

An optimization model of signal timing plan and traffic emission at intersection based on Synchro

Yajun Shen¹

¹Nanjing Tech University Pujiang Institute, Nanjing , 211200, China

Abstract. With the rapid development of urbanization in China, the pressure of urban traffic keeps increasing. The problem of traffic pollution is increasingly serious as the automobile exhaust has been one of the main sources of urban air pollution. The major causes of traffic emission are the traffic jam and delay in the urban road intersections. Many advanced traffic signal control methods have been widely applied in the traffic management to reduce traffic jam. This paper proposes an optimization model of signal timing plan that comprehensively considers operating efficiency and traffic emission, which is based on signal timing plan for building a model of network topology and simulation for optimizing the signal timing. Meanwhile, this plan is to improve the efficiency of intersections, reduce queuing time and harmful emission. Taking some intersections in Harbin as an example, the measured pollutant emissions data at the intersections before and after signal optimization were collected and compared, then the levels of vehicle exhaust pollution and emissions of various emissions under different control strategies were analyzed, thus the emissions under different traffic management and control were evaluated. All these data has a great importance both in theoretical and practical value.

1. Introduction

With the continuous improvement of urbanization, vehicles play a more and more important role in the urban transportation system. Consequently, the urban traffic pressure keeps increasing, the vehicle exhaust emission problem is increasingly serious, traffic congestion and traffic emission problems need to be solved.

The low efficiency of road intersections is one of the main reasons of urban traffic congestion and vehicle exhaust pollution. Vehicles are affected by signal control at intersections. Normally, they need decelerate in the queue or accelerate away from the traffic lights. However, frequent acceleration and deceleration during the queuing process will result in a decrease of speed of the traffic flow, a sharp decline of approach capacity and a significant increase in delay. The operation condition of the vehicle in the road is relatively stable and the fuel utilization rate is relatively high. However, the acceleration and deceleration process easily leads to changes in the operation conditions of the motor vehicle at the intersection. The fuel is not fully burned, and the problem of exhaust emissions is more serious than the road section.

There is a great deal of research [1] has shown that the optimization of signal timing in the intersection is one of the effective methods to reduce traffic congestion and decrease traffic pollution. A rational signal timing plan can remarkably improve the traffic efficiency of signalized intersections, meantime alleviate congestion, and reduce emissions. What's more, combining the reduction of traffic emissions with traffic management control can improve the transportation service level and provide a theoretical basis for the implementation of energy saving and pollutant reduction strategies.



2. Model and methodology

To build the optimization model of traffic emission reduction, firstly, the Synchro was used to build the optimization model for intersection delay which takes account of the properties of traffic emission. Then the traffic emission model and optimization model of intersection operation were combined. Finally, the optimization model which minimized the traffic emission and ensured the operation efficiency at the intersections was constructed.

2.1 Synchro software

Synchro is a complete set of simulation software for signal timing analysis and optimization of urban road network developed by Traffic ware company according to the HCM standard of the US Department of Transportation. It contains a few functions, like analysis and simulation of intersection capacity and coordinating control, which can meet the requirements of signal timing evaluation [2]. In the signal timing process, Synchro can not only use the minimization of the average delay, which is commonly used in traditional independent intersection timing design, but also can achieve the signal chain target of maximization of the green light bandwidth.

2.2 Optimization model of traffic signal timing plan and traffic emission

In this paper, in order to study the issue of intersection emissions and delay consumption, it is necessary to achieve two goals of reducing intersection delay and deducting exhaust emissions. Therefore, in addition to the intersection signal optimization model and model of intersection delay, a calculation model for traffic exhaust emissions needs to be established in combination with the characteristics of exhaust gas emissions.

2.2.1 Optimization model of signal timing plan. The optimization of signal timing at road intersections started from phase optimization, cycle time optimization, and green split optimization.

(1) phase optimization

The basic operation idea of phase optimization was to list all possible phases in the form of a network topology. According to the phase optimization method, conflict points were reduced, redundant phases are deleted, and the phases reserved by the signal light were finally retained. In the optimization process, it was firstly necessary to analyze whether the effective green time provided by each phase can satisfy 90% of the traffic volume of the lane group. If it can't be satisfied, they will analyze whether it can meet the traffic volume of 70% and 50% of the lane groups in turn. If the green time can meet the traffic volume of 90% of the lane group, it means that about 90% of all the stranded vehicles can be cleared during a green light release, and the intersection efficiency can be effectively improved.

(2) cycle time optimization

As the most important parameter in the signal timing technology of the intersection, the signal cycle length has a significant effect on the operating efficiency of the intersection. In order to optimize the signal period, phase optimization and phase time adjustment based on the natural cycle time were required to calculate the acceptable shortest cycle time. If a certain percentage of lane group traffic was met, this set period was used, otherwise the period length would be increased [3]. Through the loop operation, the required period length can be obtained. In this adjustment process, Synchro's performance indicators needed to be calculated. And if all solutions failed to meet a certain percentage, the cycle time corresponding to the lowest performance index P would be selected. The calculation model of performance index P is as follows:

$$P = \frac{D \times 1 + S_t \times 10 + Q_p \times 100}{3600} \quad (1)$$

In the formula, P is the performance index; D is the percentage signal delay; S_t is the number of stops; Q_p is the number of affected vehicles.

After getting the signal cycle time of the intersection, it was also necessary to verify whether the

green time of each signal phase can meet pedestrian safety crossings [4]. The shortest green time calculation method for pedestrian crossings is:

$$t_p = 7 + \frac{L_p}{v_p} - I \quad (2)$$

In the formula, t_p represents the shortest green light duration; L_p is the road width; V_p is the default walking speed of 1.2m/s; I is the default green light interval time of 3s.

(3) green split optimization

The signal period is composed of two parts: the signal loss time and the effective green light green time. And the green split is the ratio of the effective green light duration of a signal phase to the signal cycle duration [5]. It is generally represented by λ . According to the determined cycle length, the green time of each phase was proportionally distributed in each phase lane traffic. The effective green light time was proportional to the flow rate ratio of the traffic lane group of this phase, so the effective green time of the i -th phase for the intersection controlled by multi-phase is:

$$g_{e,i} = (C - L) \times \frac{y_i}{Y} \quad (3)$$

In the formula, g_{ei} represents the green time of the i -th phase; y_i represents the flow ratio of the i -th phase; C is the cycle duration of the calculation of the mainline coordination control; L is the total loss time of a signal cycle; Y is the sum of flow rate ratios of the key cycle corresponding to all signal phases.

2.2.2 Delay model. In addition to the Webster model of delay [6] provided in HCM2000, Synchro software also applies the percentile delay method (PDM). The PDM method is mainly divided into two steps. Firstly, the per-cycle delay and per-vehicle delays are calculated for a certain percentage of traffic in the lane group. Then, the percentage traffic group adjustment traffic and the average percentage delay are calculated. The formula for calculating the delay per period is:

$$V_{D_p} = \frac{v_p \times (C - G)^2}{2 \times (1 - v_p / S)} \quad (4)$$

In the formula, V_{D_p} and v_p respectively represent the vehicle delay and traffic flow per cycle when the percentage is case p ; s is the saturation flow rate; G is the green light duration.

The formula for calculating the average delay of vehicles is:

$$D_p = \frac{C \times [2 - (G / C)]^2}{2 \times (1 - \frac{v_p}{s})} \quad (5)$$

In the formula, D_p represents the delay per vehicle at the time p ; C is the signal period length; G is the green time.

The calculation formula for percentage adjustment of traffic volume is:

$$v_p = v + (z_p \times \sqrt{\frac{v \times C}{3600}}) \times \frac{3600}{C} \quad (6)$$

In the formula, v represents the traffic volume; z_p corresponds to different ratios according to different percentages; -1.28 when 10%, -0.52 when 30%, 0 when 50%, 0.52 when 70%, and 1.28 when 90%.

2.2.3 Traffic emission model. The traffic emission model is used to quantify vehicle exhaust emissions and to predict emissions in the future. Combined with traffic emission factors, intersection traffic, queue length, and signal timing, the traffic emission model is used to quantify vehicle exhaust emissions and to predict emissions in the future. Combined with traffic emission factors, intersection traffic, queue length, and signal timing, the various types of pollutant emissions at the intersection can be calculated. Stathopoulos and Noland used the VISSIM and the CMEM model to analyze vehicle exhaust emissions data for a city's road network. The results of the research show that under the condition that the traffic flow is constant, enhancing the road network capacity and improving signal control can effectively relieve traffic congestion and reduce vehicle traffic emission [7-8]. The calculation formula for certain pollutant emissions of vehicles at intersections is:

$$\sum_i (EF^{PCU} \times q_i \times L_0) + \frac{1}{3600} \sum_i EFI^{PCU} \times q_i \times d_i \quad (7)$$

In the formula, E is the intersection discharge of certain pollutants (g/h);

i represents the signal phase of the intersection;

q_i is traffic flow arriving within phase i (pcu/h);

L_0 is the length of the entrance section of the intersection (km);

D_i is average delay of the vehicle in phase i (s/pcu);

EF^{PCU} is the standard car unit emission factor (g/(pcu*h));

EFI^{PCU} is the Standard Car Unit Idling Emission Factor (g/(pcu*km)).

Through the signal timing optimization model, the queuing delay of the vehicle at the intersection is calculated. And on the basis of the known queuing delay, the emission of the exhaust gas from the intersection is obtained. Based on the three models above, under the condition of ensuring the minimum queuing delay, taking the intersection emission as the objective function, the signal timing plan can be calculated when achieving the minimum emission target.

3. Simulation of signal timing plan

The optimization of signal timing can effectively balance the traffic flow at each entrance of the intersection and comprehensively consider the signal timing of similar intersections. In order to achieve the goal of minimizing tail gas emissions at intersections, this section mainly validates the effectiveness of the traffic optimization model through simulation of signal timing optimization. Firstly, it analyzes the timing of existing intersections and find out the main problems, then it constructs a Synchro simulation topology. After optimizing the signal timing, it analyzes the increase and decrease of the green time of each phase. Thus it compares the improvement of traffic flow at several major entrances in the study area through controlling the two indicators of delays and the stopping number. In order to carry out an empirical analysis, this paper compares the operational efficiency and traffic emission data before and after signal optimization, which takes the intersection of the Songshan Road and the Huaihe Road as a detailed example.

3.1 Current situation of the intersections

By investigating the timing of several signalized intersections in Harbin City, it was found that the traffic flow at each entrance of the intersection is not balanced, and the signal timing needed to be adjusted. In addition, the traffic flow at the intersection during peak hours was near the saturated traffic condition. The graph of traffic flow direction and volume at each intersection is shown in Figure 3-1.

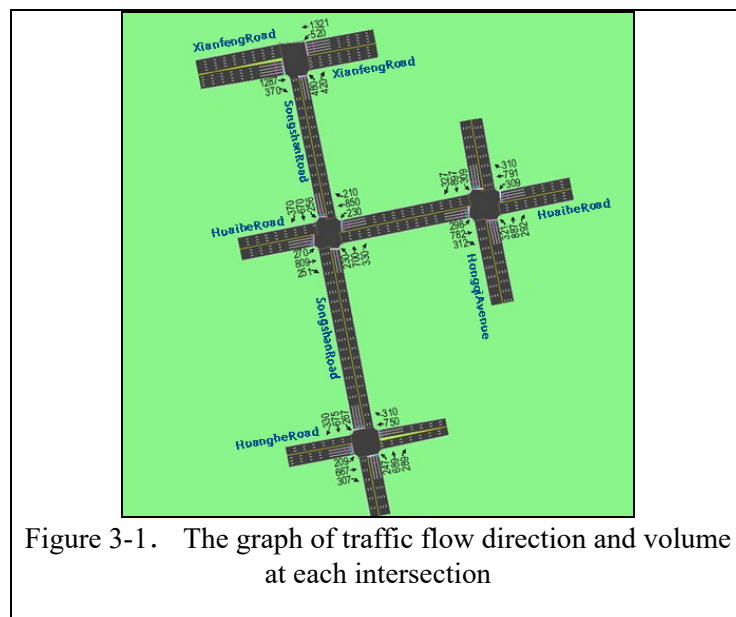


Figure 3-1. The graph of traffic flow direction and volume at each intersection

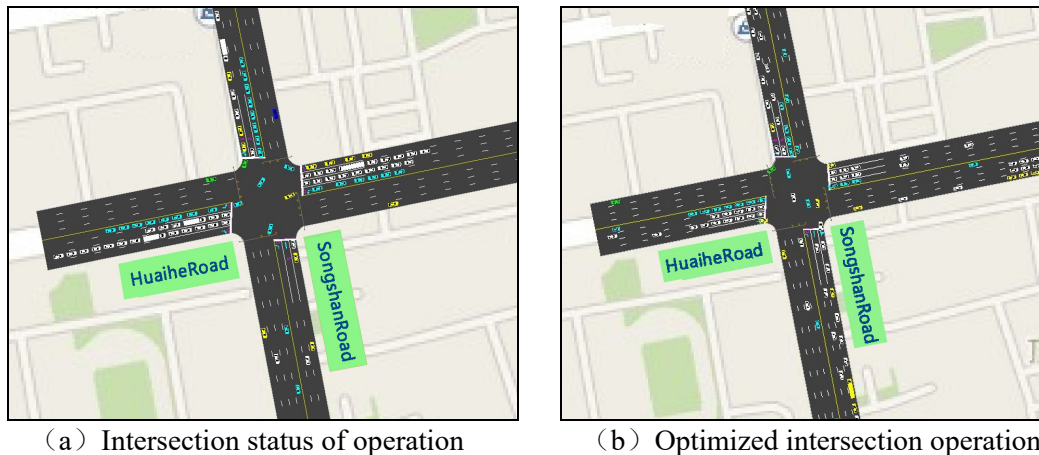
The current signal timing at the intersection (taking the intersection of Songshan Road and Huaihe Road as an example) is shown in Table 3-1.

Table 3-1. The current signal timing at the intersection of Songshan Road and Huaihe Road

Signal timing diagram					
Phase	North-south turn left	Straight southbound and left turn	North-South straight	East-west turn left	East-west Go straight
Phase time	19s (Yellow light time: 5s)	24s (Yellow light time: 4s)	35s (Yellow light time: 4s)	24s (Yellow light time :4s)	40s (Yellow light time: 4s)

3.2 The Optimization of Intersection simulation and timing

In signal timing optimization, this article comprehensively considers the unbalanced conditions of traffic flow at each entrance and the timing of near-saturation at intersections. The current road network, intersection traffic volume and current status signal timing data were imported into Synchro for simulation, and we can obtain the simulation evaluation results: the four intersections appeared low service levels, large traffic volume, and the plan of signal timing needed to improve. According to the signal timing optimization model in chapter 2.2, comprehensively considering the distance and traffic flow of each intersection, it realized the signal timing optimization of the intersection through providing with the optimal signal timing cycle time and the green time of each entrance. The operation of the vehicle before and after signal timing optimization of the intersection of Songshan Road and Huaihe Road is shown in Figure 3-2. It is observed that the optimized intersection operation and the service level have been greatly improved before the optimization.



(a) Intersection status of operation (b) Optimized intersection operation
Figure 3-2. Comparison of the operation before and after the intersection optimization

Using Synchro to optimize the timing of signals at each intersection, results are shown in Table 3-2. The data of total signal cycle time before and after optimization can be collated as shown in Table 3-3.

Table 3-2. List of Optimized Signal Timing at the Intersection of Songshan Road and Huaihe Road

Signal timing diagram					
Phase	North-south turn left	North straight and left turn	North-South straight	East-west turn left	East-west Go straight
Phase time	23s (Yellow light time: 4s)	9s (Yellow light time: 3s)	39s (Yellow light time: 3s)	24s (Yellow light time: 4s)	40s (Yellow light time: 4s)

Table 3-3. Comparison of cycle time after optimization of signal timing at each intersection

Intersection	Signal cycle time (s)	
	Before optimization	After optimization
Songshan Road and Xianfeng Road	105	90
Songshan Road and Huaihe Road	142	135
Songshan Road and Huanghe Road	158	125
Songshan Road and Hongqi Avenue	111	137

3.3 The optimal result

In order to verify the effectiveness of the optimization program, a comparison was made between the timing plans before and after optimization at each intersection in the study area. The conclusions were as followed:

(1)The intersection of Songshan Road and Xianfeng Road is a T-junction. Though the traffic volume is large, the number of lanes is large. After optimization, the signal cycle time is changed to 90 seconds, in which the traffic from the east to the left increases by 7 seconds. And there are many straight-to-drive lanes in the east-west direction, which can meet the traffic volume of the current demand and reduce the travel time after overall analysis.

(2)The intersection between Songshan Road and Huaihe Road is cross-shaped intersection. Considering that there are many relatively vehicles that go straight and turn left in the north, it needs to exclusively open up a phase for vehicles that turn straight and turn left in the north, meantime abandoning the original phase that turns left and straight in the south. Which is a coordinated change based on the actual state of traffic flow. Thus the total signal cycle length has remained basically equal

to the previous, only a 7-second reduction in travel time.

(3) The intersection between Songshan Road and Huanghe Road is cross-shaped intersection. The original signal timing and phase scheme at this intersection were relatively complex and could not meet the existing traffic circulation. According to the analysis of current traffic flow, and combined with the original signal timing scheme, the phase of the signal is reduced from five to four after optimization, with eliminating the previous south-to-left and straight-line phases. Although the signal cycle length is reduced and the phase scheme is changed, the traffic delay at the intersection and the stopping number are both reduced.

(4) The intersection of Huaihe Road and Hongqi Avenue is a cross-shaped intersection. The optimized phase scheme has remained the same at this intersection. However, in light of the analysis of the traffic data of the current survey, the green light duration per phase has been appropriately changed. The total cycle time is increased from 111 seconds to 137 seconds, meanwhile the traffic capacity of the intersection is found to improve.

According to the optimized signal timing scheme, the traffic conditions of the intersection were simulated and compared under the condition of remaining the traffic volume the same. And then the optimization effect of the model was verified. After the simulation for 10 minutes, the comparison of delay and the stopping number before and after optimization is shown in Table 3-4. Through the comparison, it can be found that the delays at the intersections of vehicles were significantly reduced. Furthermore, the stopping number at each intersection is also significantly decreased after optimization.

Table 3-4. Comparison of Delays and parking times of Before and After Optimization

Intersection	Delay / Veh (s)		Parking times	
	Before optimization	After optimization	Before optimization	After optimization
Songshan Road and Xianfeng Road	115.1	85.3	689	621
Songshan Road and Huaihe Road	101.0	79.7	798	600
Songshan Road and Huanghe Road	124.0	113.4	802	766
Songshan Road and Hongqi Avenue	136.2	103.5	985	810

4. The optimization of traffic emission

Through the optimization of signal timing, the operational efficiency of the intersection has been significantly improved. And on this basis, the improvement of traffic emission needs further verification. In order to evaluate the changes in the exhaust emissions of motor vehicles before and after optimization, the type of pollutants to be studied must be selected as the evaluation factor firstly. In addition, microscopic operating parameters such as the instantaneous speed and acceleration of the motor vehicle must be obtained. Finally, the local micro model of traffic emission was used to calculate the pollutant emissions of the vehicle before and after optimization.

4.1 The selection of Motor Vehicle Pollutant Emission Factors and Measurement Type

There are many indicators for measuring the emission of pollutants from motor vehicles. According to the sources of access, they can be divided into the use of models to calculate emission factors and the measurement of emissions from motor vehicles. The vehicle emission factor refers to the amount of pollutants emitted by a vehicle's operating unit mileage or hour or unit fuel consumption. It is the most widely used measurement method currently, which is generally determined by simulation and calculation of vehicle operating modes. There are many factors that affect the emission factor, such as vehicle type, driving conditions, fuel type, and so on. Integrating the main components of motor vehicle exhaust, carbon monoxide, hydrocarbons, and nitrogen oxides are selected as emission factors to calculate for this paper [9]:

4.1.1 Carbon Monoxide. Carbon monoxide is an intermediate product of the combustion of organic oxides, and it's also with the greatest harmful concentration in the exhaust gas of motor vehicles which is produced by the incomplete combustion of motor vehicles. If it is absorbed by the human body, it will causes headaches, nausea and other symptoms, even endangering human life.

4.1.2 Hydrocarbons. Hydrocarbon is an organic compound composed of only two elements, carbon and hydrogen, which will cause harm to humans to a certain extent, including irritating eyes and respiratory tract, causing nausea and anemia.

4.1.3 Nitrogen Oxides. The product of oxygen and nitrogen remaining in the combustion of fuel at high temperature is nitrogen oxides. And the emission of motor vehicles is mainly NO_x. When the concentration reaches a certain value, it will cause harm to the central nervous system of humans and animals.

4.2 The analysis of gas emissions results and impact

In order to evaluate the effectiveness of the optimization plan, the OD survey during the 17:30~18:30 night peak was taken as the basic OD demand. And this paper evaluated the operational efficiency and traffic emissions of the signal timing optimization program during the evening peak period.

4.2.1 The optimization result of each type of vehicle. In order to improve the accuracy of the calculation results, the emission rates of the three types of light-duty vehicle, medium-duty vehicle and bus were simulated and calculated respectively, and the duration of the simulation experiment was set 60 minutes. The optimized signal timing plan reduces the number of acceleration and deceleration of motor vehicles, and it enables vehicles to run under better conditions. In addition, the emission rates of the three pollutants discharged from light-duty vehicles, medium-sduty vehicles, and buses have been significantly reduced, as shown in Table 4-1.

Table 4-1. Comparison of signal timing optimization of transient emission rate in vehicle region

parameter	CO (mg/s)		HC (mg/s)		NO _x (mg/s)	
	Before optimization	After optimization	Before optimization	After optimization	Before optimization	After optimization
Light-duty vehicle	2.224	2.012	0.223	0.205	0.663	0.589
Medium-duty vehicle	3.456	3.124	0.425	0.376	0.267	0.189
Bus	4.853	3.907	1.453	1.325	15.86	14.96

From the above table, it can be seen that the decline in the quality emission rate of the three types of emission pollutants of light-duty vehicles is obvious. Both CO and NO_x have a reduction of about 10%; the emission rates of CO and NO_x in medium-duty vehicles are reduced by 2.1% and 12.7%; and the emission rates of CO and NO_x in buses are reduced by 10.9% and 3.6% respectively. However, for the HC, the emission rate of the three models changes slightly, thereinto, the quality of the buses increases only 0.3%.

4.2.2 Regional emission optimization. Figure 4-1 shows the changes in total hourly emissions before and after signal timing optimization. It can be found that through the comprehensive consideration and reasonable optimization of regional signal timing, the hourly emissions of three kinds of pollutants from motor vehicles have been reduced, and the total hourly emissions have been reduced by 7.93%.

Before optimizing the signal timing, because the traffic time was not properly balanced according to the amount of traffic passing through the intersection, the stopping number of vehicles at the entrance of the intersection was large, and the ratio of acceleration and deceleration of the motor vehicle was high, and the power of the motor vehicle was in a much higher interval. Through

optimization of signal timing, the number of times of acceleration and deceleration is effectively reduced, and the operating conditions of motor vehicles are improved, and the total discharge of three types of emissions is decreased. The comparison result shows that the optimized signal timing scheme can effectively improve regional emissions while increasing regional traffic capacity at the same time.

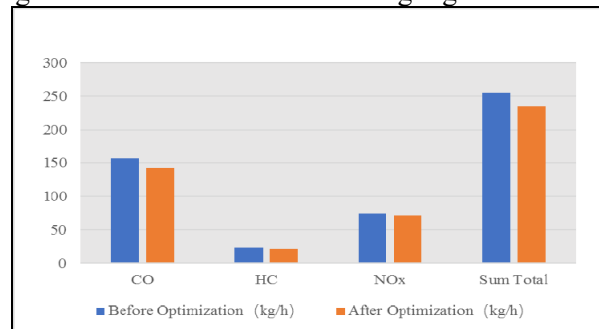


Figure 4-1. Changes in total hourly emissions after regional optimization of signal timing

5. Conclusion

Signalized intersection is the key point of urban road traffic and the important node in the traffic management and control. The intersection signal timing plan which based on traffic delays and traffic capacity is not systematic if the traffic emissions are not considered. Therefore, it is of great practical significance to reduce the traffic emission while improving the service level of intersections. This paper, considering the operation efficiency and environmental protection demand of intersection signal control, provided the optimization model of intersection signal control which considering the traffic emission. A comprehensive signal optimization model is proposed to improve the vehicle operation status and reduce the emission of vehicle pollutants. It provides a positive improvement for the environment of the residents and pedestrians by optimizing the signal timing without any change of road facilities, and has good ecological and social benefits.

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