISCUSSIONS

The following flowchart summarizes the overall design ideas and process.
As the flowchart described, before the design, it’s necessary to collect the related data. By processing and analyzing the data, we can find the existing problems at the intersection from the results. Here, another important way to evaluate the intersection status is to use simulation method. However, due to the randomness of the simulation model, it’s important to check and verify the model repeatedly to make sure that the simulation model can describe the actual situation well. Like this, the simulation result can be valuable. Here, we used the traffic volume and intersection delay to verify the model quantitatively; at the same time, the simulation model can present the traffic phenomenon of actual situation, and this proves that the simulation model is reliable qualitatively. Hence, it’s reliable to use the simulation results to evaluate and analyze the intersection. To solve the found problems, two channelization plans are put forward, and two kinds of signal timing plans are provided with each plan. Then, simulate each plan based on VISSIM. By comparing the simulation results to determine the optimum plan B.

After improvement, the promotion rate of delay is 73%, and the promotion rate of average queue length is 82.67%. The level of service of the intersection is changed from D to B. From these, we can see that the effect of the improved plan is obvious. The simulation result also presents a good traffic operation condition of the improved design. This paper also indicates that it is effective to introduce Synchro timing results into VISSIM for simulation evaluation, and traffic simulation is an effective measure for analyzing the complex traffic operation at intersection when theoretical method unable to make it.

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