

# Signal Timing Optimization Model of Urban Road Intersection Based on Multi-factor

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**Abstract:** As the congestion point of urban road network, it is critical to keep the intersection traffic clear. The model was built targeting on decreasing vehicle delays and vehicle emissions, taking traffic queues, stopping time, road capacity and capacity utilization as verification indicators with two constraint conditions which are cycle time length and green ratio by means of genetic algorithm. And the dynamic vehicle emissions rate was taken into account. According to the data of Ke Ji Road—Feng Huinan Road intersection and Tong Yi Road—Tong De Road intersection, which show that the method is practical, and traffic queues, stopping time, vehicle delays, vehicle emissions decrease 34.03%, 28.79%, 48.73% and 28.04% at most, road capacity and capacity utilization increase 15.67% and 7.74% at most.

## 1 Introduction

As the congestion point of urban traffic network, traffic problems at the intersection are becoming more and more serious, how to maintain the smooth traffic at the intersection is an urgent problem to be solved in urban traffic. At present, signal control is widely used to manage traffic flow in order to reduce streamline interference and improve the operating environment of intersections.

Many domestic and foreign scholars have studied the signal timing method at the intersection, Yuliu and others[1] set up a signal timing optimization model aimed at reducing emissions and average delays, and developed a corresponding algorithm program for the model; From the economic point of view, Wang Yuquan and others[2] have established a cross-intersection signal cycle selection model with the goal of the lowest cost of travel per vehicle; Wang Qiuping[3] established a nonlinear function model for signal timing optimization in urban single-intersection intersections with the shortest average delay time and the average number of parking minimum as the goal and phase effective green light time, saturation and period length as the constraint; Based on the exhaust emissions of motor vehicles, Zhou Shenpei[4] have established a two-layer multi-objective optimization model for signal control of intersections; Zhang Yingying[5] studied the characteristics of exhaust emissions under different signal timing schemes; Unal[6] found that the signal timing scheme will affect the emissions of motor vehicles at the intersection. A reasonable signal timing plan will effectively reduce vehicle exhaust emissions. For the study of signal timing methods, you can also refer to the literature [7-16]. In summary, there have been few studies that have comprehensively considered delays,

emissions, queue lengths, number of stops, capacity, capacity utilization, and other factors from the perspective of comprehensive benefits. We generally use fixed values for the emission rate of motor vehicles and have neglected the relation between exhaust emission rate and idle time. It causes the signal timing plan to be unreasonable. Therefore, this article introduces dynamic vehicle exhaust emission rates and established a signal timing optimization model for urban road intersections based on comprehensive benefits under multi-factor conditions. And this article combined the different types of intersections to verify the model. The research results have a certain significance for improving the signal timing theory and coordinating the urban traffic network.

## 2 The implementation target of signal timing optimization at urban road intersections

(1) Reduce the queue length of the vehicle: The longer the vehicle queues is, the longer it takes for the vehicle to cross the intersection. Therefore, when the signal timing is optimized, the traffic congestion can be reduced by reducing the queue length to improve the service level of the intersection.

(2) Reduce the number of vehicle stops: When the traffic passing through the intersection is more continuous, there is less parking. On the contrary, the parking frequency is relatively high. Considering that the continuous driving environment is easily accepted by the drive, the optimization goal can be characterized as the number of vehicles passing through the intersection is significantly reduced.

(3) Improve the capacity of intersections: Capacity is one of the important indicators that affect the service level of intersections, In general, the greater the capacity is, the greater the number of vehicles passing through the intersection per unit of time are, the smoother the traffic flow is, and the more conducive to reducing urban traffic pressure. In order to avoid the urban road intersection due to the traffic capacity too small to affect the operation of the regional traffic, We should improve traffic capacity when optimizing signal timing.

(4) Improve utilization of traffic capacity at intersections: Intersection capacity needs to be adapted to actual vehicle traffic conditions, otherwise it will cause waste of resources. We introduced the utilization of intersection capacity to assess the use of intersections here. Improving the utilization rate of intersection capacity to improve the use efficiency of intersections.

(5) Reduce the average delay of vehicles: Drivers often judge the use of intersections with average delays. Average delay is inversely proportional to service level, the greater the delay, the lower the level of service at the intersection, the less easily accepted by the drivers. When the delay is reduced, the operating efficiency of the intersection is greatly improved.

(6) Reduce vehicle exhaust emissions: Exhaust, as an important part of atmospheric pollution, can be reduced through traffic management. There are a large number of urban road traffic network intersections, unreasonable signal timing solution increases vehicle emissions at Intersections. we select CO and HC emissions as the optimization target here to minimize exhaust emissions.

After considering the above indicators, this paper uses the reduction of the queue length, the number of stoppages, the improvement of traffic capacity and the utilization of traffic capacity as verification indicators to reduce average delays and reduce emissions as an optimization goal. In order to achieve the rationalization of the signal timing scheme for Urban Road intersection, this paper uses the cycle time length and the green time ratio to contact the verification index and the optimization target.

### 3 Signal timing optimization model for urban road intersections

#### 3.1 Verification indicator

(1) The length of queue

The queuing length of each lane at the beginning of the green light is the sum of the remaining number of vehicles  $Q_1$  in the previous green time and the number of vehicles  $Q_2$  arriving in the red time. [17] which is:  
 When saturation  $x_{ij} > 0.5$ :

$$Q_1 = 0.25cap[(x_{ij} - 1) + \sqrt{(x_{ij} - 1)^2 + \frac{8(x_{ij} - 0.5)}{cap}}] \quad (1)$$

otherwise  $Q_1 = 0$ .

$$Q_2 = T \frac{q_{ij}(1 - \lambda_i)}{3600(1 - \lambda_i x_{ij})} \quad (2)$$

$$Q_m = Q_1 + Q_2 \quad (3)$$

The average queuing length  $Q_j$  of the j-th inlet lane is the average of the average queuing length  $Q_m$  for each lane of the inlet lane, the average queue length  $Q_{ave}$  at the intersection is the average of the average queue length  $Q_j$  for each entrance lane. The goal of signal timing optimization is to reduce the average queue length  $Q_{ave}$ , which is:

$$\begin{aligned} Min Q_{ave} &= Min(\sum_j Q_j / Maxj) \\ &= Min[\sum_j (\sum_m Q_m / Maxm) / Maxj] \end{aligned} \quad (4)$$

In Formula(1)~Formula(4),  $cap$  is the lane capacity,  $pcu \cdot h^{-1}$ ;  $\lambda_i$  is the green time ratio of the i-th phase;  $x_{ij}$  is the saturation of the j-th phase of the i-th phase;  $T$  is the cycle length, s.

(2) Parking times

The number of parking times for the i-th phase can be expressed as[17]:

$$h_i = \sum_i 0.09 \frac{T - g_{ei}}{1 - y_{ij}} \quad (5)$$

The average number of stops at an interperiodic intersection is calculated by the weighted evaluation of the actual traffic volume of each phase, so the objective function to reduce the number of stops is:

$$Min h = Min \frac{\sum_i h_i \cdot q_i}{\sum_i q_i} \quad (6)$$

In Formula(5)~Formula(6),  $y_{ij}$  is the flow ratio of the j-th inlet of the i-th phase;  $g_{ei}$  is the effective green time of the i-th phase, s;  $q_i$  is the sum of the actual arrival-equivalent traffic volume for each i-th phase ingress road,  $pcu \cdot h^{-1}$ .

(3) Traffic capacity

Intersection capacity can be weighted according to each entrance, Therefore, the objective function for improving the capacity of intersections is[18]:

$$Max CAP = Max \sum_{j=1} w^j c^j = Max \sum_{j=1} w^j s^j \frac{g_{ei}}{T} \quad (7)$$

In Formula(7),  $c^j$  is the capacity of the j-th entrance at the intersection,  $pcu \cdot h^{-1}$ ;  $w^j$  is the weight coefficient of the j-th inlet of the intersection;  $s^j$  is the saturated flow rate at the j-th inlet of the intersection,  $pcu \cdot h^{-1}$ .

(4) Capacity utilization ratio

Intersection capacity utilization  $ICU$  indicates steady state of traffic flow, Its mathematical expression is[19]:

$$ICU = \frac{\sum_{i=1} Max(t Min(v/s)_i T) + tL_i}{T} \quad (8)$$

The goal of signal timing optimization is to improve the utilization of traffic capacity at intersections, which is:

$$Max ICU = \frac{\sum_{i=1} Max(t Min(v/s)_i T) + tL_i}{T} \quad (9)$$

In Formula(8)~Formula(9),  $tL_i$  is the green light loss time of the  $i$ -th phase,  $s$ ;  $t_{Min}$  is the shortest green light duration,  $s$ ; The remaining parameters are the same as above.

### 3.2 The optimization goal

#### (1) Average delay

The average delay  $d$  at the intersection consists of the consistency delay  $d_{ui}$  and the random delay  $d_{ri}$ , which is<sup>[3]</sup>:

$$d_{ui} = \sum_i \frac{T(1-\lambda_i)^2}{2(1-y_{ij})} \quad (10)$$

$$d_{ri} = \sum_i \frac{x_{ij}^2}{2q_{ij}(1-x_{ij})} \quad (11)$$

$$d_i = d_{ui} + d_{ri} \quad (12)$$

The average delay in one cycle intersection is calculated by the weighted evaluation of the actual arrival equivalent traffic of each phase, Therefore, its optimization goal is:

$$Mind = Min \frac{\sum_i d_i q_i}{\sum_i q_i} \quad (13)$$

In Formula(10)~Formula(13),  $d$  is the average delay in a period intersection,  $s$ ;  $d_i$  is the average delay time of the  $i$ -th phase,  $s$ ;  $y_{ij}$  is the flow ratio of the  $j$ -th inlet of the  $i$ -th phase;  $x_{ij}$  is the saturation of the  $j$ -th inlet of the  $i$ -th phase; The remaining parameters are the same as above.

#### (2) Exhaust emission

Exhaust emissions from vehicles include  $CO$ 、 $HC$  and  $NO_x$ [20], Considering that  $NO_x$  emission is less during idling, and the idle time of the vehicle at the intersection is longer, Therefore, this article mainly considers  $CO$  and  $HC$  emissions.

Second, this paper introduces dynamic vehicle exhaust emission rates, that is the standard model exhaust emissions per unit of time, and this article comprehensively considers the relation between exhaust emission rate and idle time<sup>[21]</sup>:

$$E_{CO} = \begin{cases} 151.0967/d - 5.965252(0s < d \leq 24s) \\ 0.330443(d > 24s) \end{cases} \quad (14)$$

$$E_{HC} = \begin{cases} 3.487390/d + 0.285907(0s < d \leq 24s) \\ 0.431215(d > 24s) \end{cases} \quad (15)$$

$$E = \alpha E_{co} + (1-\alpha)E_{hc} \quad (0 < \alpha < 1) \quad (16)$$

The total amount of pollutants discharged when vehicles pass through the intersection is:

$$E_{Tot} = x_a \cdot E \cdot d \quad (17)$$

Minimization of pollutant emissions required for signal timing optimization, Therefore, the optimization goal is:

$$Min E_{Tot} = Min x_a \cdot E \cdot d \quad (18)$$

In Formula(14)~Formula(18),  $E_{Tot}$  is the total pollutant emissions,  $mg \cdot h^{-1}$ ;  $x_a$  is the sum of the equivalent amount of traffic actually arrived at each entryway in a cycle,  $pcu \cdot h^{-1}$ ;  $E$ 、 $E_{CO}$ 、 $E_{HC}$  are the integrated emission rate,  $CO$  emission rate, and  $HC$  emission rate of  $CO$  and  $HC$  at the intersection per unit time for the standard model at idle speed,  $mg / pcu \cdot h$ ;  $\alpha$  is the weight factor ( $0 < \alpha < 1$ );  $d$  is idle time,  $s$ . general approximation equals average delay, therefore, the multi-objective model can be converted into a single-objective model for solving.

### 3.3 Constraint condition

The constraints of the model include the signal duration  $T$  and the green ratio  $\lambda_i$  of each phase. Reasonable  $T$  and  $\lambda_i$  are conducive to reducing vehicle congestion and improving the operating environment of the intersection. It also helps to reduce vehicle congestion and improve the operating environment of the intersection. The expression of the constraint is:

$$s \cdot t \begin{cases} 0.05 \leq \lambda_i \leq 0.95 \\ 25 \leq T \leq 180 \end{cases} \quad (19)$$

In summary, an integrated multi-factor signal timing optimization model for urban road intersections can be established. which is:

$$\begin{cases} \text{Verify indicators} \begin{cases} Min Q_{ave} \\ Min h \\ Max CAP \\ Max ICU \end{cases} \\ \text{optimization goal} \begin{cases} Min d \\ Min E_{Tot} \end{cases} \end{cases} \quad (20)$$

$$s \cdot t \begin{cases} 0.05 \leq \lambda_i \leq 0.95 \\ 25 \leq T \leq 180 \end{cases} \quad (21)$$

### 3.4 Model solving

The above model is a complex nonlinear optimization model. This paper uses genetic algorithm to solve the model. Compared with other algorithms, the genetic algorithm has a fast convergence rate, a high calculation accuracy, a wide range of applications, and has a strong robustness. According to the characteristics of the model, the number of individuals in the algorithm  $M$  takes 100, terminate the evolutionary algebra  $T$  take 500. The crossover probability  $P_c$  is 0.9. The probability of variation  $P_m$  is 0.1. The specific solution steps are as follows:

*Step 1:* Parameter initialization, make evolutionary algebra  $T$  equal to 0;

*Step 2:* Coding, randomly generate 100 initial individuals and substitute the survey data at the intersection into the model to program the formulas in the model;

*Step 3:* Calculate individual fitness in the population, and choose to replicate individuals based on fitness;

*Step 4:* Determine whether the crossover probability  $P_c$  and the mutation probability  $P_m$  meet the requirements, If so, let  $T=T+1$ , Otherwise do crossover operation, until the crossover probability and the mutation probability meet the requirements;

*Step 5:* Repeat iterative calculations, Until the termination of evolutionary generation  $T$  is greater than 500, the cycle time and green time ratio at this time are the results of the model.

*Step 6:* Calculate average delays and tail gas emissions using cycle time and green time ratio, substitute solution results into verification indicators, calculate queue length, number of stops, capacity and capacity utilization, and compare the optimization results.

### 4 Examples demonstrate

In this paper, two different types of intersections are selected for example verification. The first kind of intersection is the intersection of technology road - Fenghui south Road (As shown in figure 1). The intersection is located in the high-tech zone of xi 'an, The peak traffic flow and traffic density are large, Long vehicle idle time, The service level is D, Traffic jams are easy; In terms of traffic organization, there is a two-way traffic from east to west and one-way traffic from north to south. Therefore, this paper optimizes the signal timing of the intersection based on the existing traffic flow.

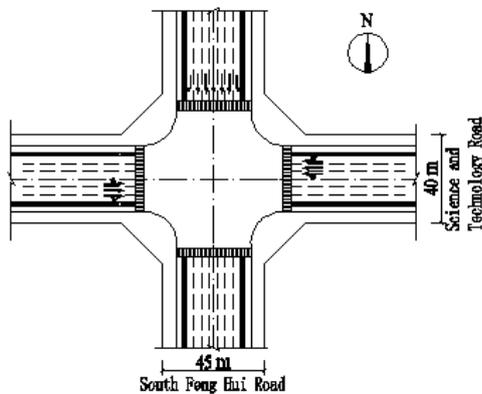


Figure 1. Figure 2 the intersection of South Fenghui Road and Keji Road

Through the investigation of the intersection, the survey of traffic volume was video recording. The instrument used was Panasonic HC-V270GK HD digital camera. The weather is all sunny. On this basis, the weekend morning peak (7:30-8:30) and the evening peak (18:00-19:00) are chosen to shoot one hour in succession; The current situation signal timing and road facilities investigation are all carried out by artificial method.

By collating the survey data, we can get the early and late rush hour traffic of each entry channel. Here, in order to facilitate the calculation of the model, the traffic volume needs to be converted into standard car equivalents, conversion factor see Table 1, And use the average value of standard car equivalents of morning and evening peak hours as the final reference data; Using formula (4) to calculate the current capacity, The weight value is calculated as the ratio of the traffic volume of each entrance road to the total traffic volume; The saturation equals the amount of traffic divided by the capacity of passage, The flow ratio is the ratio of traffic to saturated flow, The service level is referenced in table 2, The final statistical analysis results are shown in Table 3.

Table 1. Conversion coefficient

Model	Conversion factor	Model	Conversion factor
Car, taxi	1.0	small truck	1.5
Medium bus, small bus	1.5	Medium truck	2.0
bus	2.0	big truck	2.5

Table 2. Service level of intersection

Service Level	saturation
A	$\leq 0.25$
B	$0.25 < S \leq 0.50$
C	$0.50 < S \leq 0.70$
D	$0.70 < S \leq 0.85$
E	$0.85 < S \leq 0.95$
F	$0.95 < S$

Table 3. Parameters of Ke Ji Road—Feng Huinan Road intersection

Parameter	Traffic volume/(pcu·h <sup>-1</sup> )	Traffic capacity/(pcu·h <sup>-1</sup> )	Weights	Saturation flow/(pcu·h <sup>-1</sup> )	saturated degree	Traffic ratio	Service Level
Inlet							
East imports	1 223	1 805	0.209	4 885	0.678	0.250	C
West imports	1 447	1 808	0.248	4 900	0.800	0.295	D
North imports	3 171	5 732	0.543	11 300	0.553	0.281	C

The data of Table 3 is used in the optimization model, and the model is solved with Matlab software and genetic algorithm. After 100 generations of iteration, it tends to the optimal solution, and the solution results are substituted into the verification index. Considering that the value of the weight coefficient  $\alpha$  is related to the composition of the traffic flow, and there are differences in the values of different types of vehicles. This article combines the traffic conditions and spatial composition of intersections, refer to related documents [1, 2]. Determine the weight coefficient  $\alpha$  equal to 0.5, And compare the optimization results. The specific results are shown in Figure 2 and Table 4.

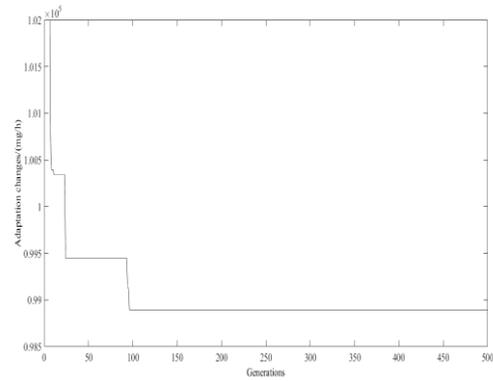


Figure 2. Optimization result diagram of model

Table 4 Comparison of optimization results of Ke Ji Road—Feng Huinan Road intersection

Compared index		status quo	Optimized	Change rate
Signal Timing Scheme	Cycle time/(s)	136	101	---
	First phase effective green light time/(s)	60	49	---
	Second phase effective green time/(s)	73	52	---
Verification indicator	Queue length/(vehicle)	13.31	8.78	-34.03%
	Number of parking / (times)	0.86	0.63	-26.74%
	(weighted) capacity/(pcu·h <sup>-1</sup> )	3 770	3 850	2.12%
	Capacity utilization	59.71%	64.33%	7.74%
optimization goal	Average delay/(s)	50.50	25.89	-48.73%
	Emissions/(mg·h <sup>-1</sup> )	112 314	98 895	-11.95%

It Can be seen from Table 4: Compared with the signal timing at the intersection status, the queue length of the intersection optimized by the signal timing is reduced by 34.03%, the number of parking stops is less than 26.74%, the average delay is less 48.73%, and the tail gas emission is reduced by 11.95%. Increased traffic capacity by 2.12%, increase utilization capacity by 7.74%, Having achieved better optimization results. It shows that when the current signal timing scheme is not reasonable, the optimization model can effectively improve the intersection operation status and improve the traffic control efficiency at the intersection. Therefore, it is suggested that the signal cycle time at this intersection should be 101 s, and the first phase effective green time and the second phase effective green time should be 49 s and 52 s, respectively.

The second type of intersection is a typical four-inlet cross-shaped intersection. This article selects the intersection of Tongyi Road and Tongde Road (See Figure 3). The intersection is located in Xifeng New City, Xixian New District. The service level of the east and west imports during the peak hours is C, and vehicle congestion may occur. Therefore, this paper optimizes signal timing and further tests the utility of the model.

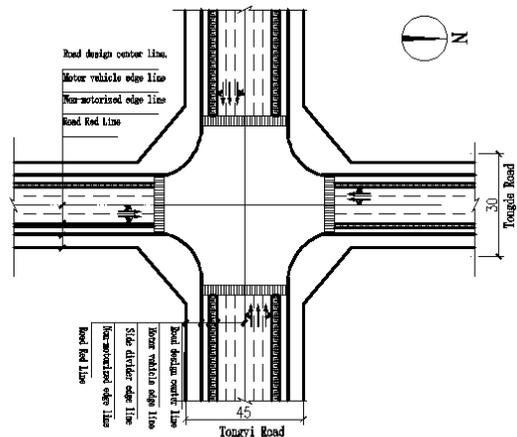


Figure 4 Schematic diagram of the Tongyi road - Tongde Road intersection

Figure 3. Tong Yi Road—Tong De Road intersection diagram

Through field investigation and statistics, the survey conditions, equipment, and sampling methods are the same as those of the first intersection. The available traffic data analysis parameters of the intersection are shown in Table 5.

Table 5. Parameters of Tong Yi Road—Tong De Road intersection

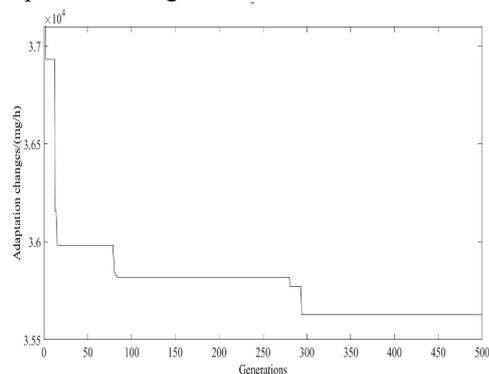
Parameter	Traffic volume/(pcu·h <sup>-1</sup> )	Capacity/(pcu·h <sup>-1</sup> )	Weights	Saturation flow/(pcu·h <sup>-1</sup> )	saturated degree	Traffic ratio	Service Level
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Inlet							
East imports	1 105	1 857	0.327	4 802	0.595	0.230	C
West imports	1 041	1 853	0.308	4 796	0.562	0.217	C
South imports	587	1 253	0.173	3 152	0.468	0.186	B
North imports	651	1 304	0.192	3 171	0.499	0.205	B

**Table 6.** Comparison of optimization results of Tong Yi Road—Tong De Road intersection

Compared index		status quo	Optimized	Change rate
Signal Timing Scheme	Cycle time/(s)	111	91	---
	First phase effective green light time/(s)	53	57	---
	Second phase effective green time/(s)	55	34	---
Verification indicator	Queue length/(vehicle)	7.48	5.56	-25.67%
	Number of parking / (times)	0.66	0.47	-28.79%
	(weighted) capacity/(pcu·h <sup>-1</sup> )	1 646	1 904	15.67%
	Capacity utilization	45.71%	48.26%	5.58%
optimization goal	Average delay/(s)	38.46	27.73	-27.90%
	Emissions/(mg·h <sup>-1</sup> )	49 555	35 658	-28.04%

Substituting the data in Table 5 into the optimization model, using Matlab software and genetic algorithm to solve the model, The optimal solution was obtained after 300 iterations, and the results before and after the optimization were compared. See Figure 4 and Table 6 for details.



**Figure 4.** Optimization result diagram of model

It can be seen from Table 6: Compared to the signal timing in the status quo at the intersection, The optimized queue length of the intersection was reduced by 25.67%, the number of stoppages was reduced by 28.79%, the average delay was reduced by 27.90%, the tail gas emissions decreased by 28.04%, the traffic capacity increased by 15.67%, and the capacity utilization increased by 5.58%. The optimization result is better. This shows that the current signal timing plan is not reasonable and needs further improvement. Therefore, it is suggested that the signal cycle time at this intersection should take 91 s, and the first phase

effective green time and the second phase effective green time should take 57 s and 34 s, respectively.

Comparing Table 4 and Table 6, the magnitude of change of each indicator after two types of intersection optimization is different. The calculation value of each indicator in the intersection of Technology Road and Fenghui South Road is greater than that at the intersection of Tongyi Road and Tongde Road. North entrance road has left and right turn dedicated lanes, reducing the interference of vehicle flow lines. Through the signal timing optimization, the green light duration is reasonably allocated, so the queue length and average delay decrease more, while the utilization capacity and capacity utilization increase less, Explaining that signal timing optimization is not easy to significantly improve the traffic capacity and capacity utilization of the intersection. In the future, the intersection can be improved by adding lanes or optimizing the canalization scheme; At the intersection of Tongyi Road and Tongde Road, the level of service is relatively high. The traffic volume of each road is relatively balanced, and the change in queue length and average delay is small. However, the change in capacity and tail gas emissions is greater than the intersection of Technology Road and Fenghui South Road. Explaining that the current conditions of use of the intersection are poor. The optimization of signal timing will benefit the traffic organization and management of the intersection.

In summary, through the verification of two different types of intersections, the results show that the model has a certain degree of practicality and can obtain a more comprehensive value of comprehensive benefits, and It is feasible to solve the model by genetic algorithm.

## 5 Conclusions

(1) This article takes the urban road intersection as the research object. Analysis six factors including queue length, number of stops, capacity, capacity utilization, average delays, and tailpipe emissions. With the introduction of dynamic exhaust emission rate, and with the constraint of cycle duration and green letter ratio, a signal timing optimization model for urban road intersections based on comprehensive benefits under multi-factor conditions was established.

(2) Selecting the intersection of Science and Technology Road-Fenghui South Road and the intersection of Tongyi Road-Tongde Road in Xi'an to optimize the signal timing, and achieved good value of benefits. It shows that the practicality of the model is verified, which can provide a theoretical reference for selecting the signal timing plan for urban road intersections.

(3) Weather conditions will also affect the vehicle's operation at the intersection. How to fully consider various influencing factors and reasonably determine the weight value of each optimization goal is the direction of further research.

## 6 Acknowledgment

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