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Urban Arterial Traffic Two-direction Green Wave Intelligent Coordination Control Technique and Its Application

Xiangjie Kong, Guojiang Shen*, Feng Xia, and Chuang Lin

Abstract: This paper presents a new two-direction green wave intelligent control strategy to solve the coordination control problem of urban arterial traffic. The whole control structure includes two layers - the coordination layer and the control layer. Public cycle time, splits, inbound offset and outbound offset are calculated in the coordination layer. Public cycle time is adjusted by fuzzy neural networks (FNN) according to the traffic flow saturation degree of the key intersection. Splits are calculated based on historical and real-time traffic information. Offsets are calculated by the real-time average speeds. The control layer determines phase composition and adjusts splits at the end of each cycle. The target of this control strategy is to maximize the possibility for vehicles in each direction along the arterial road to pass the local intersection without stop while the utility efficiency of the green signal time is at relatively high level. The actual application results show the proposed method can decrease the average travel time and average number of stops, and increase the average travel speed for vehicles on the arterial road effectively.

Keywords: Artificial neural networks, arterial traffic, coordination control and fuzzy theory.

1. INTRODUCTION

As the number of vehicles grows and the need for mobility increases on a worldwide scale, the frequency and duration of traffic jams in major cities increase [1]. High fuel cost and environmental concerns provide important incentives for minimizing traffic delays. In the short term, the most effective measures to deal with traffic jams seem to be construction of new roads - an option which is often not viable due to lack of space and/or budget, or due to environmental or societal requirements, - and a more efficient use of the existing infrastructure and capacity through advanced traffic management and control [2]. Dynamic traffic control in an urban setup has always been very attractive to traffic engineers and has been around for quite some time now [3-7].

Urban arterial roads have great attraction to drivers [8]. However, large numbers of vehicles entering urban arterial roads can cause traffic congestions, even lead to traffic accidents [9]. It is necessary to reduce travel time and the number of stops for vehicles on arterial roads. The objective is to obtain a smoother flow of traffic on the principal arterial roads.

Green wave control is a kind of arterial traffic coordination control method, that coordinates traffic signals of adjacent intersections on arterial road to make vehicles driving by a certain speed meet no or less red lights. In other word, traffic signals of adjacent intersections become green one by one according to a certain time sequence in a direction, like a rolling "green wave". [10-12]

Urban arterial green wave coordination control provides numerous advantages [13]: 1) A higher level of traffic service is provided in terms of higher overall speed and reduced number of stops. 2) Traffic flows more smoothly, often with an improvement in capacity. 3) Vehicle speeds are more uniform because there is no incentive to travel at excessively high speeds to reach a signalized intersection within a green interval that is not in step. Also, the slow driver is encouraged to speed up in order to avoid having to stop for a red light. 4) There are fewer accidents because the platoons of vehicles arrive at each signal when it is green, thereby reducing the possibility of red signal violations or rear-end collisions. 5) More motorists and pedestrians obey the signal commands because the motorist tries to keep within the green interval and the pedestrians stay at the curb because the vehicles are more tightly spaced. 6) Through traffic tends to stay on the arterial road instead of diverting onto parallel minor roads.

Little *et al.* proposed MAXBAND [14-16] that considers a two-direction arterial road with n intersections and specifies the corresponding offsets to

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Xiangjie Kong, Feng Xia, and Chuang Lin are with the School of Software, Dalian University of Technology, Dalian 116620, China (e-mails: xjkong@dlut.edu.cn, f.xia@ieee.org, linchuang_78 @sina.com).

Guojiang Shen is with the Department of Control Science and Engineering, Zhejiang University, Hangzhou 310027, China (e-mail: gjshen1975@126.com).

* Corresponding author.

maximize the number of vehicles that can travel within a given speed range without stop. Splits are considered in MAXBAND as given. Based on MAXBAND, Gartner *et al.* proposed MULTIBAND [13,17], that introduces a number of significant extensions in the MAXBAND in order to consider a variety of new aspects such as time of clearance of existing queue, left-turn movements, and different bandwidths for each link of the arterial road. Those researches use mixed-integer linear programming method to maximize the inbound and outbound bandwidths respectively. MAXBAND and MULTIBAND have been applied to several road networks in North America and beyond. However, they can't effectively adapt varying traffic conditions because they are fixed-time coordinated control methods. The main drawback of MAXBAND and MULTIBAND is that their settings are based on historical rather than real-time traffic infomation. When traffic demands change because of incidents or other reasons, the optimized settings will be "aging".

In this paper, we present a two-direction green wave intelligent control strategy based on hierarchical control structure and fuzzy neural networks (FNN). Through information exchanging and coordination between coordination layer and control layer, public cycle time, splits, inbound offset and outbound offset are optimized in real-time. The control strategy can achieve "green wave" effects in the two directions on arterial road and make sure the high green signal usage ratio. The practical application on Zhongxing Road, Shaoxing, China, proves efficiency and practicality of the control strategy.

The organization of the rest of the paper is as follows. In the next section, we present the two-layer hierarchical system structure. In Section 3 the detailed arterial traffic control strategy is described. The control process is presented in Section 4. Section 5 describes the details of the application and shows our results. Finally, the conclusion is given in Section 6.

2. SYSTEM STRUCTURE

In order to describe clearly, we first define following parameters:

C: public cycle time of all intersections on arterial road;

λ : split, relative green duration of each phase (as a portion of the cycle time);

$t_{\mathrm{p,in}}$: inbound offset, phase difference for successive intersections in inbound direction along arterial;

$t_{\mathrm{p,out}}$: outbound offset, phase difference for successive intersections in outbound direction along arterial;

t_{in}: start time of inbound coordinated phase;

t_{out}: start time of outbound coordinated phase.

As Fig. 2 shows, the arterial traffic control system uses two-layer hierarchical structure - the coordination layer and the control layer. The coordination layer includes Traffic Information Management Module (TIMM) and Optimal Coordination Control Module (OCCM). TIMM mainly pre-processes the traffic information to eliminate the abnormal data and then save them into database. OCCM calculates key parameters of two-direction green wave control strategy, including C, λ, $t_{\mathrm{p,in}}$, $t_{\mathrm{p,out}}$, t_{in} and t_{out}, based on historical and real-time traffic information provided by TIMM. Thus, OCCM develops real-time dynamical optimal signal control plan. Then the coordination layer sends the control strategy to the control layer.

The control layer composed by bottom terminal equipments is in charge of collecting basic traffic information and executing traffic control plan. The control layer has certain autonomy capability to adjust optimal signal-timing plan from the coordination layer, such as determining phase composition, adjusting splits, judging "lag-open" and "advanced-close" of left-turn signal. Then the optimal signal control plan is achieved.

In this paper, the coordination layer is realized by software control platform in traffic control center, while the control layer is realized by intersection intelligent signal controller. This system has downgraded control function. If there is serious fault with communication between traffic control center and intersection intelligent signal controllers, the system will switch hierarchical structure to fixed-time control structure. Then intersection intelligent signal controllers will execute pre-defined multi-time multi-plan control strategy to ensure normal operation of the system.

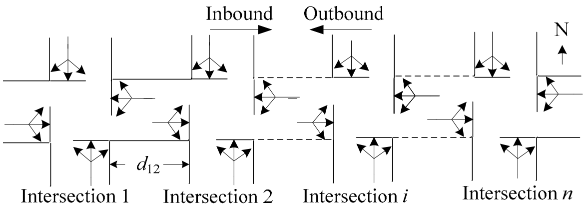

Fig. 1. Sketch map of an urban arterial road.

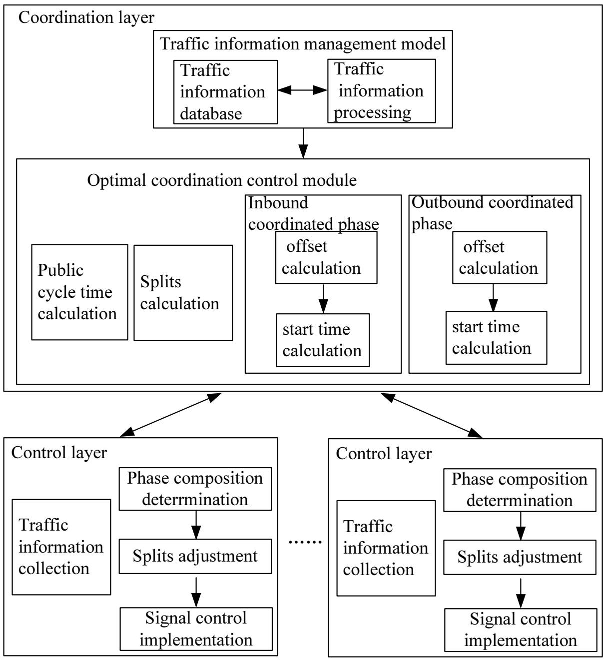

Fig. 2. Structure of hierarchical control system.

3. CONTROL STRATEGY

In this section, we present the details of the proposed control strategy.

3.1. Overview

C, λ, $t_{\mathrm{p,in}}$, $t_{\mathrm{p,out}}$, t_{in}, and t_{out} are key parameters of two-direction green wave control strategy and should be designed optimally. In order to make traffic signal of each intersection coordinated, the cycle time of all intersections should be equal. First, cycle time of each intersection is calculated in the coordination layer by isolated intersection design method [18]. Then the maximal value is selected as public cycle time C, and the corresponding intersection is defined as the key intersection. Splits of each intersection are unequal, and usually calculated in the coordination layer according to real-time traffic information to trace the instantaneous traffic variety. Inbound offset and outbound offset are determined by link length and average vehicle speed between adjacent intersections. If the control plan is adjusted frequently, the unstable traffic flow may be generated by aggregate wave or evanescent wave caused by plan alternation. Thus signal cycle time, inbound offset and outbound offset keep unchanged within a period, such as 8 cycles. However, splits are changed each cycle.

3.2. Phase setting

For arterial traffic control, phase composition has major impact on intersection capacity and efficiency. Previously when designing urban arterial traffic control strategy, some researchers assume there is no left-turn vehicles considering heavy traffic burden of the arterial road [19]. However, it doesn't agree with the actual traffic condition. Practice indicates left-turn vehicle flows uncontrolled will severely disturb straight-go vehicles and impact on safety of pedestrians, even if left-turn vehicle flows on arterial road are not heavy. Hence, the control strategy presented by us allows vehicles left-turn, using "lag-open" and "advanced-close" method to reduce the impact on straight-go vehicles.

In order to improve the throughput volume of vehicles on arterial and simplify the control strategy, as Fig. 3 shows, the pre-design phase composition has only 3 phases. Phase 1 is inbound traffic on the arterial road; phase 2 is outbound traffic on the arterial road; and phase 3 is traffic from two-direction on the branch road. However, in actual implementation, the green time of phase 1 and phase 2 possibly overlap. During this overlap time, vehicles on the arterial should be prohibited to turn left to avoid the impact of straight-go vehicles, thus creating the phase 4 (as Fig. 4 shows). Phase 4 is "overlap Phase" of phase 1 and phase 2.

The basic idea of arterial traffic two-direction green wave control strategy proposed by this article is: inbound direction coordinates phase 1 according to certain offsets, and out-bound direction coordinates phase 2 according to certain offsets. As in the actual application, the section length between each intersection is not same, so the intersections of the phase are not always continuous. In the implementation process, there will be 3 kinds of situations: 1. Phase 1 and phase 2 are continuous, i.e., phase 2(or phase 1) starts just when phase 1(or phase 2) ends. The control effect of this situation is best among 3 situations. However, because the length of road section and vehicle mean speed on road section are heterogeneous, there is a weak possibility that situation 1 happens; 2. Phase 1 and phase 2 are overlapped, i.e., phase 2(or phase 1) starts when phase 1(or phase 2) is still running. Situation 2 will cause redundant green time that can be assigned for other phases according to factual conditions; 3. Phase 1 and phase 2 are separate, i.e., phase 2(or phase 1) starts when phase 1(or phase 2) has ended for some time. We can adjust green time of every phase suitably according to factual conditions. When situation 2 or situation 3 happens, the green wave bandwidth may be lowered. The optimum target of the control strategy is to avoid situation 3 if possible, and make phase 1 and phase 2 overlapped time as short as possible when situation 2 happens.

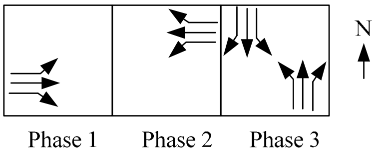

Fig. 3. Pre-design phase composition.

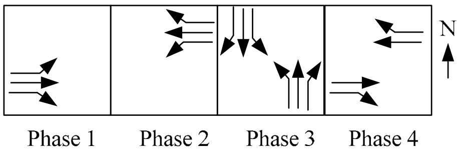

Fig. 4. Phase composition in actual application.

3.3. Public cycle time

Public cycle time C is adjusted according to saturation degree X of the key intersection.In order to make traffic signal of each intersection coordinated, the cycle time of all intersections should be equal. The optimum cycle time C_{opt}, the maximum cycle time $C_{\max}$ and the minimum cycle time $C_{\min}$ of the key intersection are decided by historical traffic statistic data. C is adjusted by saturation degree X of the key intersection. According to traffic control theory, the longer C is, the lower X is, and the shorter C is, the higher X is. The optimal value of X generally is 0.9. Here, C is adjusted through a fuzzy control algorithm to remain saturation degree as 0.9.

X is calculated as:

$$X = \frac{\sum_{i=1}^{3} Q_i}{\sum_{i=1}^{3} \lambda_i S_i}, \tag{1}$$

where Q_i, λ_i, S_i are traffic flow, split and saturated flow of phase i of an intersection respectively. In con-

Table 1. Domain and membership degree of saturation degree.

Lingual value	Saturation degree										
	<.40	[.40,.55)	[.55,.70)	[.70,.80)	[.80,.85)	[.85,.90)	[.90,.91)	[.91.92)	[.92,.94)	[.94,.97)	[.97,1.0)
VB								0.1	0.4	0.7	1.0
B							0.2	0.7	1.0	0.7	0.1
LB						0.2	0.6	1.0	0.6	0.1	
M				0.1	0.6	1.0	0.7	0.2			
LS		0.1	0.6	1.0	0.6	0.2					
S	0.1	0.7	1.0	0.7	0.2						
VS	1.0	0.7	0.4	0.1							

crete calculation, if there are several lanes in phase i, Q_i and S_i can select those of the key lane.

X can be seemed as fuzzy variable $\underset{\sim}{x}$, which domain and membership degree is as Table 1 shows. Lingual value of X is defined as $\underset{\sim}{x}_1$ (VB), $\underset{\sim}{x}_2$ (B), $\underset{\sim}{x}_3$ (LB), $\underset{\sim}{x}_4$ (M), $\underset{\sim}{x}_5$ (LS), $\underset{\sim}{x}_6$ (S), $\underset{\sim}{x}_7$ (VS). Cycle increment ΔC can be seemed as fuzzy variable $\Delta\underset{\sim}{c}$, which domain and membership degree is as Table 2 shows. Lingual value of ΔC is defined as $\Delta\underset{\sim}{c}_1$ (PB), $\Delta\underset{\sim}{c}_2$ (PM), $\Delta\underset{\sim}{c}_3$ (PS), $\Delta\underset{\sim}{c}_4$ (Z), $\Delta\underset{\sim}{c}_5$ (NS), $\Delta\underset{\sim}{c}_6$ (NM), $\Delta\underset{\sim}{c}_7$ (NB) [20-22].

According to control experience of traffic police, seven control rules usually can be concluded:

$$\text{If } \underset{\sim}{x} = \underset{\sim}{x}_i \text{ then } \Delta\underset{\sim}{c} = \Delta\underset{\sim}{c}_i,\ i = 1, 2, \cdots, 7. \tag{2}$$

Concrete cycle increment can be gained by looking up Table 3.

Because the fuzzy sets and the fuzzy relations are fixed, thus using this fuzzy decision to adjusting public cycle time cannot win high control accuracy. Moreover, it possibly reduces the controller's robustness. A potential method for controlling traffic flow is one that employs learning so that dynamic changes in traffic are learned on-line and accommodated with the proper use of control technique. One such method is based on the use of artificial Neural Networks (ANNs). The learning capability and universal approximation property of ANNs make them suitable for control of uncertain nonlinear and time-varying dynamic systems such as vehicular traffic [23-27].

In this article, we use 3 3-layer BP neural networks to implement fuzzification, fuzzy reasoning and defuzzification respectively, i.e., using BP neural networks to simulate input and output character of fuzzy control.

Table 2. Domain and membership degree of cycle increment.

Lingual value	Cycle increment								
	-16	-12	-8	-4	0	4	8	12	16
PB							0.2	0.6	1.0
PM						0.1	0.5	1.0	0.5
PS					0.1	0.8	1.0	0.8	0.1
Z			0.1	0.6	1.0	0.6	0.1		
NS	0.1	0.8	1.0	0.8	0.1				
NM	0.5	1.0	0.5	0.1					
NB	1.0	0.6	0.2						

Table 3. Fuzzy rules of cycle adjustment.

IF $\underset{\sim}{x}$ =	VS	S	LS	M	LB	B	VB
THEN $\Delta\underset{\sim}{c}$ =	NB	NM	NS	Z	PS	PM	PB

The first ANN with single input and 7 outputs is used for fuzzification. Its input is saturation degree, output is saturation degree's membership of fuzzy set "VS, S, LS, M, LB, B, VB", and hidden layer has 5 neurons. The first ANN is trained based on the experience data provided by Table 1 until the error less than specified value. The second ANN with 7 inputs and 7 outputs is used for fuzzy reasoning. Its input is degree's membership of fuzzy set "VS, S, LS, M, LB, B, VB", output is cycle increment's membership of fuzzy set "NB, NM, NS, Z, PS, PM, PB", and hidden layer has 4 neurons. The third ANN with 7 inputs and single output is used for defuzzification. Its input is cycle increment's membership of fuzzy set "NB, NM, NS, Z, PS, PM, PB", output is cycle increments, and hidden layer has 5 neurons. The second ANN and the third ANN is trained based on the empirical data provided by Table 3 and Table 2 respectively.

As Fig. 5 shows, the 3 ANNs connect with each other to construct a fuzzy controller. The neural mapping of the fuzzy relation can be described by

$$\Delta C = \text{FNN}(X). \tag{3}$$

The relationship between input and output of neurons is a sigmoid function, that is

$$\begin{cases} V = \dfrac{1}{1+e^{-S}} \\ S = \sum \omega_i x_i - \theta, \end{cases} \tag{4}$$

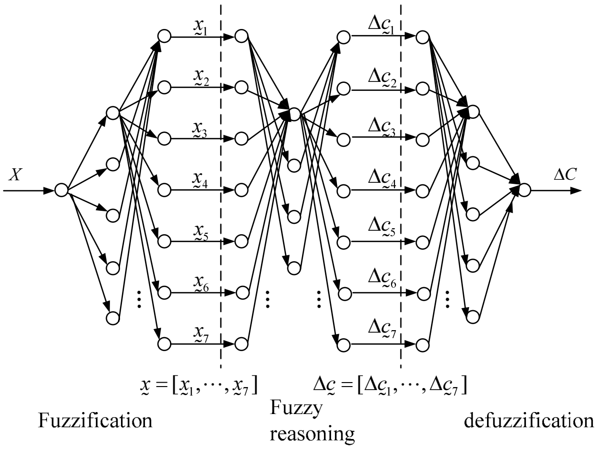

Fig. 5. ANNs implementation of fuzzy controller.

where x_i and V are the input and output of neurons respectively, ω_i are the adjustable weights of x_i and θ is threshold value.

In order to accelerate learning speed and prevent the BP neural network from trapping in local minimum, an improved BP algorithm is used in this article.

The input of neuron node j in L layer is:

$$n_j^{(L)}(k)=\sum_{i=1}^{q}\omega_{ji}^{(L)}(k)O_i^{(L-1)}(k)-\theta_j^{(L)}(k), \tag{5}$$

where $O_i^{(L-1)}(k)$ is the output signal of neuron node i in the previous layer (L-1), $\omega_{ji}^{(L)}(k)$ is connection weight between neuron node i in layer (L-1) and neuron node j in L layer, $\theta_j^{(L)}(k)$ is the threshold value of neuron node j in L layer, and q is the number of neurons in layer (L-1).

The output of neuron node j in L layer is:

$$O_j^{(L)}(k)=\frac{1}{1+\exp[-n_j^{(L)}(k)]}. \tag{6}$$

$\omega_{ji}^{(L)}(k)$ and $\theta_j^{(L)}(k)$ are adjusted as follow:

$$\Delta\omega_{ji}^{(L)}(k)=-\eta\delta_j(k)O_i^{(L-1)}(k)+\alpha\Delta\omega_{ji}^{(L)}(k-1), \tag{7}$$

$$\Delta\theta_j^{(L)}(k)=-\eta\delta_j(k)+\alpha\Delta\theta_j^{(L)}(k-1), \tag{8}$$

where α is impulse factor, $\alpha\in(0,1)$, and η is correction coefficient.

$\delta_j(k)$ is divided into two cases:

If j is an output node, $\delta_j(k)$ is

$$\delta_j(k)=\delta_j^{(L)}(k)=[y_{oj}(k)-y_j(k)]y_j(k)[1-y_j(k)]. \tag{9}$$

If j is an hidden node, $\delta_j(k)$ is

$$\delta_j(k)=\delta_j^{(L)}(k)=O_j^{(L)}(k)[1-O_j^{(L)}(k)]\sum\delta_i^{(L+1)}(k)\omega_{ij}^{(L+1)}(k). \tag{10}$$

In this article, the before-mentioned BP algorithm is improved as follow. 1) During self-learning course, η takes the smaller value in starting procedure and ending procedure, otherwise takes the larger value, 2) The factual outputs of neuron nodes are limited to a certain range. Thus, expression (6) is changed as follows:

$$\begin{cases} O_j^{(L)}(k)=0.999 & \text{if } O_j^{(L)}(k)>0.9999 \\ O_j^{(L)}(k)=0.0001 & \text{if } O_j^{(L)}(k)<0.00001 \\ O_j^{(L)}(k)=1/1+\exp[-n_j^{(L)}(k)] & \text{else.} \end{cases} \tag{11}$$

Using improved BP algorithm to train the neural network, we find the network can converge preferably, the rate of convergence is fast, and iterative error descends steadily.

New cycle time $C=C+\Delta C$ is gained. If $C>C_{\max}$, then $C=C_{\max}$. If $C<C_{\min}$, then $C=C_{\min}$. Cycle adjustment can be calculated and sent to every intersection controller by systematic software in traffic control center.

3.4. Splits

Splits of each intersection are unequal, and usually calculated in the coordination layer according to real-time traffic data to trace the instantaneous traffic variety. First, the minimum green time $t_{i,\min}$ and maximum green time $t_{i,\max}$ of each phase shown in Fig. 4 are calculated by historical traffic statistic information of each intersection. The calculation process is as follows.

1) The average corrected flows of phase $i(i=1,2,\cdots,n)$ in every signal cycle

$$\tilde{Q}_i(k)=\alpha Q_i(k)+\beta\tilde{Q}_i(k-1)+\gamma\bar{Q}_i(k), \tag{12}$$

where $\tilde{Q}_i(k)$ is corrected flows of the phase i in the kth signal cycle; $Q_i(k)$ is factual flow of phase i in the kth signal cycle; $\bar{Q}_i(k)$ is historical average flow of phase i; positive parameters α, β and γ satisfy: $\alpha+\beta+\gamma=1$. The lager α is, the better real-time performance is, and the lager β and γ are, the better stability performance is. Generally take $\alpha=0.5$, $\beta=0.3$, $\gamma=0.2$.

2) Splits:

The split of phase i is defined by

$$\lambda_i(k+1)=\frac{\tilde{Q}_i(k)}{\sum_{i=1}^{n}\tilde{Q}_i(k)}. \tag{13}$$

3) Effective green time:

The effective green light time of phase i is given by

$$t_i=\lambda_i(C-Y_{\text{all}}-R_{\text{all}}), \tag{14}$$

where Y_{all} is the sum of yellow time in a cycle, R_{all} is the sum of red time in a cycle.

If $t_i<t_{i,\min}$, then $t_i=t_{i,\min}$. The lack of green time is proportionally complemented by other phases. The complementary time of phase j is defined by

$$t_{j,\text{ded}}=\frac{\lambda_j}{\sum_{k=1,2,\cdots,n;k\neq i}\lambda_k}(t_{i,\min}-t_i). \tag{15}$$

If $t_i>t_{i,\max}$, then $t_i=t_{i,\max}$. The excessive green time is proportionally assigned to other phases. The shared time of phase j is defined by

$$t_{j,\text{add}}=\frac{\lambda_j}{\sum_{k=1,2,\cdots,n;k\neq i}\lambda_k}(t_{i,\max}-t_i). \tag{16}$$

In order to ensure wide bandwidth of two-direction green wave coordination control. $t_{1,\min}$ and $t_{2,\min}$ should be selected bigger value.

3.5. Offset

For arterial traffic two-direction green wave control, offset is divided as inbound offset $t_{\mathrm{p,in}}^{j,j+1}(k)$ and outbound offset $t_{\mathrm{p,out}}^{j+1,j}(k)$,

$$t_{\mathrm{p,in}}^{j,j+1}(k)=\frac{d_{j,j+1}}{v_{j,j+1}(k)}, \tag{17}$$

$$t_{\mathrm{p,out}}^{j+1,j}(k)=\frac{d_{j+1,j}}{v_{j+1,j}(k)}, \tag{18}$$

where $j=1,2,\cdots,n-1$ is the number of intersections on the arterial road. $d_{j,j+1}$, $v_{j,j+1}$ are inbound link length and inbound speed between intersection j and j+1. $d_{j+1,j}$, $v_{j+1,j}$ are outbound link length and outbound speed. Observably, $d_{j,j+1}=d_{j+1,j}$.

3.6. Start time of phase1 and phase 2

In order to achieve effects of arterial traffic green wave coordination control, start time of phase 1 and phase 2 shown in Fig. 3 must be decided according to C, $t_{\mathrm{p,in}}^{j,j+1}$ and $t_{\mathrm{p,out}}^{j+1,j}$.

Suppose start time t_{in}^{1} of phase 1, intersection 1 in inbound direction is 0 second. In order to attain coordinative effect, start time t_{in}^{j} of phase 1 in the jth intersection should be staggered according to inbound offset. t_{in}^{j} is given by the following equation:

$$t_{\mathrm{in}}^{j}=\sum_{k=2}^{j} t_{\mathrm{p,in}}^{k-1,k}-mC;\ m=1,2,\cdots;\ j=2,3,\cdots n, \tag{19}$$

where the value of m should meet $0 \le t_{\mathrm{in}}^{j} < C$.

Suppose start time t_{out}^{n} of phase 2, intersection \$n\$ in outbound direction is t second. Start time t_{out}^{j} of phase 2 in the jth intersection should be staggered according to outbound offsets either. t_{out}^{j} is given by the following equation:

$$t_{\mathrm{out}}^{j}=t+\sum_{k=j}^{n-1} t_{\mathrm{p,out}}^{k,k+1}-mC;\ m=1,2,\cdots;\ j=n-1,\cdots 2,1, \tag{20}$$

where the value of m should make $0 \le t_{\mathrm{out}}^{j} < C$.

Suppose $t_{\mathrm{in}}^{j,g}$ and $t_{\mathrm{out}}^{j,g}$ are green time of phase 1 and phase 2 in the jth intersection respectively. According to aforementioned optimum target, we look for optimal control parameter t in (20) to firstly satisfy optimal performance index J_1 that is to minimize the possibility that situation 3 happens, and then satisfy optimal performance index J_2 that is to minimize the overlapped time when situation 2 happens.

$$J_1=\min\left(\sum_{j=1}^{m}\left|t_{\mathrm{in}}^{j}-t_{\mathrm{out}}^{j}\right|>a^{j}\ ?1:0\right),$$

$$a^{j}=\begin{cases} t_{\mathrm{out}}^{j,g} & \text{if } t_{\mathrm{out}}^{j}>t_{\mathrm{in}}^{j} \\ t_{\mathrm{in}}^{j,g} & \text{else,} \end{cases} \tag{21}$$

$$J_2=\max\left(\sum_{j=1}^{m}\left|t_{\mathrm{in}}^{j}-t_{\mathrm{out}}^{j}\right|\right). \tag{22}$$

Search algorithm of t is as follows:

Firstly, t (t is integer, $t\in[0,C]$) meeting J_1 is calculated using enumeration method. If t is a unique value, then calculation is finished. If t is not unique, then use the enumeration method in accordance with J_2 to find optimal control parameter t.

When phase 1 and phase 2 overlaps, “lag-open” and “advanced-close” of left-turn signal are selected to avoid conflict between left-turn traffic flow and straight traffic flow. It is assumed that the optimal start time of phase 1 and phase 2 in the jth intersection is $\tilde{t}_{\mathrm{in}}^{j}$ and $\tilde{t}_{\mathrm{out}}^{j}$ respectively; phase 1 starts before phase 2, i.e., $\tilde{t}_{\mathrm{in}}^{j}<\tilde{t}_{\mathrm{out}}^{j}$; overlapped time of phase 1 and phase 2 is t^{j}. Then left-turn signal “advanced-close” time of phase 1 is $\Delta t_{\mathrm{in}}^{j}=t_{\mathrm{in}}^{j,g}-t^{j}$, while left-turn signal “lag-open” time of phase 2 is $\Delta t_{\mathrm{out}}^{j}=t_{\mathrm{out}}^{j,g}-t^{j}$.

4. CONTROL PROCESS

Two-layer hierarchical structure taken by the proposed green wave control is as Fig. 6 shows. The coordination layer adjusts cycle time and offset according to traffic statistic information in a period. Then the coordination layer decides start time of phase 1 and phase 2 of each intersection, and transfers cycle, offset and start time of phase 1 and phase 2 of each intersection to the control layer. The control layer decides phase composition and calculates splits according to historical and real-time data in cycle end. Then the control layer calculates left-turn vehicle flows “advanced-close” or “lag-open” time of phase 1 and phase 2, and transfers traffic information to coordination layer in the end of the cycle. The detailed control process is as follows.

Step 1: First, the coordination layer decides public cycle time **C**, inbound offset $t_{\mathrm{p,in}}^{j,j+1}$ and outbound offset $t_{\mathrm{p,out}}^{j+1,\ j}$ of every intersection on the arterial road according to historical and real-time traffic information in a period. Second, the inbound coordinative and outbound coordinative start time $\tilde{t}_{\mathrm{in}}^{j}$ and $\tilde{t}_{\mathrm{out}}^{j}$ of every intersec-

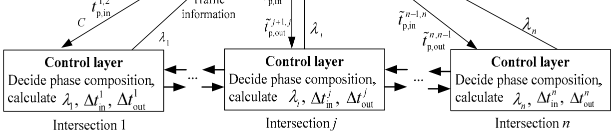

Fig. 6. Flow chart of control process.

tion, “advanced-close” Δt_{in}^{j} and “lag-open” time $\Delta t_{\text{out}}^{j}$ of left-turn signal are calculated further.

Step 2: Let the count parameter l be 0.

Step 3: The control layer opens green signal according to the parameters set by the coordination layer, and adjusts splits according to historical and real-time traffic information to make the vehicle average delay time less. The control layer sends values of traffic flow detected by vehicle detector and splits to the coordination layer at the end of cycle.

Step 4: Set l=l+C. If l>8C, then go to step 5, otherwise go back to step 3.

Step 5: According to new traffic information and splits of key intersection, the coordination layer predicts traffic flow saturation degree of the key intersection in next one period, and decides the next cycle time to keep the traffic flow saturation degree 0.9. At the same time, the inbound offset $t_{\text{p,in}}^{j,j+1}$ and outbound offset $t_{\text{p,out}}^{j+1,\ j}$, starting time $\tilde{t}_{\text{in}}^{j}$ and $\tilde{t}_{\text{out}}^{j}$, “advance-close” time Δt_{in}^{j} and “lag-open” time $\Delta t_{\text{out}}^{j}$ of left light signal are determined. At last, return step 2.

5. APPLICATION EXAMPLE

The developed arterial traffic green wave intelligent coordination control technique has been implemented in C++ as center software module and intersection software module. The two software modules have been embedded respectively in TCMS traffic control software system (shown in Fig. 7) and ACS-3 model intelligent traffic controller (shown in Fig. 10) that are made in Zhejiang Supcon Information Co., Ltd, China. Supported by the National High Technology Research and Development Program of China (2007AA11Z216), Zhejiang University cooperates with Traffic Police Branch of the Department of Shaoxing Police and Zhejiang Supcon Information Co., Ltd in building an arterial traffic intelligent coordination control system on Zhongxing Road at Yuecheng District Shaoxing City in 2007. The developed traffic control technique, TCMS traffic control software and ACS-3 model intelligent traffic controller (shown in Fig. 8) are adopted in this system. The performance of the developed control technique in this article is evaluated by application result.

Fig. 7. TCMS traffic control software system.

Fig. 8. ACS-3 model intelligent traffic controller.

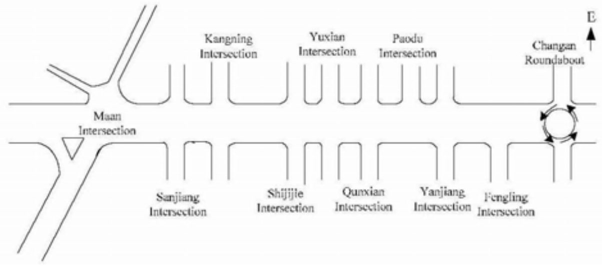

Fig. 9. Rough map of Zhongxing Road in Shaoxing.

Before system updates, Zhongxing Road mainly used simple isolated intersection multi-phase multi-time fixed-time control method. In the early days, this control method made great contributions to Shaoxing traffic development. However, with the socio-economic development and the increase in the number of vehicles, this control method can no longer meet the increasing traffic demand, and isolated intersection fixed-time control method can not meet the needs of modern intelligent traffic control. The traffic feature of Zhongxing Road is as follow [28]:

1) Traffic congestion often appears, but the road capacity utilization is inadequate. 2) Traffic control signals between intersections have no coordination, so traffic does not flow smoothly. 3) There is large difference between flows on Zhongxing Road and flows on branch roads. 4) The number of stops at intersection is big, and disobeying traffic signals occurs from time to time. 5) Pedestrians crossing the road seriously disturb the flow of traveling motor vehicles. 6) Maan intersection is close to the Shaoxing tollgate of Hangzhou-Ningbo Highway. If there are many vehicles in and out the tollgate, it may cause vehicle queuing on Zhongxing Road. 7) There are many places of interest on the corners of Changan roundabout. Thus, traffic condition near Changan roundabout

Table 4. Vehicle flow per hour on Zhongxing Road and branch roads.

		Maximum traffic flow (veh./h)	Maximum traffic flow (veh./h)	Average traffic flow (veh./h)
Rush hours	Zhongxing Road	1392	552	1100
	Branch roads	348	24	200
Others	Zhongxing Road	1020	320	750
	Branch roads	236	24	105

Table 5. Application results.

	Before	Now	Impr(%)
ATT(min)	19.1	8.3	57%
ATS(km/h)	43	76	77%
ANS(number/veh)	4.7	0.4	92%

is heavier than it is on other intersections.

Table 4 shows maximum traffic volume, minimum traffic volume and average traffic volume per hour on Zhongxing Road and branch roads in rush hours and the others.

The inductive loop detectors are installed at each intersection on Zhongxing Road. In the north of Maan intersection, a video vehicle detector is installed to detect the traffic condition between Maan intersection and the Shaoxing tollgate of Hangzhou-Ningbo Highway. Based on the collected traffic information, the short-time traffic flow integrated forecasting methods which joins the artificial neural network to researches in other areas is adopted [29].

Since October 2007, green wave arterial traffic coordination control system on Zhongxing Road has been working stably. The coordination layer is implemented by TCMS traffic control software system in server of traffic Police Branch of the Department of Shaoxing Police. The control layer is implemented by ACS-3 model intelligent traffic controller. Communication between the coordination layer and the control layer is implemented by optical fiber leasing from NetCom Co., Ltd, China. The results are compared with isolated intersection fixed-time control system that was adopted at each intersection in Zhongxing Road before. In order to evaluate the performance under rush hours and the others, Average Travel Time (ATT), Average Travel Speed (ATS) and Average Number of Stops (ANS) of vehicles on Zhongxing road are used as index of performance. The results are summarized in Table 5 which shows the ATT, ATS and ANS per vehicle, and the improvement of the proposed method over the isolated intersection fixed-time control method.

In accordance with the requirements of traffic Police Branch of the Department of Shaoxing Police, design maximum speed as 80km/h during the day and 70km/h during the night in arterial road. The initial public cycle time is 100 seconds, the green time of phase 1 and phase 2 is 40 seconds respectively when beginning. Table 5 lists the actual effects of updated system. These data show that dynamic green wave coordination control strategy can improve arterial traffic conditions and the effect is obvious. The proposed method in this article shows good performance. It shows improvements 57% in ATT, 77% to in ATS and 92% in ANS over the isolated intersection fixed-time control method.

6. CONCLUSIONS

From the results presented above, we can conclude that this proposed arterial traffic intelligent coordinated control method can optimize traffic flow effectively. We have investigated the use of fuzzy theory and artificial neural networks technique for adaptive traffic control. A hierarchical architecture is considered where the timing parameters at each intersection are adjusted using local information and parameters from traffic control center. Vehicles traveling through Zhongxing Road with less number of stops are realized. We also have developed actual control system, and the application results show its effectiveness.

Although some substantial improvements have been achieved in this article, we find the following should be noted in the future.

1) In this paper, we assume that detectors can give us what we want, but in the real world such assumption is very fragile. Because the detectors cannot be fixed each intersection in the road network and the detectors failure may appear in sometime. Thus, studies on uncertainty of detectors and the method which can cope with such problem are needed.

2) In some developing country, such as China, the road traffic flow is composed of motorized vehicles, non-vehicles and pedestrians. Non-vehicles and pedestrians share the same lane with motorized vehicles, and the feature of mixed traffic flow is very obvious. Thus the traffic model and control method under mixed traffic condition shall be further studied.

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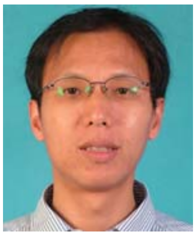
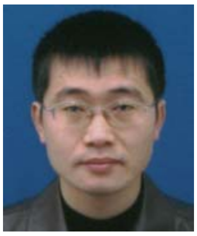


Xiangjie Kong received his Ph.D. degree from Zhejiang University, Hangzhou, China in 2009. Currently, he is an assistant professor in Dalian University of technology, Dalian, China. His current research interests include urban road traffic modeling and control technology, cyber physical systems and complex networks.



Guojiang Shen received his Ph.D. degree from Zhejiang University, Hangzhou, China in 2004. Currently, he is an associate professor in Zhejiang University, Hangzhou, China. His current research interests include intelligent control theory and application, advanced control technology and application, urban road traffic modeling and control technology.

Feng Xia received his Ph.D. degrees from Zhejiang University, China, in 2006. He is currently an associate professor in Dalian University of technology, Dalian, China. His research interests include cyber-physical systems, wireless sensor/actuator networks, real-time and embedded systems, ambient intelligence, and real-time control.

Chuang Lin received his Ph.D. degree from Harbin Institute of Technology, Harbin, China, in 2008. Currently, he is an assistant professor in Dalian University of Technology, Dalian, China. His current research interests include information hiding, multiple description coding, and information security etc.