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Procedia - Social and Behavioral Sciences 96 (2013) 2404 – 2413

Procedia
Social and Behavioral Sciences

13th COTA International Conference of Transportation Professionals (CICTP 2013)

A traffic emission-saving signal timing model for urban isolated intersections

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Abstract

In the light that traditional traffic signal timing models consider vehicle's traffic efficiency and management benefit, thus ignoring traffic environmental benefit, a traffic emission-saving traffic signal timing model for urban isolated intersections is presented. Firstly, with different statuses of vehicles on the road, for example moving with a constant speed, slowing down speed, idling speed or an increasing speed, there are different kinds of degree of contamination. Based on which the urban road pollutant emissions model, and the criteria pollutant emissions model are established. Secondly, in order to analyze the dependence of the traffic signal evaluation indexes, the qualitative analysis and the quantitative analysis based on the numerical statistics are adapted. Also, based on the selecting principle of evaluation index, selected performance indicators for the emission factors, and taken them into consideration while establishing the traffic signal timing model based on relative evaluation index system. Then, an improved real-coded genetic algorithm to solve the traffic signal timing model is presented. Lastly, the three algorithms are proved by a great deal of numerical calculation. The result shows that the presented algorithm has a high precision while solving the models, and has a very good effect on reducing emissions and the efficient of controlling the traffic roads.

Keywords: Intelligent transportation; Traffic signal; Emission model; Timing model; Genetic Algorithm

1. Introduction

With the environmental problems caused by transportation being more and more severe, urban traffic congestion, road safety and pollution have become the common issues that large cities in China confront. Rational

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doi:10.1016/j.sbspro.2013.08.269

organization of signal control in isolated intersections can improve traffic efficiency, reduce traffic congestion and exhaust emissions, which is the key to solve urban traffic problems.

Optimization of intersection signal timing theory was initiated in the 1950s, Webster was the first to introduce the method to optimize intersection signal timing targeted at shortest delay, the F-B method. On the basis of the F-B method the "Parking compensation coefficient" was introduced, and it was combined with vehicle delay to evaluate the effect of signal timing optimization (1981). Robertson found the relevance between the delay, stops, and fuel consumption. In the TRANSYT system built by him, fuel consumption is regarded as a benchmark, and the direct operating expenses are regarded as the objective function (1980). Based on the research above, besides delay and stops, capacity was added into the objective function as a performance indicator while considering the actual situation of the urban road traffic in China (Gu, 1998). However, the traffic signal control researches listed above are all based on the average delay, number of queuing vehicles, stops, intersection saturation degree and capacity, etc., emissions was not included in the traffic signal control metrics.

Zhou established emissions-saving bi-level programming model targeted at emission control, but the model does not take the motor vehicle's acceleration and deceleration process in intersection area into account, so it lacks the micro-estimation ability (2008, 2009). A set of emission measurement system based on the real-time operation of the vehicle was developed to analysis the impact of the speed and acceleration parameters on the emission factors and fuel consumption, but the concept and significance of the model were not presented (Ren, 2003). Ma focused on the fundamental problem of cycle length optimization based on the vehicle movement in intersection area, and researched the application of the optimized cycle length by introducing the concept of "marginal benefit" and "marginal cost", however it was only the data list without establishing a detailed model including emissions of each stage (2010).

In summary, existing researches on traffic signal control considering emission factors are in the preliminary stage. They are lack of the systematic research on the standardization of the intersection emission model. On the foundation of the traditional principle of traffic signal control based on the statistic model, this paper focuses on the traffic signal control method considering emission factors in urban intersections, aim of introduce traffic emission factors, establish the traffic signal timing model considering environmental protection issues, and propose the improved Real number coding genetic algorithm model. Verify the utility of the model and arithmetic through an example of a typical isolated intersection. The remainder of this paper is organized as follows. Section Ⅱ establishes the model of the exhaust emission according to the vehicle travel process, as well as the criteria pollutant model through introducing equivalent value of pollutant emission. Section Ⅲ establishes the dimensionless traffic signal timing model by analysis the performance index. Section Ⅳ presents the improved genetic algorithm. Section Ⅴ evaluates the proposed emission-saving signal timing model with actual intersection data. Section Ⅶ conclude the work.

2. Standard pollutant discharge modeling.

2.1. The model of the intersection vehicle emissions process

Process of vehicle's movement on the road is shown in Figure 1 and Figure 2. Exclude the special circumstances, vehicle moves in a constant speed, when there is an intersection, vehicles will first decelerate until cease and then accelerate to the initial speed.

According to the process of vehicle's movement on the urban road, the emission of pollutant j E_j, including the driving emission E_{cl} on the road, and parking vehicle's idling emission E_I, accelerated emission E_a, reduction emission E_d, and non-parking vehicle's driving emissions E_{ca} on the approach. Establish the model respectively as follows, thereinto, i represents the phase, j represents the species of pollutants. In addition, emission factor was introduced in national standard GB5181-58, which represents mass emission, means each type vehicle's average emissions of a pollutant under the influence of various factors.

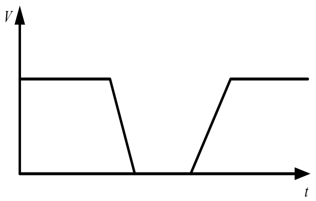

Fig. 1. Diagram of change process of vehicles' speed at the intersection

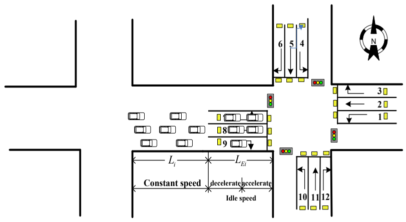

Fig. 2. Diagram of Process of vehicles' movement at the intersection

- Driving emissions on the road

According to the definition of standard vehicle's driving emission factor $EF_j^{PCU}(g/(pcu \cdot km))$, driving emission on the road is the product of the road vehicle number V_i^{PCU} (pcu/h), driving emission factor and the road length L_i (km), in which vehicles with a constant speed.

$$E_{cl}^{ij} = V_i^{PCU} \cdot EF_j^{PCU} \cdot L_i \tag{1}$$

- Emissions on the approach

A. idling emission

According to the definition of the standard vehicle's idling emission factor $EFI_j^{PCU}(g/(pcu \cdot h))$, the idling emissions of the parking vehicle on the approach, is the product of stops, idling emission factors and idle time. Generally recognizing, the idle time is the average delay d_i $(s)$of the approach. Stops is the product of the arrived vehicle's number and the parking rate in Webster h_i.

$$E_I^{ij} = \frac{1}{3600} V_i^{PCU} \cdot h_i \cdot EFI_j^{PCU} \cdot d_i \tag{2}$$

B. Accelerate and decelerate emission

According to the definition of standard vehicle's accelerate and decelerate emission factor e_{aij}^{PCU} and e_{dij}^{PCU} (g/pcu), the emissions of the parking vehicle which on the approach, are the product of the stops and the vehicle's accelerate and decelerate emission factors(pcu/h).

$$E_a^{ij} = V_i^{PCU} \cdot h_i \cdot e_{aij}{}^{PCU}, E_d^{ij} = V_i^{PCU} \cdot h_i \cdot e_{dij}{}^{PCU} \tag{3}$$

C. Driving emission on the approach

Driving emission on the approach is the product of the Non-parking vehicle number, driving emission factor and the approach length L_{Ei}(km):

$$E_{ca}^{ij} = V_i^{PCU} \cdot (1-h_i) \cdot EF_j^{PCU} \cdot L_{Ei} \tag{4}$$

Summing up the above, establish the model of pollutant j in phase i as Formula 5:

$$E^{ij} = V_i^{PCU}(EF_j^{PCU} \cdot L_i + \frac{1}{3600} \cdot EFI_j^{PCU} \cdot d_i \cdot h_i + (e_{aij}{}^{PCU} + e_{dij}{}^{PCU}) \cdot h_i + EF_j^{PCU} \cdot L_{Ei} \cdot (1-h_i)) \tag{5}$$

Generally recognized that the emission of the vehicle's pollutant from an acceleration and deceleration, $e_{aij}^{PCU} + e_{dij}^{PCU}$, equals to emission of the idle speed in100s (Ma, 2010). Therefore, the phase emission could be simplified as Formula 6.

$$E^{ij} = V_i^{PCU}(EF_j^{PCU} \cdot L_i + \frac{1}{3600} \cdot EFI_j^{PCU} \cdot d_i \cdot h_i + \frac{1}{36} \cdot EFI_j^{PCU} \cdot h_i + EF_j^{PCU} \cdot L_{Ei} \cdot (1-h_i)) \tag{6}$$

Here, E^{ij} is the emission of pollutant j in phase i in the intersection, g/h;

The sum of the pollutants in all phases in the intersection is as follows.

$$E^j = \sum_{i=1}^{n} E^{ij} \tag{7}$$

Here, n is the number of phases in a cycle.

2.2. Emission model of standard pollutant

- Definition of standard pollutant's emission

There are many kinds of emissions of pollutants from the vehicles exhaust in the intersection. This paper mainly research on three pollutants including CO, CH, NO. Different pollutants match different order and cause different damage degree. So the emission of the pollutants in the intersection does not equal to the sum of these three pollutants. This paper introduces standard pollutant, E_S *(g)*, which means degree of the sum of pollutants in the intersection. Emission of standard pollutants is defined as the weighted average of the three type's pollutants emission, shown as Formula 8.

$$E_S = w_1 E_{CO} + w_2 E_{HC} + w_3 E_{NO} \tag{8}$$

Here, E_{CO}, E_{HC}, E_{NO} represent the emission of the pollutants CO,CH, NO in the intersection respectively; w_1, w_2, w_3 represent the weight coefficient of the three pollutants respectively, and $\sum_{k=1}^{3} w_k = 1$, $w_k \in [0,1]$.

- Weight determination

The equivalent value of pollutant emission E_{ev}, means the weight of pollutant for per unit cost. The pollutant's equivalent weight was introduced as the quotient of the pollutant's emission and the equivalent value. Considering the damage degree, biological toxicity and the cost of the pollutants, according to Measures for the administration of national pollutant discharge fee collection standards (2003), the equivalent values of each pollutant are shown in Table 1. Where, the weight of HC is averaged by the equivalent value of the pollutants of the matter.

Table 1 The equivalent value of the pollutants (kg)

CO	CH	NO
16.7	5.1	0.95

The equivalent value of pollutants is standard reference data for collecting cost of pollutants. According to state regulations, the cost of every pollutant per equivalent is the same. So, in terms of economic benefits of every pollutant, the weights are determined as the equivalent values of per 1*kg* pollutant each. And according to the definition of the standard pollutant, the weight of the three kinds of pollutants needs normalization.

The equivalent weight of pollutant is calculated as Formula 9.

$$The\ equivalent\ weight\ of\ a\ pollutant = \frac{Emission\ of\ the\ pollutant}{Equivalent\ value\ of\ the\ pollutant} \tag{9}$$

According to (9), the weights of pollutants are calculated as Formula 10.

$$w_j = \frac{\frac{1}{E_{ev}^j}}{\sum_{j=1}^{3} \frac{1}{E_{ev}^j}} \tag{10}$$

By calculating, the weights of pollutants CO, CH, NO are 0.046, 0.15 and 0.804 respectively. The emission model of standard pollutant is shown as Formula 11.

$$E_S = 0.046 E_{CO} + 0.15 E_{HC} + 0.804 E_{NO} \tag{11}$$

3. The signal timing model based on emission

3.1. analysis of performance index

Existing research have found that the Capacity (Saturation) has the most important relationship with the Cycle, then the Queue length, Delays and Stops, based on a survey on the interdependence coefficients between the Cycle of typical intersection and some associated factors. Research results show that the Saturation of the road is proportional to the Capacity, the same with the Queuing length with the Stops and the Delay with the Stops. In order to satisfy the demand of the traffic control target, it's necessary to choose some conflict indexes as many as possible together with the modeling in consideration of the environment.

In traditional traffic control, the target functions are usually built up with the Delay, Stops and Capacity. In order to build the function of timing model taking the traffic environment into consideration, average Delay, Capacity and the standard pollutant emission are chosen as the performance evaluation index of adapted traffic control stratagem.

According to applicability of different delay model in intersections with different Saturation, the research and practice shows that the WEBSTER model fit the current situation of traffic in our country well. So the calculation of the standard pollutant emission is done by the model presented in this paper, with adapted WEBSTER model as the calculation model of the delay performance, as Formula 12

$$d_i = \frac{(C-g_i)^2}{2C(1-y_i)} + \frac{(C-g_i)}{2Cq_i} + \frac{q_i C^2}{2s_i g_i (s_i g_i - q_i C)} \tag{12}$$

Here, d_i is the average delay in phase i, g_i is the effective green time in phase i, q_i is the arrived traffic flow in phase i, s_i is the capacity of the intersection in phase i, y_i is the traffic intensity in phase i, C is the period.

The total delay of the vehicles in the intersection of every period is: $\sum_i d_i q_i C$.

Capacity is calculated by the model in HCM2000 as Formula 13

$$Q_i = S_i \cdot u_i ; Q_i = S_i \cdot \frac{g_i}{C} \tag{13}$$

3.2. Signal timing modeling

While building the target functions with the absolute value of the performance indexes, because of the disunities of different dimensions of different indexes, and if one of the index calculations occupies the monopoly advantage with a higher magnitude, it's possible for the optimization problem of multi-objective to a single objective. Hence, in order to avoid the different magnitude of performance indexes, simple the weighted calculation and make the target function non-dimensional, this paper introduces the relative index modeling of performance indexes by comparing the absolute value with a standard value of the evaluation index.

With the influence of the characteristic feature of different intersections, it's hard to build a unified standard of delay and capacity. So this research based on the Webster timing plan (TRRL) the corresponding evaluation indexes as criteria, and then establish the evaluation system of the relative indexes. The traffic emission-saving signal timing model as Formula 14:

$$\begin{aligned} &\max CPI = k_1 \times (1 - \frac{avgD}{avgD_{TRRL}}) + k_2 \times (1 - \frac{avgE}{avgE_{TRRL}}) + k_3 \times (\frac{Q}{Q_{TRRL}} - 1) \\ &s.t.\ \ g_{\min} \le g_i \le g_{\max} \\ &\qquad \sum g_i + L = C \\ &\qquad C_{\min} \le C \le C_{\max} \\ &\qquad 0 \le k_n \le 1 \\ &\qquad \sum k_n = 1 \end{aligned} \tag{14}$$

Here, *CPI* is the comprehensive performance index of the traffic signal control based on the emissions. *avgD*, *avgE* and *Q* are the average delay time, average emission of standard pollutant, traffic capacity respectively. $avgD_{TRRL}$, $avgE_{TRRL}$ and Q_{TRRL} are the standard values of parameters calculated by Webster timing plan.. g_i is the effective green time in phase *i*. *C* is the period. g_{min} and g_{max} are the minimum and maximum time of the green lights. C_{max} is the maximum period. *L* is the total waste time of the intersection. k_1、k_2、k_3 are the weight coefficient of delay, stop rate and traffic throughput respectively, with adaptive adjustment by traffic demand variation to meet the optimization objectives of different traffic condition at intersections; Three weighted coefficient values are calculated by Formula 15.

$$U_1 = \frac{1-Y}{X}, \quad U_2 = 1-Y, \quad U_3 = \frac{X}{1-Y}$$
$$k_i = \frac{U_i}{\sum_{i=1}^{3} U_i} \qquad (15)$$

In Formula 15, U_i is the temporary weights of index *i*, *Y* is the total flow rate of intersections; *X*, the weight correction factor, is the total saturation of intersections. k_1、k_2 decrease with the increase of flow rate ratio, k_3 increases with the increase of flow rate ratio, which makes the control objectives focus on reducing delays in idle state, and let the traffic smooth and safe; In smooth condition, the control objectives focus on reducing delays and stops, and makes the operation at intersections efficient; In the busy and congestion state, the control objectives focus on improving the throughput, and maximizes the intersection management efficiency. Thus, the weighted models achieve the traffic control strategies optimization under different traffic status.

4. Solution for the model

Traffic signal timing model is a model of nonlinear, multi-objective and optimization. As with too many model parameters and constraints, the traditional genetic algorithm in solving optimization is slow to reach the optimal solution, and it's difficult to meet the constraint conditions while the algorithm is convergence. A GA-based heuristic (AARGA) extended form the Yang's method has been developed to yield approximate solutions for each control interval during the entire optimization period (Yang, 2009). The AARGA generates the initial population and ensures the quality of the initial population by punishment mechanism based on the sort of classification. Meanwhile, cross rate and mutation rate is adaptive according to generation and fitness value. The process of improved AARGA are as follows:

(1) Initialization: generate initial population, which meet the signal constraints and principle of individuals different from each other, and initialize GA parameters, while, population size M=150, evolutional generation *Gen*=100, maximum cross rate $maxP_c$=0.9, minimum cross rate $minP_c$=0.5, maximum mutation rate $maxP_m$=0.1, minimum mutation rate $minP_m$=0.01.

(2) Fitness Evaluation: Fitness evaluation adopted the comprehensive performance index *CPI* of emission-saving signal control.

(3) Selection: roulette wheel selection.

(4) Crossing: non-uniform arithmetic crossover operator.

(5) Mutation: non-uniform mutation operator, by which the degree of mutation is adaptively adjusted with generation and fitness value.

(6) Elite retention strategy: replace the worst individual in current-generation with the best individual in parent-generation.

(7) Judgment of termination principle: if n<Gen, go to Step2. Otherwise, output the best solution and the value of evaluation indices.

5. Case study

5.1. Case narration

Shenzhen Lianhua- Xinzhou signal control intersection is a key intersection in Shenzhen, where the traffic is busy and each flow distribution is significantly different and characterized by uneven arrival. The control effect of the existing timing model is poor during the rush hours, hence it is the traffic black spot in Shenzhen. Currently, restriction of left turn in the traffic control method is adapted for the transportation guide. This paper selects such intersection as research object, to validate the proposed timing model and optimization algorithm.

The plane geometry layout of the intersection, road traffic organization and phase structure are shown in figure 3, widening the approach way of the intersection; channelizing the right turn traffic, which will not controlled by the traffic signal; while adapting standard four phase structure.

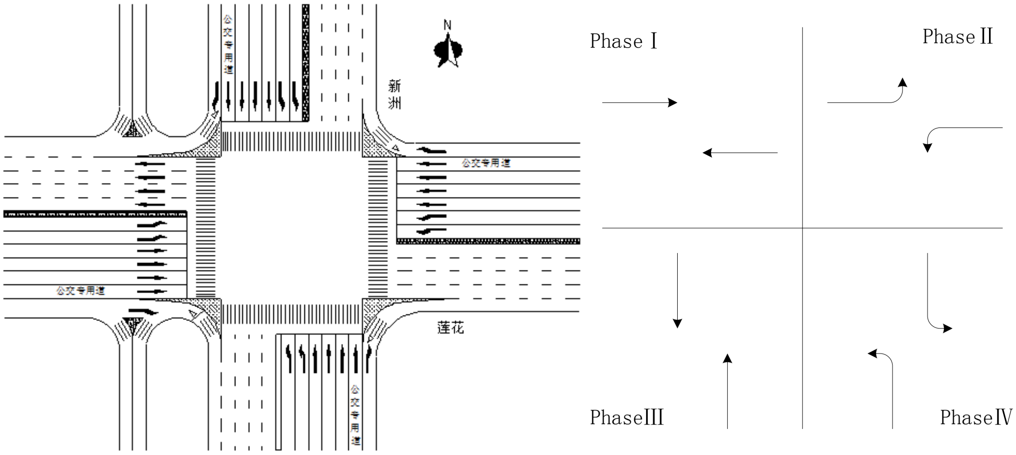

Fig. 3. (a)Lianhua- Xinzhou Road organization diagram; (b) Lianhua- Xinzhou phase diagram

Adapting the mean value of the measured traffic flow of the intersection induction coil in different status within one month for the research (2008.03.01-2008.03.31), the statistical results are shown in the Table 2.

Table 2 Intersection hour's statistical average flow

Phase name	*A*	*B*	*C*	*D*
Included traffic	ES*,WS	EL,WL	NS,SS	NL,SL
Idle traffic volume *q (veh / h)*	126,76	52,64	271,325	28,120
Smooth traffic *q (veh / h)*	604,494	404,317	1107,1389	236,530
Busy traffic *q (veh / h)*	822,642	513,384	1619,1764	252,529
Congested traffic *q (veh / h)*	945,738	589,441	1861,2028	290,608
Phase Saturation flow *S*(veh / h)*	6600,6600	3100,3100	6600,6600	3100,3100
Saturation limits	0.95	0.95	0.95	0.95

Note: S * represents the saturation flow, by adding the corresponding lane saturated flow; ES: Go straight from east. EL: Turn left from east.

Traffic signal control plan is affected by the parameters like geometry, timing and traffic flow, etc. Green light interval, as well as other static timing parameters value according to the traffic flow characteristics in various state, phase loss time G and other parameters are set as shown in Table 3 (Yang, 2009):

Table 3 Threshold values of timing parameters

Traffic state	*G(s)*	*yi*	*Oi*	*xp*	*gmin(s)*	*gmax(s)*	*Cmin(s)*	*Cmax(s)*
Idle	4	[0，0.42]	0.35	0.95	10	45	56	120
Smooth	5	(0.42，0.54]	0.35	0.95	12	60	60	180
Busy	6	(0.54，0.80]	0.35	0.95	15	75	84	250
Congestion	6	(0.80，0.95]	0.35	0.95	15	90	84	300

Due to the intersection in this study is an urban intersection, based on the results of national natural science fund project of southeast university, 《Urban transport system energy consumption and environmental impact analysis method》 (Wang, 2002). Take the data of EF_j^{PCU} and EFI_j^{PCU} when the speed of vehicle is 40*km/h*.

j	*CO*	*HC*	*NOx*
$EF_j^{PCU}(g/(veh \cdot h))$	44.27	5.12	2.01
$EFI_j^{PCU}(g/(veh \cdot h))$	640.76	72.07	7.34

According to multi objective weights determination method based on fuzzy evaluation, the weight values of delay, standard pollutant emission, and traffic capacity in four states are as shown in Table 4:

Table 4 Weight table of instance performance indicators in each state

Traffic state	*D*	*SE*	*Q*
Idle	0.88	0.12	0
Smooth	0.71	0.29	0
Busy	0.42	0.35	0.23
Congested	0.10	0.22	0.68

5.2. Results Analysis

- Performance Analysis

Evolutionary process of AARGA and RGA algorithm are shown in Figure 4. Compared to the RGA algorithm (Chen, 2008), in the course of evolution, the fitness value of AARGA algorithm after running 50 generations tends to be stable, with less average iterations, fast convergence speed, and overall fitness value is better than RGA algorithm. In the 50 times independent numerical calculations, a feasible solution can be obtained in AARGA algorithm each time, and with more times of the convergence, small fitness value fluctuations, suggesting that in this paper, the presented AARGA algorithm for this research instance has a good application effect. Moreover, even in congested traffic condition, the single running time of AARGA algorithm is usually no more than 180s, can meet the real time demand of the control system.

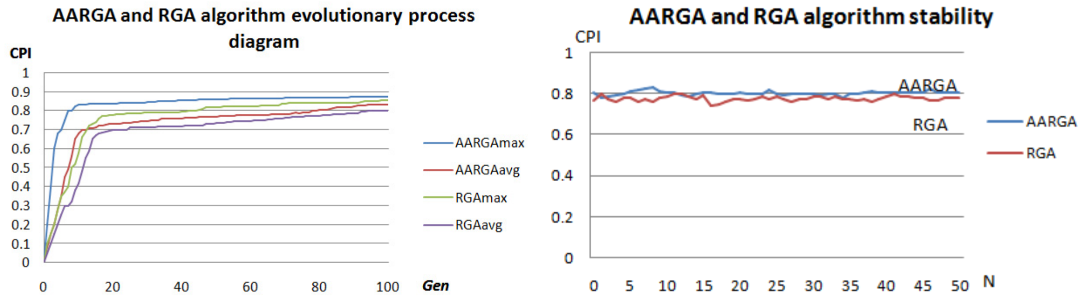

Fig. 4. AARGA and RGA algorithm evolutionary process diagram and stability

- Control effect

Under different traffic states, Contrast the best timing scheme of the AARGA and RGA and classic Webster (TRRL) algorithm timing scheme. Statistical evaluation numerical calculation results are shown in Table 5:

Table 5 Performance indicators calculated results of AARGA, the RGA and TRRL algorithm

Traffic state	algorithm	*C(s)*	*d(s)*	$E_S(g)$	*Q(veh/h)*	*g1(s)*	*g2(s)*	*g3(s)*	*g4(s)*
Idle	AARGA	56	19.63	6.77	3473	10	10	10	10
	RGA	56	19.63	6.77	3473	10	10	10	10
	TRRL	63	20.71	9.74	3702	10	10	15	12
Smooth	AARGA	118	43.52	13.73	4160	16	19	39	24
	RGA	122	46.87	17.83	4185	17	19	40	26
	TRRL	107	53.48	19.87	3751	14	18	28	23
Busy	AARGA	148	64.55	43.92	4327	24	27	46	27
	RGA	158	67.78	51.90	4275	27	23	48	29
	TRRL	156	71.37	58.88	4199	23	29	48	32
Congested	AARGA	223	85.24	68.91	4559	34	45	74	46
	RGA	239	88.59	70.90	4491	36	48	80	51
	TRRL	250	90.58	73.89	4510	39	51	83	53

Note: *C* is the cycle. *g1-g4* is the effective green time of the phase 1-4. *d* is the average stop delay. E_S is the average equivalent value of standard pollutant. *Q* is the traffic capacity.

As can be seen from Table 5, the control effect of AARGA algorithm is better, which can reduce control delays and emissions, and increase the intersection traffic capacity. Take the contrast of AARGA algorithm and TRRL algorithm as an example, AARGA algorithm improves in the delays, emissions and capacity with about 1% to 15% improvement. In the congested state, AARGA algorithm can effectively improve the capacity, but still lacking of emissions and delay improvement, however this depends on the control objectives, and the volatility is low, therefore, the method in the paper is reasonable and effective.

6. Conclusion

A traffic emission-saving signal timing model considering the operation characteristics of vehicles in urban isolated intersections is presented in this paper. Firstly, the urban road intersections emissions model of vehicles is established. Secondly, the criteria pollutant emissions model is established. Thirdly, traffic signal timing model considering emissions factors, based on traffic signals with relative evaluation index system is established. Then, real-coded genetic algorithm is improved to solve timing model while designing. Finally, a test is conducted in the typical intersection, in the non-peak and peak traffic scenarios, using three kinds of control strategy for numerical calculation. The experimental results are shown as below. Compared with RGA and TRRL control methods, on the performance of the algorithm, AAGRA algorithm has improved quality and higher calculation efficiency. On the control effect, AARGA algorithm can effectively reduce the intersection delay and the stops and increase travel speed, which is consistent with the actual traffic management objectives.

However, this research only used a numerical calculation method to evaluate the effectiveness of the model and algorithm. The proposed method will be verified by Vissim microscopic simulation, and the traffic signal control mechanism road which under the circumstance of collaborative environment for emission will be researched in the future.

Acknowledgement

The work of this study is supported by National Science Foundation of China (Project No. 50408034) and Shanghai Educational Foundation for Innovation (Project No. 11ZZ27).

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