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A two-level identification model for selecting the coordination strategy for the urban arterial road based on fuzzy logic

Haochen Sun, Feng Qiao* and Zhaoyan Wang

Faculty of Information and Control Engineering,
Shenyang Jianzhu University,
9 Hunnan East Road, Shenyang, China
Email: h.c.sun@qq.com
Email: fengqiao@sjzu.edu.cn
Email: 1479733309@qq.com
*Corresponding author

Lingzhong Guo

Department of Automatic Control and Systems Engineering,
University of Sheffield,
Sheffield, S1 3JD, UK
Email: l.guo@sheffield.ac.uk

Abstract: A novel model for identifying the traffic condition of urban arterial roadways is proposed in this paper to improve the operational efficiency and safety of the urban traffic arterial road system. During the identification process, fuzzy analytic hierarchy process and fuzzy integrated evaluation are employed to identify the traffic condition on the arterial road; according to the fuzzy logic scheme, a proper coordination strategy is then generated based on the resulting identification of each way of the artery. To verify the effectiveness of the proposed method, a numerical experiment is carried out by using the microscopic traffic simulation software VISSIM, where a traffic flow simulation system is generated according to the real-time traffic data. The comparison results show that the proposed model works well to fit with the actual operating condition of the arterial traffic and the proposed coordination strategy can provide a better performance for the traffic management.

Keywords: traffic condition identification; coordination strategy; urban arterial road; fuzzy logic.

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Biographical notes: Haochen Sun received his BEng in Electrical Engineering and Automation from the Beihua University, Jilin, China in 2016. He is currently a postgraduate student of the Shenyang Jianzhu University (SJZU), Shenyang, China, majoring in Systems Engineering. And he was appointed as the General Secretary of ISSPM 2018. His research interests include modelling and simulation, optimisation and decision making.

Feng Qiao received his BEng in Electrical Engineering and MSE in Systems Engineering from the Northeastern University, Shenyang, China in 1982 and 1987, respectively; and PhD in Intelligent Modelling and Control from the University of the West of England, Bristol, UK in 2005. During the period between 1987 and 2001, he worked at the Automation Research Institute of Metallurgical Industry, Beijing, China, as a Senior Engineer in Electrical and Computer Engineering. He is currently a Professor at Faculty of Information and Control Engineering, SJZU. His research interests include modelling and simulation, intelligent computation, control theory and application. Currently, he is acting as the Editor-in-Chief of the *International Journal of Simulation and Process Modelling*, a member of editorial board of the *International Journal of Modelling, Identification and Control*, and he serves on many international conferences as IPC and OPC members.

Zhaoyan Wang received her Bachelor's degree in Electrical Engineering and Automation from Shenyang Urban Construction University, Shenyang, China in 2016. Currently, she is studying in Faculty of Information and Control Engineering, SJZU, majoring in Control Science and Engineering for Master's degree. Her study direction is urban arterial traffic signal coordinated control.

Lingzhong Guo received his BSc and MSc degrees in China, and PhD degree from University of the West of England, UK. He is currently a Lecturer in the Department of Automatic Control and Systems Engineering of the University of Sheffield, UK. His research interests include modelling, analysis and control of nonlinear dynamical systems, multiscale modelling with application to biomedical systems, and computationally efficient modelling and simulation.

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1 Introduction

Efficient transportation is a key factor that influences the social and economic development. At present, the increasing number of vehicles on the roads is posing a great challenge to traffic supply, which makes the conflict between the traffic demand and traffic supply more intense and deteriorates the traffic system, such as traffic congestion. There are two main reasons for traffic congestion: the first, also the direct one, is that the traffic supply cannot meet the rapidly increasing demand; the second, the primary one, is the low level of traffic management, resulting in that the traffic flow cannot be dispersed timely and effectively. Therefore, to alleviate the traffic congestion problem, the main measure is to refurnish transportation infrastructure and expand the road network to increase the traffic capacity. Additionally, it is very important to improve the performance of traffic management and optimise the transportation systems and traffic management systems.

Virtually, it is impossible that the operation of each road in the traffic system is consistently at full loads and very often, there are just a few roads having congestion. However, because the drivers lack the real-time traffic information and effective traffic guidance, the traffic flow cannot be distributed well which aggravates the existing congestion, and wastes the limited road resource. Furthermore, in most severe scenario, the partial congestion may evolve into whole-network congestion, causing the overall transportation system collapse. Therefore, obtaining the real-time traffic condition and making an effective traffic management plan according to the traffic condition will have a great realistic significance and research value.

The main methods for identifying the traffic conditions can be categorised into two groups: traditional congestion identification (TCI) and automatic congestion identification (ACI) (Elhenawy et al., 2016a). Although TCI methods have many great advantages, it needs huge work load and is difficult to use. Over the past decades, many ACI algorithms have been developed (Elhenawy et al., 2016a, 2015; Elhenawy and Rakha, 2016; Jiang et al., 2010; Xiang, 2014; Bo et al., 2014; Herring et al., 2010). But all the methods of ACI have not been utilised to solve the identification of traffic conditions sufficiently, and the exiting methods cannot deal with the condition of unbalanced traffic volume.

In order to improve the performance of the existing identification models, in this paper, a fuzzy evaluation scheme is applied to identify the real-time condition of arterial roadways. First, a two-level fuzzy identification model is proposed, which contains a low level (evaluating the condition of each side of the road, respectively) and a high level (integrating the resulting evaluation from the low level). Second, during the process of identification, at the low level, fuzzy analytic hierarchy process (FAHP) and fuzzy integrated evaluation (FIE) are used to identify the condition of each way of the arterial road. At the high level, fuzzy logic is then applied to evaluate the integrated traffic condition of the whole two-way arterial roadway to make a proper decision to select a preferred coordination strategy. By using this model, the traffic condition can be identified effectively, and the coordination of arterial traffic system can be accomplished more reasonably and sufficiently.

The remaining part of this paper is organised as follows. In Section 2, the background knowledge used in this paper is presented. In Section 3, based on the basic knowledge in Section 2, the time-varying traffic condition of the urban arterial road is identified and evaluated. Then, the fuzzy rules for selecting the proper coordination optimisation strategy are listed in Section 4. And in Section 5, a numerical experiment for a three-intersection urban arterial roadway is simulated and analysed with MATLAB and VISSIM. The conclusions are drawn in Section 6.

2 Background knowledge

2.1 Analysis of traffic congestion

Currently, the quantification of traffic congestion has not been well defined in many countries, the level of service (LoS) presented in HCM2000 is preferred to evaluate the traffic congestion. When a road is carrying traffic in equal volume to its capacity, within ideal traffic conditions, the operating conditions of the road become deteriorated, with the slowing down of vehicle speed and the increasing of delays and stops. The term LoS of urban roads is defined as a qualitative measure for describing the operation conditions of traffic flow based on many evaluation indexes, such as the average travel speed. And, for example, the classification of LoS for the urban road based on the average travel speed is given in Table 1 (National Research Council, 2010).

Table 1 Vehicle LoS thresholds of the urban street

Street class	*I*	*II*	*III*	*IV*
LoS	*Average travel speed (km/h)*			
A	> 72	> 59	> 50	> 41
B	56–72	46–59	39–50	32–41
C	40–56	33–46	28–39	23–32
D	32–40	26–33	22–28	18–23
E	26–32	21–26	17–22	14–18
F	⩽ 26	⩽ 21	⩽ 17	⩽ 14

2.2 Fuzzy logic

Fuzzy logic was proposed to deal with uncertainty, which has been developed into a wide-ranging collection of concepts and techniques for dealing with complex problems which are suitable to be analysed by classical methods based on probability theory and bivalent logic. Ahead of the following research, some basic and necessary definitions are listed, referring to the correlational research work (Cornelis et al., 2004).

Definition 2.1

If X is a set of objects denoted generically by x, then a ***fuzzy set*** *A in X is a set of ordered pairs:*

$$A = \{(x, m) | x \in X\}$$

where the function $m = \mu_A(x)$ *is called the* ***membership function*** *of x in fuzzy set A, and* $m{:}X \rightarrow [0, 1]$*; and the reference set X is called* ***universe of discourse****.*

Note that the range of the membership function is a subset of the non-negative real numbers whose supremum is finite, and the elements with a zero degree of membership are normally not enumerated.

Definition 2.2

For a finite fuzzy set A, the ***cardinality*** *|A| is defined as*

$$|A| = \sum_{x \in X} \mu_A(x) \tag{1}$$

and then the ***relative cardinality*** *of A is expressed as*

$$\|A\| = |A| / |x| \tag{2}$$

which can be interpreted as the fraction of the elements of X being in fuzzy set A.

Definition 2.3

Assuming A and B are fuzzy sets that A, B $\subseteq x$*, and x is any element in the universe X, then the common definition of the fuzzy set operations are as follows:*

a *The membership function* $\mu_C(x)$ *of the* ***intersection*** $C = A \cap B$ *is pointwise defined by*

$$\mu_C(x) = \min\{\mu_A(x), \mu_B(x)\}, x \in X \tag{3}$$

b *The membership function* $\mu_D(x)$ *of the* ***union*** $D = A \cup B$ *is pointwise defined by*

$$\mu_D(x) = \max\{\mu_A(x), \mu_B(x)\}, x \in X \tag{4}$$

c *The membership function of the* ***complement*** *of a normalised fuzzy set A,* $\mu_{\neg A}(x)$ *is defined by*

$$\mu_{\neg A}(x) = 1 - \mu_A(x), x \in X \tag{5}$$

2.3 Fuzzy integrated evaluation

The FIE is one of the major methods for evaluating the objective affected by multiple factors, so the FIE is also called multi-objective decision. The procedure of FIE are shown as follows (Herring et al., 2010):

Step 1 Establish the factor set $U = \{u_1, u_2, \ldots, u_n\}$, and the judge set $V = \{v_1, v_2, \ldots, v_n\}$.

The factor set is made up by the factors which have an effect on the evaluation objectives. And the judge set is the set of all the possible judge results.

Step 2 Estimate the normalised priority weight set $W = \{w_1, w_2, \ldots, w_n\}$.

In general, each single factor has a different effect on the objectives, some effects are significant, while some are weak. So, it is necessary that weighting each factor to display the different degree of importance.

Step 3 Evaluate each of the factors considered and get the evaluation matrix R.

In this step, the factors are judged one by one. Assuming the i^{th} factor is denoted as u_i, and the membership value of the factor v_i to the j^{th} element v_j in set V is given by r_{ij}. Then, the resulting judgement of u_i can be represented by a fuzzy subset $r_i = (r_{i1}, r_{i2}, \ldots, r_{in})$. And combining the r_is, we can obtain the evaluation matrix R, which is written by

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix} \tag{6}$$

Step 4 Select an integrated evaluation model and obtain the integrated evaluation set B.

With the obtaining of the weight set W and the evaluation matrix R, the integrated evaluation set B is easy to get as $B = W * R = (b_1, b_2, \ldots, b_n)$, where the operator * means the generalised fuzzy operation, so, for further, the element in set B can be written as

$$b_i = \left(w_1 \hat{*} r_{ij}\right) \check{*} \ldots \check{*} \left(w_n \hat{*} r_{nj}\right), j = 1, 2, \ldots, n \tag{7}$$

where the operator $\hat{*}$ represents the *generalised fuzzy intersection*, and $\check{*}$ means the *generalised fuzzy union*.

Step 5 Calculate the whole fuzzy evaluation set (normalised set) $\tilde{B}$.

After Step 4, the evaluation set B is obtained, then normalise it, and get a new fuzzy evaluation set $\tilde{B}$ which is represented as $\tilde{B} = (\tilde{b}_1, \tilde{b}_2, \ldots, \tilde{b}_n)$ and the sum of each element $\sum_{j=1}^{n} \tilde{b}_j = 1$.

2.4 *Fuzzy analytic hierarchy process*

In Step 2, it is important and necessary to determine the weight set W. There are many ways to deal with the estimation of the weight set. In this paper, FAHP is employed (Aydin and Kahraman, 2011). First, some basic definitions and theorems are necessary to be listed.

Definition 2.4

Assuming a fuzzy matrix $R = (r_{ij})_{n\times n}$, *if it meets the condition* $r_{ij} + r_{ji} = 1$ *and* $i, j = 1, 2, \ldots, n$, *the matrix R is called* ***fuzzy complementary matrix.***

Definition 2.5

Assuming a fuzzy matrix $R = (r_{ij})_{n\times n}$, *if it meets the condition* $r_{ij} = r_{ik} - r_{jk} + 0.5$ *and i, j, k are arbitrary, the matrix R is called* ***fuzzy consistent matrix***.

Theorem 2.1 (Aydin and Kahraman, 2011).

Suppose a matrix $\overline{A} = (\overline{a}_{ij})_{n\times n}$ is a fuzzy consistent matrix, and $W = (w_1, w_2, \ldots, w_n)^T$ *is the corresponding weight vector, which meets the constrains that (1)* $0 \le w_i \le 1$, ($i = 1, 2, \ldots. n$, and (2) $\sum_{i=1}^{n} w_i = 1$, then there must be a positive number α makes the expression $\overline{a}_{ij} = \alpha(w_i - w_j) + 0.5$, ($i, j = 1, 2, \ldots, n$) come into existence. Additionally, the weight w_i is obtained by $w_i = \frac{1}{n} - \frac{1}{2\alpha} + \frac{1}{n\alpha}\sum_{k=1}^{n} a_{ik}$, ($i = 1, 2, \ldots, n$), where $\alpha \ge \frac{n-1}{2}$.

The procedure of FAHP is shown as follows:

Step 1 Analyse the interrelationship between every two factors and structure the hierarchy.

At the beginning of the process, the decision maker determines the goal, criteria and alternatives in a hierarchical form. A complete hierarchy has to give the whole details of information on the established structure, so that there should not be any lack of fact about the practical problem.

Step 2 Make fuzzy complementary matrix.

In this step, suppose that there are n alternatives making a set $A = \{A_1, A_2, \ldots, A_n\}$, and the fuzzy complementary matrix that represents the relative importance between every two alternatives is expressed as

$$A = \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \ldots & a_{nn} \end{bmatrix} \tag{8}$$

where $0 \le a_{ij} \le 1$, $a_{ii} = 0.5$, $aij + a_{ji} = 1$.

In the expression above, a_{ij} represents the membership value of the importance of A_i corresponding to A_j. The greater a_{ij} is, the more important A_i will be than A_j.

Step 3 Convert the fuzzy complementary matrix to the fuzzy consistent matrix.

During the process of decision making, the construction of the fuzzy matrix is not always consistent, due to the complexity of unsolved problems and the incompleteness of the cognition via decision makers, who use experimental data, perception, background, knowledge, etc. to make decisions. So, here, we have several methods to transform the structured matrix A to the fuzzy consistent matrix $\overline{A}$ (Zhang et al., 2014; Liu et al., 2010).

Step 4 Calculate the priority weight vector according to the fuzzy consistent matrix.

With the obtained consistent matrix $\overline{A} = (\overline{a}_{ij})_{n\times n}$, and the corresponding weight vector $W = (w_1, w_2, \ldots, w_n)^T$, according to Theorem 2.1, the weight vector can be worked out. While as for the fuzzy complementary matrix, the least square method is presented to get the weight vector, which actually means that the obtainment of the weight vector W is transformed into solving a constrained programming problem:

$$\begin{cases} \min \quad z = \sum_{i=1}^{n}\sum_{j=1}^{n}\left[0.5 + \alpha\left(w_i - w_j\right) - r_{ij}\right]^2 \\ \text{s.t.} \qquad \sum_{i=1}^{n} w_i = 1, w_i \ge 0, (1 \le i \le n) \end{cases} \tag{9}$$

By using the Lagrangian multiplier λ, the constrained programming problem can be converted into an unconstrained programming problem:

$$\min L(w, \lambda) = \sum_{i=1}^{n} \sum_{j=1}^{n} \left[0.5 + \alpha \left(w_i - w_j \right) - r_{ij} \right]^2 + 2\lambda \left(\sum_{i=1}^{n} w_i - 1 \right) \tag{10}$$

Then, take the partial derivative of $L(w, \lambda)$ with respect to $w_i (i = 1, 2, \dots. N)$, and make the partial derivative $\frac{\partial L(w, L)}{\partial w_i} = 0$, so an equation set consists of $(n + 1)$ equations is obtained, they are expressed as

$$\begin{cases} \sum_{k=1}^{n} \left[2\alpha^2 \left(w_i - w_j \right) + \alpha \left(r_{ji} - r_{ij} \right) \right] + \lambda = 0 \\ w_1 + w_2 + \ldots + w_n = 1 \end{cases} \tag{11}$$

where $i = 1, 2, \dots, n$.

According to the obtained equation set, it is easy to get the weight vector $W = (w_1, w_2, \dots, w_n)^T$.

2.5 *Some frequently-used indexes for identifying the urban arterial roadway condition*

The selection of evaluation indexes to identify the urban road condition makes a strong effect on the resulting evaluation. In this paper, the degree of saturation, average travel speed, average travel delay, average traffic density, and time occupancy are employed.

1 Degree of saturation

$$s = 60\bar{q} / (C \times n) \tag{12}$$

where $\bar{q}$ is the number of average vehicle during T minutes on the road; T means the duration of observation time; C is the traffic capacity of the road; and n represents the number of lanes.

2 Average travel speed

$$\bar{v} = Q \Big/ \sum_{i=1}^{T} \left(q_i \big/ v_{\int} \right) \tag{13}$$

where Q is the total number of passing vehicles during T minutes; q_i is the number of passing vehicles in the i^{th} minute; and v_i is the average vehicle speed in the i^{th} minute.

3 Average travel delay

$$d = \max\left\{ 3{,}600 \left(1/\bar{v} - 1/v_0 \right), 0 \right\} \tag{14}$$

where v_0 is the free travel speed.

4 Average traffic density

$$\rho = N / (l \times n) \tag{15}$$

where N is the number of vehicles on the road; and l is the length of the road.

5 Time occupancy

$$[= \left(\sum t_i / T \right) \times 100\% \tag{16}$$

where t_i represents the time spend on the i^{th} vehicle passing through an observation point.

3 Traffic condition identification of urban arterial roadway based on fuzzy logic

3.1 *Establish the factor set and judge set*

According to the evaluation indexes introduced in Subsection 2.5, the factor set for identifying the traffic condition of the urban arterial roadway is expressed as $U = \{s, \bar{v}, d, \rho, p\}$; and the judge set is expressed as $V = \{v_1, v_2, v_3\}$, where v_1, v_2, and v_3 represent free, normal, and congestion, respectively.

3.2 *Construct the membership function of each evaluation index*

It is important to select the proper membership function to build the traffic condition identification model. Triangular membership functions, trapezoidal membership functions, Gaussian membership functions are all the commonly used membership functions (Adil et al., 2015). In this paper, the trapezoidal membership function is used. And in order to make the evaluation process clearer, the standards of the evaluation indexes are listed in Table 2 (National Research Council, 2010).

Table 2 The standard of evaluation indexes for identifying the traffic conditions in urban arterial roadways

Level	*1*	*2*	*3*	*4*	*5*
Degree of saturation	0~0.56	0.56~0.79	0.79~0.94	0.94~1	>1
Average travel speed (km/h)	>35	25~35	18~25	13~18	<13
Average travel delay (s/km)	0~2.3	2.3~5.9	5.9~13.3	13.3~39	>39
Traffic density (veh/(l*km))	0~12	12~44	44~70	70~90	>90
Time occupancy (%)	0~5	5~15	15~25	25~30	>30

From Table 2, we can construct the membership functions of the selected evaluation indexes and obtain the corresponding diagrams, respectively.

1 The membership function of the degree of saturation

$$MF_{11}=\begin{cases} 1 & x\le 0.56 \\ \dfrac{1}{0.23}(0.79-x) & 0.56<x\le 0.79 \\ 0 & x>0.79 \end{cases}$$

$$MF_{12}=\begin{cases} 0 & x\le 0.56 \\ \dfrac{1}{0.23}(x-0.56) & 0.56<x\le 0.79 \\ 1 & 0.79<x\le 0.94 \\ \dfrac{1}{0.06}(1-x) & 0.94<x\le 1 \\ 0 & x>1 \end{cases}$$

$$MF_{13}=\begin{cases} 0 & x\le 0.94 \\ \dfrac{1}{0.06}(x-0.94) & 0.94<x\le 1 \\ 1 & x>1 \end{cases}$$

2 The membership function of the average travel speed

$$MF_{21}=\begin{cases} 1 & x\le 13 \\ \dfrac{1}{5}(18-x) & 13<x\le 18 \\ 0 & x>18 \end{cases}$$

$$MF_{22}=\begin{cases} 0 & x\le 13 \\ \dfrac{1}{5}(x-13) & 13<x\le 18 \\ 1 & 18<x\le 25 \\ \dfrac{1}{10}(35-x) & 25<x\le 35 \\ 0 & x>35 \end{cases}$$

$$MF_{23}=\begin{cases} 0 & x\le 25 \\ \dfrac{1}{10}(x-25) & 25<x\le 35 \\ 1 & x>35 \end{cases}$$

3 The membership function of the average travel delay

$$MF_{31}=\begin{cases} 1 & x\le 2.3 \\ \dfrac{1}{3.6}(5.9-x) & 2.3<x\le 5.9 \\ 0 & x>5.9 \end{cases}$$

$$MF_{32}=\begin{cases} 0 & x\le 2.3 \\ \dfrac{1}{3.6}(x-2.3) & 2.3<x\le 5.9 \\ 1 & 5.9<x\le 13.3 \\ \dfrac{1}{25.7}(39-x) & 13.3<x\le 39 \\ 0 & x>39 \end{cases}$$

$$MF_{33}=\begin{cases} 0 & x\le 13.3 \\ \dfrac{1}{25.7}(x-13.3) & 13.3<x\le 39 \\ 1 & x>39 \end{cases}$$

4 The membership function of the average traffic density

$$MF_{41}=\begin{cases} 1 & x\le 12 \\ \dfrac{1}{32}(44-x) & 12<x\le 44 \\ 0 & x>44 \end{cases}$$

$$MF_{42}=\begin{cases} 0 & x\le 12 \\ \dfrac{1}{32}(x-45) & 12<x\le 44 \\ 1 & 44<x\le 70 \\ \dfrac{1}{20}(90-x) & 70<x\le 90 \\ 0 & x>90 \end{cases}$$

$$MF_{43}=\begin{cases} 0 & x\le 70 \\ \dfrac{1}{20}(x-70) & 70<x\le 90 \\ 1 & x>90 \end{cases}$$

5 The membership function of the time occupancy

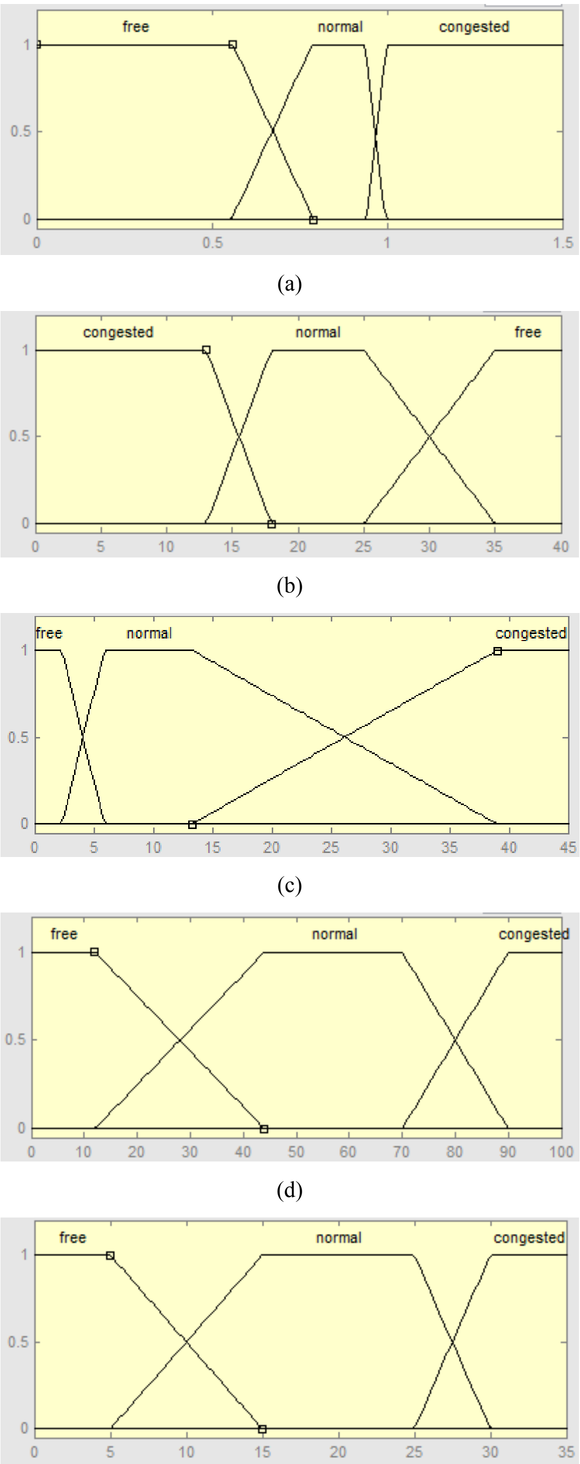
$$MF_{51}=\begin{cases} 1 & x\le 5 \\ \dfrac{1}{10}(15-x) & 5<x\le 15 \\ 0 & x>15 \end{cases}$$

$$MF_{52}=\begin{cases} 0 & x\le 5 \\ \dfrac{1}{10}(x-5) & 5<x\le 15 \\ 1 & 15<x\le 25 \\ \dfrac{1}{5}(30-x) & 25<x\le 30 \\ 0 & x>30 \end{cases}$$

$$MF_{53}=\begin{cases} 0 & x\le 25 \\ \dfrac{1}{5}(x-25) & 25<x\le 30 \\ 1 & x>30 \end{cases}$$

The diagrams of the membership functions are shown in Figure 1.

Figure 1 The diagrams of the membership functions of different variables, (a) the membership function of the degree of saturation (b) the membership function of the average travel speed (c) the membership function of the average travel delay (d) the membership function of the average traffic density (see online version for colours)



(a)

(b)

(c)

(d)

(e)

3.3 *Obtain the weight of each evaluation index*

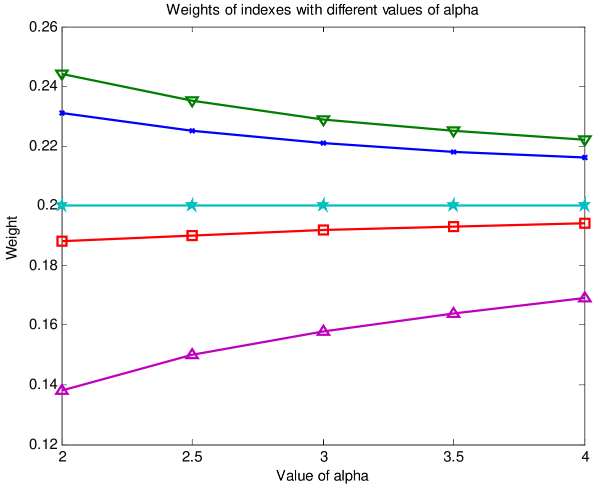
To obtain the weight of evaluation indexes, it is necessary to make the fuzzy complementary matrix A_1 and fuzzy consistent matrix A_1, based on traffic experts' experience.

$$A_1 = \begin{array}{cc} \begin{array}{c} s \\ \bar{v} \\ d \\ \rho \\ p \end{array} & \begin{bmatrix} 0.5 & 0.4 & 0.7 & 0.6 & 0.8 \\ 0.6 & 0.5 & 0.7 & 0.6 & 0.8 \\ 0.3 & 0.3 & 0.5 & 0.5 & 0.7 \\ 0.4 & 0.4 & 0.5 & 0.5 & 0.7 \\ 0.2 & 0.2 & 0.3 & 0.3 & 0.5 \end{bmatrix} \end{array}$$

$$A_2 = \begin{array}{cc} \begin{array}{c} s \\[2ex] \bar{v} \\[2ex] d \\[2ex] \rho \\[2ex] p \end{array} & \begin{bmatrix} \frac{1}{2} & \frac{19}{40} & \frac{47}{80} & \frac{9}{16} & \frac{11}{16} \\[1ex] \frac{21}{40} & \frac{1}{2} & \frac{49}{80} & \frac{47}{80} & \frac{57}{80} \\[1ex] \frac{33}{80} & \frac{31}{80} & \frac{1}{2} & \frac{19}{40} & \frac{3}{5} \\[1ex] \frac{7}{16} & \frac{33}{80} & \frac{21}{40} & \frac{1}{2} & \frac{5}{8} \\[1ex] \frac{5}{16} & \frac{23}{80} & \frac{8}{5} & \frac{3}{8} & \frac{1}{2} \end{bmatrix} \end{array}$$

According to Theorem 2.1, the weight of each index can be obtained. In this paper, the different values of α are selected to compute the corresponding weight vector, and then considering the needs of decision making and the knowledge of experts, according to Theorem 2.1, α should be greater than 2, to make a set of comparison, it is selected that $\alpha = 2$, $\alpha = 2.5$, $\alpha = 3$, $\alpha = 3.5$, $\alpha = 4$ are taken into account. The results are shown in Table 3 and Figure 2.

Figure 2 The weights of indexes with different values of α (see online version for colours)



From Figure 2, it can be observed that the degree of dispersion of weights become less and less with the growing of the value of α, and as the $\alpha = 2$, the weight vector is more suitable for the reality. So, in this paper, the weight vector with $\alpha = 2$ is the preferred one.

Table 3 Weight of each index

Index	*Corresponding weights with different values of α*					*Weight*
	$\alpha = 2$	$\alpha = 2.5$	$\alpha = 3$	$\alpha = 3.5$	$\alpha = 4$	
Degree of saturation	0.231	0.225	0.221	0.218	0.216	0.231
Average travel speed	0.244	0.235	0.229	0.225	0.222	0.244
Average travel delay	0.188	0.190	0.192	0.193	0.194	0.188
Average traffic density	0.200	0.200	0.200	0.200	0.200	0.200
Time occupancy	0.138	0.150	0.158	0.164	0.169	0.138

3.4 *Get the evaluation matrix and FIE*

To get the evaluation matrix R, one can make a single-factor evaluation for the five evaluation indexes, respectively.

$$R = \begin{bmatrix} s_1 & s_2 & s_3 \\ \overline{v}_1 & \overline{v}_2 & \overline{v}_3 \\ d_1 & d_2 & d_3 \\ \rho_1 & \rho_2 & \rho_3 \\ p_1 & p_2 & p_3 \end{bmatrix} \tag{17}$$

where s_i, $\overline{v}_i$, d_i, ρ_i, p_i (i = 1, 2, 3) represent the values of memberships of the degree of saturation, average travel speed, average travel delay, average traffic density, and time occupancy corresponding to the elements in the judge set $V = \{v_1, v_2, v_3\}$, respectively.

Then, it is easy to obtain the FIE set B. The elements b_1, b_2 and b_3 mean the values of membership of the traffic conditions of the investigated road corresponding to the levels of evaluation v_1, v_2 and v_3, respectively. Use the weighted average model $M(°, +)$, which is more accurate than model $M(\wedge, \vee)$, and the resulting integrated evaluation set B is normalised directly. So, the FIE set B is expressed as

$$B = W \circ R = \left(w_1, w_2, w_3, w_4, w_5\right) \circ \begin{bmatrix} s_1 & s_2 & s_3 \\ \overline{v}_1 & \overline{v}_2 & \overline{v}_3 \\ d_1 & d_2 & d_3 \\ \rho_1 & \rho_2 & \rho_3 \\ p_1 & p_2 & p_3 \end{bmatrix} \tag{18}$$

3.5 *Evaluate the traffic condition of urban road*

According to the evaluation set B, compare the elements b_1, b_2, b_3 and select the greatest one b_i, therefore the final evaluation of the traffic condition of the urban road is v_i (corresponding to b_i) in set V.

4 State transformation between one-way and two-way green waves

As the traffic condition of the urban road is known, it can be selected the proper way (one-way or two-way green wave) to optimise the operation efficiency of the urban artery road based on fuzzy theory. The input factors are the traffic conditions of two ways, the output is the proper type of green wave that is suitable for the real-time traffic condition. The fuzzy logic rules are shown in Table 4. The *way1* and *way2*, as shown in Figure 3, represent the *westward way* and *eastward way*, respectively. The judgement result *twowayGW* means the coordination strategy that is suitable for the certain condition of the two-way green wave coordination optimisation. Similarly, *way2GW* and *way1GW* mean the coordination strategies that are preferred to implement on the coordination optimisation of arterial road green wave to the eastward way only and the westward way only, respectively.

Table 4 Fuzzy rules

Way2 *Way1*	*Free*	*Normal*	*Congested*
Free	twowayGW	way1GW	way1GW
Normal	way2GW	twowayGW	way1GW
Congested	way2GW	way2GW	twowayGW

5 Numerical simulation

In this numerical simulation, a three-intersection arterial urban road was considered as shown in Figure 3. According to Figure 3, three scenarios were taken into consideration: *peak period* (morning and afternoon/evening), and *off-peak period*. As it was morning, a number of vehicles moved on the westward way, and afternoon or evening, lots of vehicles moved on the eastward way. The details of the traffic flow are listed in Table 5. In Table 5, it should be noted that the observation time was not corresponding to the real time, it was just for making the numerical simulation simple, so the during of peak period and off-peak period were both equal to 1 hour. Then, based on the results obtained from the proposed method, the conditions of each way of the arterial roadway were identified as shown in Figure 4. And then, the microscopic simulation software – VISSIM was used to verify the proposed model, the results show that the proposed model can identify the real-time traffic condition suitably. Note that it was assumed that the proportions of left-turn, right-turn and straight traffic flow on each approach at each intersection were equal, respectively, that is, for instance, the proportions of left-turn vehicle flow on all approaches at all three intersections were equal.

Figure 3 Sketch map of a typical three-intersection arterial urban road

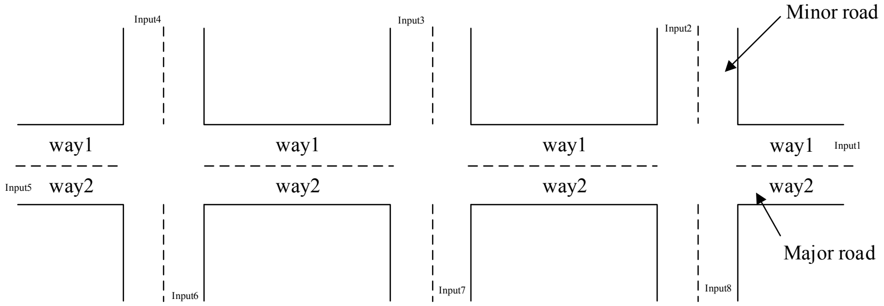
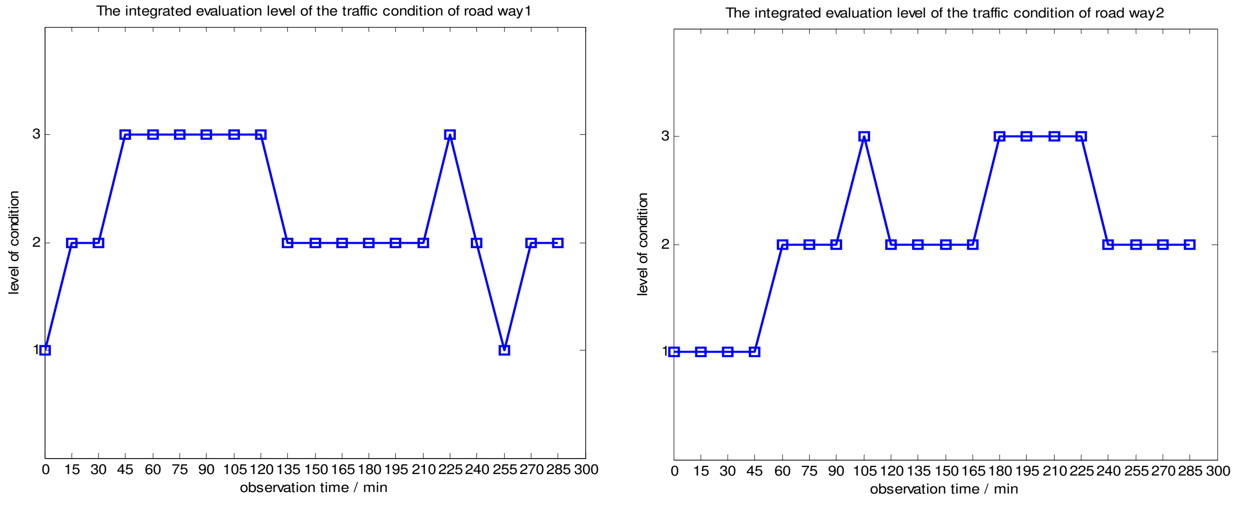


Table 5 The volume of traffic flow on each approaching in different observation time duration

Observation time	*The volume of traffic flow in each approaching (pcu/h)*							
	Input1	*Input2*	*Input3*	*Input4*	*Input5*	*Input6*	*Input7*	*Input8*
Off-peak period 1 (daybreak)	400	200	200	200	400	200	200	200
Peak period 1 (in the morning)	1,800	500	500	500	800	500	500	500
Off-peak period 2 (at noon)	1,000	400	400	400	1,200	400	400	400
Peak period 2 (in the evening)	8,000	500	500	500	1,800	500	500	500
Off-peak period 2 (late at night)	400	300	300	300	500	300	300	300

Figure 4 Traffic condition at different observation time for both roads, (a) the traffic condition of way1 at different observation time (b) the traffic condition of way2 at different observation time (see online version for colours)

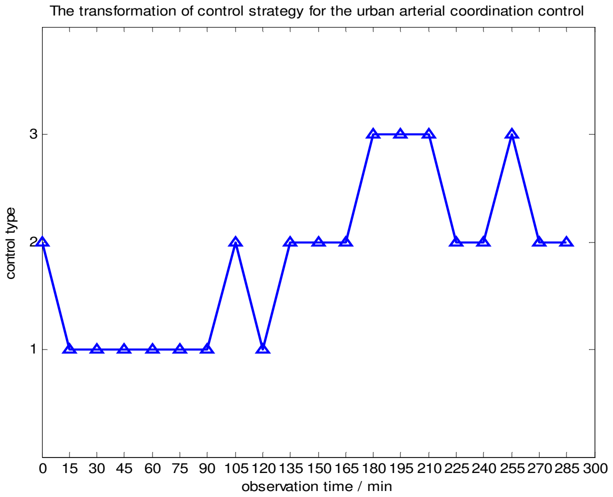


(a) (b)

As the resulting evaluations of traffic conditions of both two roads above were obtained, it is reasonable and easy to get the best arterial coordination plan to meet the actual real-time traffic condition. Based on the fuzzy logic and the proposed nine fuzzy rules, an integrated evaluation of the whole investigated urban arterial road in different observation time with different traffic volume were obtained, thus, the best coordination strategy was determined corresponding to the real-time traffic condition of the arterial road. Three coordination optimisation types were considered: 1, 2, and 3, which represent the green wave coordination implemented on road way1 only, on both two roads (way1 and way2), and on way2 only, respectively. The resulting selection of the arterial coordination strategy is pictured in Figure 5.

In Figure 5, it is clearly recognised that before the peak period in morning, the traffic condition of way1 was worse than that of way2, so the one-way green wave coordination strategy should be implemented on the road way1 to alleviate the traffic congestion, and during the peak period in afternoon or evening, the one-way green wave coordination strategy should be used on way2. And in the other off-peak period durations, it was preferred to employ the two-way green wave coordination strategy on the arterial road to make the traffic efficient.

Figure 5 The selection of optimisation strategies for urban arterial road at different time (see online version for colours)



6 Conclusions

In this paper, a two-level fuzzy identification model has been proposed to determine the best coordination strategy to make the traffic system more efficient. At the low level, five evaluation indexes have been taken into consideration, including the degree of saturation, the average travel speed, the average travel delay, the average traffic density, and the time occupancy. It has shown that based on the fuzzy evaluation scheme, by using the FIE method and FAHP, the real-time traffic condition of each way of the investigated urban arterial road can be identified. And at the high level, one can get the integrated evaluation of traffic condition of the whole urban arterial road based on fuzzy theory. Compared with the actual operation of the urban arterial road, the simulation in this study can meet the actual traffic condition, and the behaviours and features of the vehicle flow at peak period and off-peak period can be shown clearly. From the results, one can clearly know the general trend of the time-varying transformation of the traffic flow on the urban arterial road, which reflects the real condition. Thus, the traffic engineers and managers can compare, analyse and select the most suitable coordination plan for the certain condition. Using this model, transportation engineers can design and manage the urban road better and more reasonable, and the operation of the urban traffic system can be easier and more efficient.

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