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RESEARCH ARTICLE

Performance Evaluation of Bus Routing Scheme During Subway Construction Using Fuzzy Aggregation

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Abstract: To evaluate the layout adjustment scheme of bus line during subway construction, the method combining quantitative survey and fuzzy aggregation is used. One criterion is transit service level, which considered nonlinear coefficient, line length, transfer distance and average waiting time. Another criterion is traffic impact degree incorporating three factors: saturation degree on work-zone section, saturation degree at intersection, passenger volume. The fuzzy aggregation is based on these two criteria. The evaluation method is applied in Ningbo of China. *Via* quantitative survey, it is found that most of the factors with respect to these two criteria are degraded, when the bus routing scheme comes out during the construction of subway # 1. For instance, new layout such as bus line relocation and bus stop displacement increases traffic volume on some of the south-north links. Most of these links intersect with work-zone links on Zhongshan Road. However, when comparing the evaluated performance of bus line adjustment condition to the one of previous condition under subway construction stage, the gap is well within the acceptable limit. Therefore, the increased traffic may affect the traffic passing on some south-north roads, but will not hinder citizen's daily travel. These analysis and evaluation of bus routing scheme provide reference for the subway construction in other cities with respect to road traffic management.

Keywords: Bus routing scheme, Fuzzy aggregation, Performance evaluation, Subway construction.

1. INTRODUCTION

Subway travel is featured by large passenger volume, high speed, low pollution, excellent safety level and strong comfort, thus it is a perfect choice as public transport for big cities. Subway proposal was approved by the Ningbo Council in 2008 and started construction in 2009. Subway # 1 goes across the Ningbo core area along Zhongshan Road. Because of the subway construction, the traffic along Zhongshan Road and adjacent roads is mostly impacted. Survey shows that the average traffic saturation along Zhongshan Road in the rush hour is 0.9, which belongs to the congestion state. Moreover, it is shown that some bus passengers had a bad experience during their travel. Buses have the highest utilization rate of road resource among various travel modes in the city. Adjusting bus operation should be an important way to reduce the negative impacts during subway construction.

As shown in Fig. (1), influenced area of subway construction is mainly distributed along (1) east-west line named Daqing Bridge <-> West Gate <-> Tianyi Square <-> Jiangxia Bridge <-> Sakura Park, (2) north-south line named Cuibai Road, Jiefang Road, Yonggang Road, *etc.* During subway construction, a total of 101 bus lines are affected. Among them, 49 bus lines, 680 operating vehicles, 10 bus stops with each serving 10 bus lines along Zhongshan Road

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$$\bar{Y} = \sum_{i=1}^m (\bar{W}_i \otimes \bar{X}_i) / \sum_{i=1}^m \bar{W}_i \tag{1}$$

where, i represents the factor whose total number is m ($m=7$ in this paper). $\bar{X}_i = \{x_i, \mu_{\bar{X}_i}(x_i) | x_i \in X_i\}$ is a fuzzy number representing the value of factor i . $\bar{W}_i = \{w_i, \mu_{\bar{W}_i}(w_i) | w_i \in W_i\}$ is the normalized fuzzy weight of factor i , which determines its importance among all the factors. X_i and W_i are fuzzy sets of factor and weight respectively. $\mu_{\bar{X}_i}$ and $\mu_{\bar{W}_i}$ are the membership functions of factor and weight respectively, which are represented as triangular functions (shown as

Fig. (2) in this study. $\sum_{i=1}^m$ and \otimes are fuzzy operations using α -cut interval analysis.

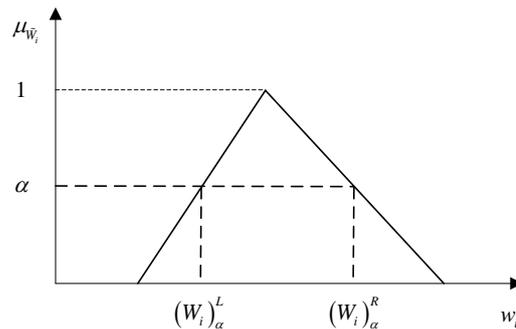


Fig. (2). Weight in terms of triangular fuzzy function.

The illustration of α -cut is shown in Fig. (2). The first step of fuzzy operation would help to understand the α -cut. The fuzzy operation in the computation of fuzzy weighted average is an extended algebraic interval operation. This operation can achieve the membership function $\mu_{\bar{Y}}$ with respect to fuzzy variable \bar{Y} , which is described in the following five steps [14].

(1) Discretize the complete range of the membership [0, 1] of the fuzzy numbers into the following finite number of n α -cuts, $\alpha_1, \dots, \alpha_n$, where an instance is shown in Fig. (2).

(2) For each α_j , using the following equations to find the corresponding interval for W_i in \bar{W} and X_i in \bar{X}_i . Denote the end-points of the intervals of \bar{W} and \bar{X}_i by $[(W_i)_{\alpha_j}^L, (W_i)_{\alpha_j}^R]$ and $[(X_i)_{\alpha_j}^L, (X_i)_{\alpha_j}^R]$, respectively.

$$W_i(\alpha_j) = \left[\min_{w_i} \{w_i \in W_i | \mu_{\bar{W}_i}(w_i) \geq \alpha_j\}, \max_{w_i} \{w_i \in W_i | \mu_{\bar{W}_i}(w_i) \geq \alpha_j\} \right] \tag{2a}$$

$$X_i(\alpha_j) = \left[\min_{x_i} \{x_i \in X_i | \mu_{\bar{X}_i}(x_i) \geq \alpha_j\}, \max_{x_i} \{x_i \in X_i | \mu_{\bar{X}_i}(x_i) \geq \alpha_j\} \right] \tag{2b}$$

(3) Construct the 2^{2m} distinct permutations of the $2m$ array $(\bar{W}_1, \dots, \bar{W}_m; \bar{X}_1, \dots, \bar{X}_m | \alpha_j)$ that involve just the interval end-points of the fuzzy number intervals.

(4) Compute $\bar{Y}_k(\alpha_j) = f(\bar{W}_1^k, \dots, \bar{W}_m^k; \bar{X}_1^k, \dots, \bar{X}_m^k | \alpha_j)$, where $(\bar{W}_1^k, \dots, \bar{W}_m^k; \bar{X}_1^k, \dots, \bar{X}_m^k | \alpha_j)$ is the k^{th} permutation of the 2^{2m} distinct permutations. Then the desired interval for $\bar{Y}(\alpha_j)$ is:

$$Y(\alpha_j) = \left[\min_k \bar{Y}_k(\alpha_j), \max_k \bar{Y}_k(\alpha_j) \right] \tag{3}$$

(5) Repeat step (2-4) for every α_j , compute $\mu_{\bar{Y}}$ using every $Y(\alpha_j)$ and an α -cut decomposition theorem, i.e., let

$$I_{\alpha_j}^{\bar{Y}} = \begin{cases} 1, & \forall \bar{Y} \in Y(\alpha_j) \\ 0, & \forall \bar{Y} \notin Y(\alpha_j) \end{cases} \tag{4a}$$

so that,

$$\mu_{\bar{Y}} = \sup_{\forall \alpha_j (j=1, \dots, m)} \alpha_j \cdot I_{\alpha_j}^{\bar{Y}} \tag{4b}$$

Since the output variables are expressed by fuzzy numbers, they should be defuzzified into a crisp number to be used as a certain level. Out of several defuzzification methods, we choose the center of gravity method due to its simplicity and ease of computation. The estimated performance is represented in Formula (5). Via comparing the bus operation performances before and after line adjustment, we can evaluate the effectiveness of bus routing scheme during road working.

$$COA(\bar{Y}) = \frac{\int \mu_{\bar{Y}}(y) \cdot y dy}{\int \mu_{\bar{Y}}(y) dy} \tag{5}$$

4. EVALUATION SYSTEM OF BUS ROUTING SCHEME

Evaluation of bus operation is mainly standing on the angle of transit service level and traffic impact degree. These two representative criteria can reflect the passenger satisfaction of transit operation and the driver satisfaction of traffic operation. The evaluation system is shown in Fig. (3), where seven factors were selected. These factors are chosen by two reasons: (1) These factors are quantitative, and can easily be detected. (2) The Ningbo government has investigated and found that these factors are considered the most important.

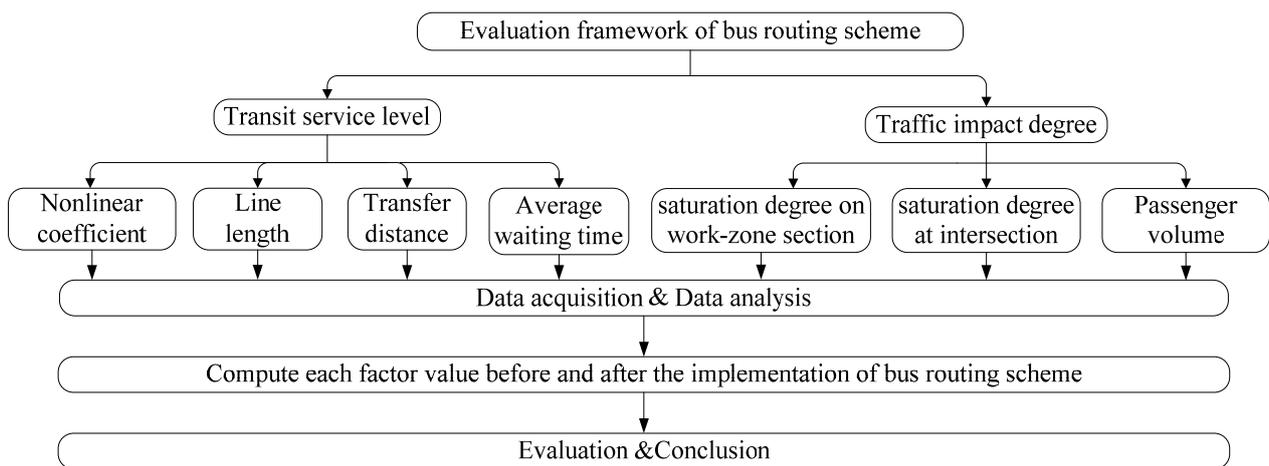


Fig. (3). Evaluation system of bus routing scheme.

4.1. Transit Service Level

4.1.1. Nonlinear Coefficient (h₁)

The nonlinear coefficient of bus line is the actual line length between first and last bus stop divided by straight-line distance. It is influenced by the indexes such as the shape of the urban road network, layout of urban land use. So we should better set the shortest line or a line closer to the shortest path as a bus line. The Code for Transport Planning on Urban Road (GB50220-95) (hereinafter referred to as the “Standards”) specified that the nonlinear coefficient [15] should satisfy $h_1 \leq [l/d]=1.4$ (d means the shortest path length). As Table 1 shows, the nonlinear coefficient increased after line adjustment, but most of the area's average nonlinear coefficient values are within the maximum nonlinear coefficient of 1.4.

Table 1. Average nonlinear coefficient before and after scheme implementation.

Section Name	# of changed lines	Previous	Implemented	Change rate (%)
West Ring Road—West Gate	7	1.12	1.51	34.82
Shifu Road—Tianyi Square	12	1.09	1.24	13.76

(Table 1) contd....

Section Name	# of changed lines	Previous	Implemented	Change rate (%)
Jiangxia Bridge-Sakura Park	12	1.25	1.37	9.60
Fuming Road-Century Avenue	9	1.19	1.28	7.56

For convenient evaluation, normalize the factor into a level index which is in the range [0, 1]. The function of level index and the factor can be shown in Formula (6). The membership functions of previous and implemented conditions are represented by μ_1^p and μ_1^i separately. The average of all the level indexes is used as a median value corresponding to maximum membership degree. The occurrence probabilities of minimum and maximum level indexes are used as the corresponding membership degrees. The triangular membership function is then constructed.

$$\begin{aligned}
 L_1 &= (1.6 - h_1) / 0.6, & 1 \leq h_1 \leq 1.6 \\
 \mu_1^p &= \begin{cases} 4.76L_1 - 2.57, & 0.54 \leq L_1 < 0.75 \\ -7.69L_1 + 6.77, & 0.75 \leq L_1 \leq 0.88 \end{cases} \\
 \mu_1^i &= \begin{cases} 3.13L_1 - 0.47, & 0.15 \leq L_1 < 0.47 \\ -7.69L_1 + 4.62, & 0.47 \leq L_1 \leq 0.6 \end{cases}
 \end{aligned} \tag{6}$$

4.1.2. Line Length (h_2)

During the period of construction, many bus lines in the influenced area are rerouted and thus their line lengths are extended. Fortunately, average bus line length in the area is within the maximum value 13 km, which is required by “Standards” (Table 2).

Table 2. Average line length before and after scheme implementation.

Section Name	# of changed lines	Previous	Implemented	Change rate (%)
West Ring Road—West Gate	7	10.35	12.12	17.10
Shifu Road—Tianyi Square	12	12.89	14.88	15.44
Jiangxia Bridge—Sakura Park	12	9.11	10.01	9.88
Fuming Road—Century Avenue	9	9.89	11.28	14.05

Level index and membership function are shown in the following.

$$\begin{aligned}
 L_2 &= (15 - h_2) / 6, & 9 \leq h_2 \leq 15 \\
 \mu_2^p &= \begin{cases} 2.08L_2 - 0.69, & 0.33 \leq L_2 < 0.81 \\ -5.26L_2 + 5.26, & 0.81 \leq L_2 \leq 1 \end{cases} \\
 \mu_2^i &= \begin{cases} 1.82L_2, & 0 \leq L_2 < 0.55 \\ -3.33L_2 + 2.83, & 0.55 \leq L_2 \leq 0.85 \end{cases}
 \end{aligned} \tag{7}$$

4.1.3. Transfer Distance (h_3)

Transfer distance is an important factor reflecting reasonability of bus line distribution and stop setting, which directly related to the convenience of bus riding. “Standard” specifies that: transfer distance for the same direction should be less than 50 m, and for opposite direction should be less than 100 m; even in the case of intersection and grade separation, transfer distance should not be longer than 150 m, and must be less than 200 m. According to the previous scheme, transfer distance in the current scheme has increased. Fortunately, most of the transfer distances are within the range which is allowed in “Standard” [16, 17] (Table 3).

Table 3. Comparison list of average transfer distance.

Stop Name	Previous	Implemented	Change rate (%)
West Ring	61.4	83.9	36.64
Da Qingqiao	68.9	83.3	20.90
West Gate	72.4	85.7	18.37
Shifu	70.9	113.3	59.80
Jiangxia Bridge	65.8	73.3	11.40
Zhangbin Bridge	59.1	71.2	20.47

(Table 3) contd....

Stop Name	Previous	Implemented	Change rate (%)
Sakura Park	58.8	111.5	89.63
Jiangdong School	66.9	80.4	20.18

Level index and membership function are shown in the following.

4.1.4. Average Waiting Time (h_3)

The average waiting time is important for evaluating transit service level. It is generally believed that passengers can accept 5 ~ 10 minutes to wait a bus. If the waiting time is more than 10 minutes, passengers will be suffering from anxiety; if the waiting time is more than 15 minutes, some passengers would consider using other travel mode. The survey covers 64 bus lines around Subway #1. The statistical distribution is shown in Fig. (4).

$$\begin{aligned}
 L_3 &= (114 - h_3) / 56, & 58 \leq h_3 \leq 114 \\
 \mu_3^p &= \begin{cases} 7.14L_3 - 5.21, & 0.73 \leq L_3 < 0.87 \\ -7.69L_3 + 7.69, & 0.87 \leq L_3 \leq 1 \end{cases} \\
 \mu_3^i &= \begin{cases} 2.13L_3, & 0 \leq L_3 < 0.47 \\ -3.23L_3 + 2.4, & 0.47 \leq L_3 \leq 0.78 \end{cases}
 \end{aligned} \tag{8}$$

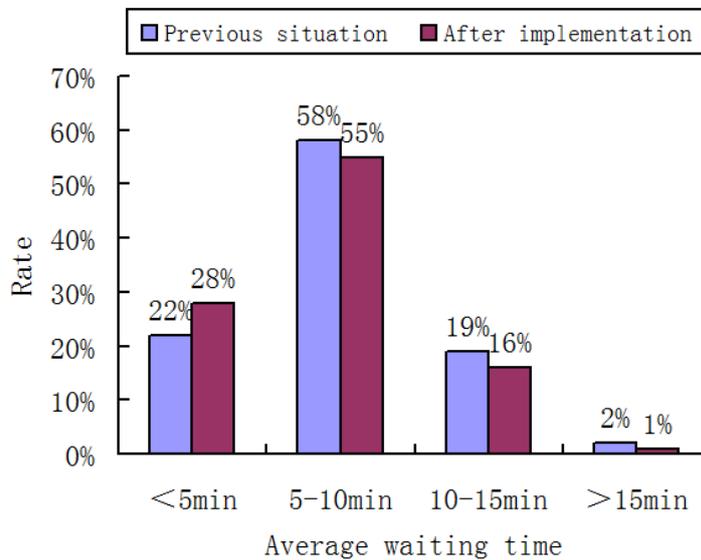


Fig. (4). Average waiting time distribution of surveyed lines.

From the figure above, we could find that most of the average waiting time is in 10 minutes around the influenced area after the implementation of the bus routing scheme. 28% of the passengers' average waiting time is less than 5 minutes, 56% of the average waiting time is 5 ~ 10 minutes.

Level index and membership function are shown in the following.

$$\begin{aligned}
 L_4 &= (30 - h_4) / 30, & 0 \leq h_4 \leq 30 \\
 \mu_4^p &= \begin{cases} 1.43L_4, & 0 \leq L_4 < 0.7 \\ -3.33L_4 + 3.33, & 0.7 \leq L_4 \leq 1 \end{cases} \\
 \mu_4^i &= \begin{cases} 1.25L_4, & 0 \leq L_4 < 0.8 \\ -5L_4 + 5, & 0.8 \leq L_4 \leq 1 \end{cases}
 \end{aligned} \tag{9}$$

In conclusion, the implementation of bus routing scheme has increased some factors of transit service level. Fortunately, the increasing degree is within the range of "Standard" specification. Therefore, the bus routing scheme can roughly satisfy the need of residents' bus travel.

4.2. Traffic Impact Degree

4.2.1. Saturation Degree on Work-zone Section (h_s)

For the construction period of Subway # 1, Zhongshan Road is the main affected zone. However, traffic of Zhongshan Road has improved *via* the proposed bus routing scheme. It was partly because the implementation of bus priority measures affected the travel mode of residents. Some residents reduce the use frequency of private car use; and alternately, they take the bus to work. The other reason of the improvement in saturation lies in that most buses take the use of south-north road around Zhongshan Road to detour.

By the survey statistics (Table 4), the average flow along the subway line in the rush hour is 2670 pcu/h before the implementation of the bus routing scheme. Moreover, the traffic saturation is 0.71 on average, with 40% of them higher than 0.9 and 80% of them higher than 0.7. After the scheme implementation, the average flow along the subway line in the rush hour is 2609 pcu/h. The average traffic saturation is 0.65, with 20% of them higher than 0.9 and 50% of them higher than 0.7.

Table 4. Traffic flow and saturation degree along Zhongshan Road in the morning rush hour.

Surveyed road	Rush-hour flow (pcu/h)		Capacity (pcu/h)	Saturation degree (V/C)	
	Previous situation	After implementation		Previous situation	After implementation
Liyuan Road~West Ring Road	2493	2316	3409	0.73	0.68
Cuibai Road~Mayuan Road	2464	2307	3563	0.69	0.65
Wangjing Road~Xiaowen Street	3442	3248	3563	0.97	0.91
Xiaowen Street~Zhenming Road	3737	3606	3563	1.05	1.01
Jiefang Road~Kaiming Street	2884	2767	3175	0.91	0.87
Kaiming Street~Qizha Street	2912	2837	3175	0.92	0.89
Jiangdong Road~Shuguang Road	2356	2249	3303	0.71	0.68
North Caihong Road~North Yonggang Road	2673	2503	3466	0.77	0.72
North Yonggang Road~Zhongxing Road	2434	2301	3413	0.71	0.67
Fuming Road~Canghai Road	1574	1308	5472	0.29	0.24
Average value	2670	2514	3996	0.71	0.64

Level index and membership function are shown in the following.

The three groups of these data show that the previous and current traffic states in Zhongshan Road are relatively stable; because the change of bus line and stops has increased the transit use on the one hand, and decreased the traffic saturation degree correspondingly on the other hand.

$$\begin{aligned}
 L_s &= (1.2 - h_s) / 1.2, & 0 \leq h_s \leq 1.2 \\
 \mu_s^p &= \begin{cases} 4L_s - 0.44, & 0.11 \leq L_s < 0.36 \\ -2.56L_s + 1.92, & 0.36 \leq L_s \leq 0.75 \end{cases} \\
 \mu_s^i &= \begin{cases} 4.17L_s - 0.67, & 0.16 \leq L_s < 0.4 \\ -2.38L_s + 1.95, & 0.4 \leq L_s \leq 0.82 \end{cases}
 \end{aligned} \tag{10}$$

4.2.2. Saturation Degree at Intersection (h_i)

Bus line updating has directly influenced traffic flow of south-north roads which crosses Zhongshan Road. Before the implementation of the bus routing scheme, the average flow and saturation degree along these south-north roads in the rush hour are 1698 pcu/h and 0.44 respectively. Moreover, 3% of traffic saturation is higher than 0.9 and 18% higher than 0.7. After the implementation of the bus routing scheme, the average flow and saturation degree along these south-north roads in the rush hour are 1735 pcu/h and 0.45 respectively. Meanwhile, 6% of traffic saturation is higher than 0.9 and 18% higher than 0.7.

The urban center owns a number of south-north links. The data show that the state of traffic flow in these links is relatively stable. Although measures such as bus line updating and bus stop shift could make the bus traffic and car traffic increase, the rise margin is low and won't have too much effect on people's daily travel. Meanwhile, the private cars are effectively restrained because of the transit service level increasing.

Level index and membership function are shown in the following.

$$\begin{aligned}
 L_6 &= (1.2 - h_6) / 1.2, & 0 \leq h_6 \leq 1.2 \\
 \mu_6^i = \mu_6^p &= \begin{cases} 1.82L_6 - 0.15, & 0.08 \leq L_6 < 0.63 \\ 5L_6 + 4.15, & 0.63 \leq L_6 \leq 0.83 \end{cases}
 \end{aligned} \tag{11}$$

4.2.3. Passenger Volume (h_7)

Currently, Public Transport occupies more than 20% of the residents' travel in Ningbo [18]. It is one of the main urban travel modes. The new bus routing scheme would inevitably cause serious impact on travel mode choice of neighboring residents along Zhongshan Road. We investigated the passenger volume at stops before and after the scheme implementation respectively.

The survey shows that the line adjustment and bus stop shift reduced passenger volume and the traffic burden of Zhongshan Road. Meanwhile, it increased the passenger volume along the north-south links crossing Zhongshan Road. The increased passenger volumes are caused by the increased by-pass buses. So traffic pressure along Zhongshan Road is reduced. Although the increased passenger may produce certain effect to north-south traffic, it would not cause too serious effect to the residents' daily travel.

Level index and membership function are shown in the following.

$$\begin{aligned}
 L_7 &= h_7 / 300, & 0 \leq h_7 \leq 300 \\
 \mu_7^p &= \begin{cases} 2.5L_7, & 0 \leq L_7 < 0.4 \\ -1.67L_7 + 1.67, & 0.4 \leq L_7 \leq 1 \end{cases} \\
 \mu_7^i &= \begin{cases} 1.37L_7, & 0 \leq L_7 < 0.73 \\ -3.7L_7 + 3.7, & 0.73 \leq L_7 \leq 1 \end{cases}
 \end{aligned} \tag{12}$$

5. EVALUATION RESULTS

In the evaluation, the weight is used to reflect the importance of the corresponding factor. The weight should be a fuzzy number, but we make it as a certain value for simplicity. We specify the 7 weights as [0.10,0.10, 0.10,0.15,0.10,0.10,0.30].

Before implementation, the evaluation result is 0.58. After implementation, the evaluation result is 0.55. Their gap is within 10%, which cannot influence the traffic state too much. Therefore, we judge the feasibility of the implementation of the bus routing scheme. In addition, if we let the weights of evaluation factors value within 20% of their original values, the performance gaps are all within 10% of their original values. It means the weight factor has little influence on the performance value. When we do a detailed analysis, we find the factors related to transit service have low values in the implemented scheme. It is the main reason why the evaluation result is lower than that of the previous condition. In the transit service criterion, average waiting time in the implemented condition is improved. The reason is that some buses take the use of south-north road around the subway constructed road to detour; and the travel reliability is improved. However, some waiting times for a few bus lines in the influenced area are long. It is easy to understand. When the bus number is not increased, lengthening the bus line inevitably leads to the extension of the average waiting time for passengers. Nonetheless, the results for the traffic impact criterion in the implemented scheme are better than those of the previous condition. It means the road saturation is improved and passenger volume is increased in the implemented scheme.

If each factor in our study is assigned its average value, the evaluation results are 0.59 and 0.61 before and after implementation respectively. They are different from the results of fuzzy aggregation. Compared with the performance evaluation with every index under the condition of certainty, our result is analyzed by considering each value of uncertain range. Thus, our method is more comprehensive and could be applied to the city where decisions should be made under the environment of uncertainty.

CONCLUSION

A series of measures such as rerouting bus lines and shifting bus stops are used to alleviate traffic congestion during subway construction. We extend quantitative survey to analyze the factor values before and after the implementation of the bus routing scheme from both passenger and car driver perspectives. We use fuzzy aggregation to evaluate the performances of these two situations. It is found that the feasibility of the implementation of the bus routing scheme can be guaranteed.

In order to improve the attractiveness of bus services and maximize the use of the existing resources during subway construction, some bus priority measures must be implemented, which can be as follows: (1) Set up bus-only lanes. Considering the road resources are limited during subway construction, we can let the use of this lane to be permitted for private cars in off-peak hours. This measure could avoid spending too much money and can maximize the use of the existing road. (2) Implement bus signal priority. We can adjust the signal cycle and set up bus-actuated signal to improve the bus operation efficiency during subway construction [19, 20]. In the future work, we would compare the traffic system performance before and after the implementation of these bus priority measures during subway construction.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

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