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Train Ride Comfort Evaluation Method Using Ensemble Fuzzy Reasoning and its Application

*Xiangyu Zeng, *Dewang Chen, Zan Hou*
State Key Laboratory of Rail Traffic Control and Safety
Beijing Jiaotong University
Beijing, China
11120319@bjtu.edu.cn; dwchen@bjtu.edu.cn; 09120300@bjtu.edu.cn

***Abstract*—This paper adopts acceleration rate to evaluate the train ride comfort. Three comfort evaluation models are developed by using fuzzy system theory and the parameters of fuzzy sets are determined according to the measured data. Furthermore, the outputs of the three models are integrated by an ensemble learning method to give a comprehensive evaluation index for the ride comfort. The measured data of the train operation control system in Beijing subway Yizhuang line are used to validate the models. Moreover, a field experiment is conducted, and the experiment results have a good consistency with this paper's methods. The results indicate that the three fuzzy models have good uniformity and the ensemble learning can enhance accuracy and robustness of the comfort evaluation.**

Keywords- acceleration rate; comfort; fuzzy system; ensemble learning

I. INTRODUCTION

With the development of rail transit and the improvement of people's living condition, high speed, heavy-load and safety are no longer the only modern railway traffic development goals [1]. People's requirement on train comfort is getting higher and higher, so ride comfort has become an important indexe of train control.

At present, international methods of evaluating comfort are various, including Sperling fited index, Diekeeman index, Janeway comfort factor and so forth [2]. Japanese scholar HaoMing suzuki considers some factors which produce physiological impact on human body such as seat shape, materials, interior air pressure, temperature, humidity, vibration , noise, air fresh degree, intensity of illumination, uses factor analysis and multiple regression calculation methods to classify and empower, as a comfort index. China does not have any uniform standard comfort evaluation now. Though the development experience of rail transportation abroad can be used as reference, the standards in different countries cannot be applied mechanically because national conditions and road conditions vary. Therefore, the study of train evaluation indexes in China is of great practical significance [3].

In the course of train operation, we can get real-time information on train speed and position which can provide basis for comfort evaluation. Acceleration and acceleration rate can both reflect the impulse of train[4]. Besides, acceleration rate can reflect the train's longitudinal impulse. Republic of China Railway Industry Standard TB/T2543-1995 provides that using the acceleration rate of train impulse to examine and assess the stable operation of passenger train driver's skills. The comfort perceptions vary depending on different persons, so it gives rise to uncertainty. Thus, fuzzy reasoning represents a suitable tool for enhancing the accuracy of the model. The ensemble learning can set different models' comfort indexes into unified comfort evaluation index, so the robustness is better. In this paper, Beijing subway Yizhuang line's data is analyzed. In the second section, we will introduce some information about Yizhuang line; the third section describes three models based on fuzzy reasoning system; in the fourth section, we apply three models to evaluate the train operation of comfort, and integrate a comprehensive index for comfort evaluation; section five mainly summarizes the work and prospects.

II. SUBWAY YIZHUANG LINE AND DATA DESCRIPTION

Beijing subway Yizhuang line connects the center of Beijing and Yizhuang Economic Development Zone, and the length of the line is 23.23 kilometers. It was officially opened on December 30, 2010 and the entire operation time is 33 minutes. The line signal system is China's first domestic model line, the performance indicators have reached international leading level, and it adopts the highest international level of security SIL4. Fig. 1 is the run route map of Yizhuang Line:

Figure 1. The run route map of Yizhuang Line

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In the automatic drive process of Beijing Subway Yizhuang Line Automatic Train, we can obtain online information of vehicle-mounted ATO operation through connection between debugging PC and serial output interface of automatic train driving system (ATO); large amounts of data provides the basis for analyzing ATO comfort indicators. According to the ATO traffic data, we can get a train acceleration rate. Fig. 2 is a journey of acceleration rate, from South Ciqu station to Ciqu station of the subway Yizhuang line.

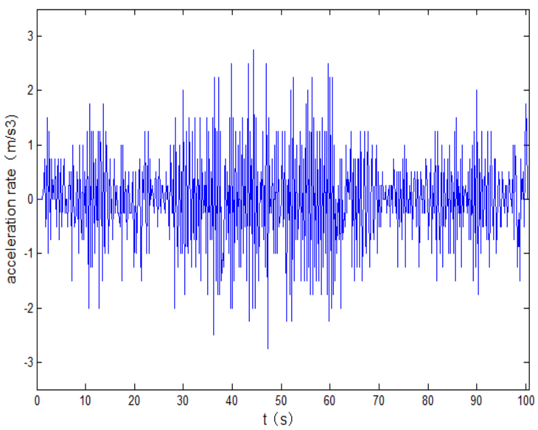

Figure 2. Acceleration rate J

III. FUZZY SETS FOR COMFORT EVALUATION MODEL

In the inertial reference system, when a train starts, the passengers will move backward; when the train suddenly stops, the passengers will pour forward, passengers will be caught unprepared and lose of balance, because the acceleration rate is too large [5]. If acceleration rate is greater than the scope of the human body can tolerate, passengers will feel uncomfortable. The degree of comfort is not perceived in the same way by different people. In 1965 professor Zadeh put forward "fuzzy set" theories, including "not compatible with principle" pointed out: the traditional system analysis technology can't handle humanities system in essence, which is great judged by human behavior, perception and emotional impact [6]. People's judgments of comfort also follows "fuzzy set" theory, according to membership functions[7]. We establish three evaluation models, using 1 represents the highest comfort, and 0 stands for the worst.

A. Triangle model

Expression is as follows:

$$f(x;a,b,c)=\begin{cases} 0, & x\le a \\ \dfrac{x-a}{b-a}, & a\le x\le b \\ \dfrac{c-x}{c-b}, & b\le x\le c \\ 0, & c\le x \end{cases} \tag{1}$$

Where a,b,c represent the three angles of a triangle abscissa. When acceleration rate is 0, the person can't feel the impulse, apparently comfort is 1. The study found that when acceleration rate is more than 3m/s^3, passengers would suffer a great influence on the vertical impulse, then comfort is set to 0 [8]. At this time, $a=-3, b=0, c=3$.

B. Gaussian model

Gaussian model is simple and has smoothness, with many fine attributes in probability and statistics [9]. Model expressed as follows:

$$f(x;\sigma,c)=e^{\frac{-(x-c)^2}{2\sigma^2}} \tag{2}$$

Gaussian model is completely determined by c and σ, where c represents the center of the model, σ determines the width of the model. Center of the model is 0, that is $c=0$; by $f(3;\sigma,0)=0$, it has $\sigma=0.8$.

C. Bell-shaped model

According to the actual situation of human perception, when acceleration rate is in a very small range (-0.5m/s^3~ 0.5m/s^3), people can't feel impact so the comfort of this range is very good. In order to reflect the physiological sense better, we apply Bell-shaped model to evaluate the comfort level. Model expressed as follows [10]:

$$f(x;a,b,c)=\frac{1}{1+\left|\frac{x-c}{a}\right|^{2b}} \tag{3}$$

Where a,c represent the width and center of the model, b is usually positive (if b is negative, the model will be an inverted bell-shaped) and can be used to adjust the rake of intersections. Center of the model is 0, that is $c=0$; both by $f(3;a,b,c)=0$ and $f(0.5;a,b,c)=1$, it has $a=1, b=4$.

IV. EVALUATE THE TRAIN RIDE COMFORT BY THE MODELS

Using triangular model we get four journey's comfort situation of Yizhuang Line, they are Xiaocun-Xiaohongmen, Jiugong-Yizhuang Brigde, Tongji South Road –Jinghai Road and South Ciqu–Ciqu.

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The mean value is defined as the entire distance's standard value of comfort, that is：

$$C = \frac{1}{n}\sum_{1}^{n} f(J) \tag{4}$$

Where f is one of the fuzzy membership functions mentioned in Section three and J is the accelerate rate between two stations.

Comfort among the four stations is as shown in table I;

Also with Gaussian model and Bell-shaped model, we get comfort of circumstances as table II and table III show;

In order to facilitate visual assessment of degree of comfort, we divided comfort into 5 levels, that with N = 1, 2, 3, 4, 5, as shown in Table IV;

The contrast of comfort of the three models is as table V;

TABLE I. TRIANGLE COMFORT TABLE

Stations	Xiaocun-Xiaohongmen	Jiugong-Yizhuang Brigde	Tongji South Road –Jinghai Road	South Ciqu - Ciqu
C	0.8231	0.7825	0.8438	0.7255

TABLE II. GAUSSIAN COMFORT TABLE

Stations	Xiaocun-Xiaohongmen	Jiugong-Yizhuang Brigde	Tongji South Road –Jinghai Road	South Ciqu - Ciqu
C	0.7651	0.7284	0.8041	0.6623

TABLE III. BELL-SHARPED COMFORT TABLE

Stations	Xiaocun-Xiaohongmen	Jiugong-Yizhuang Brigde	Tongji South Road –Jinghai Road	South Ciqu - Ciqu
C	0.8421	0.8131	0.8592	0.7336

TABLE IV. COMFORT CLASSIFICATION

C	>0.8	0.6-0.8	0.4-0.6	0.2-0.4	<0.2
N	1	2	3	4	5
Comfort Conditions	Very comfortable	Quite comfortable	Slightly uncomfortable	Less comfortable	Very uncomfortable

TABLE V. THE COMFORT CONTRAST OF THE 3 MODELS

Stations		Xiaocun-Xiaohongmen	Jiugong-Yizhuang Brigde	Tongji South Road –Jinghai Road	South Ciqu - Ciqu
C	***Triangle***	0.8231	0.7825	0.8438	0.7255

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	Gaussian	0.7651	0.7284	0.8041	0.6623
	Bell-shaped	0.8421	0.8131	0.8592	0.7336
N		1 or 2	1 or 2	1	2
Comfort Conditions		Very comfortable or Quite comfortable	Very comfortable or Quite comfortable	Very comfortable	Quite comfortable

Table V shows that: although the three models have different values, the overall trend is basically the same. For some cases, the comfort levels of the three evaluation models are different, such as in Xiaocun-Xiaohongmen stations, the comfort level of Gaussian model is different from the other two models. Then we need to use ensemble learning methods to reunification. Ensemble learning methods are as follows:

a) When three models come with the same level of comfort, then this comfort level is the ultimate comfort level.

b) When two models have the same level, while the other does not, according to the principle of the minority should subordinate to the majority, then comfort level with the same results of two models is the ultimate comfort level of value.

c) When the comfort levels of the three models are not same, take the middle value as the ultimate comfort level.

The ultimate comfort condition is as table VI.

The ensemble learning sets three models' comfort indexes into unified comfort evaluation index, so it is more convenient and practical in the actual scene.

In order to verify the reliability of this method, we conduct a field experiment. The specific method is: We have 8 experiment persons, through the questionnaire, we evaluate the comfort of a train according to these persons' own feelings. Similarly, we divided comfort into 5 levels, that with N = 1, 2, 3, 4, 5, as shown in Table IV.

The experiment statistics are as shown in Table VII and VIII (The brackets for the number of statistics):

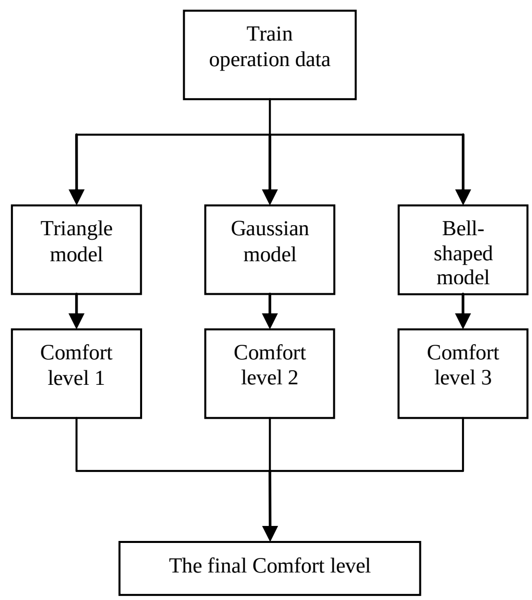

Figure 3. The ensemble learning process

TABLE VI. THE COMFORT CONDITION TABLE

Stations	Xiaocun-Xiaohongmen	Jiugong-Yizhuang Brigde	Tongji South Road – Jinghai Road	South Ciqu - Ciqu
N	1	2	1	2
Comfort Conditions	Very comfortable	Quite comfortable	Very comfortable	Quite comfortable

TABLE VII. THE STATISTICS OF UPLINK

Station	Songjiazhuang-Xiaocun	Xiaocun-Xiaohongmen	Xiaohongmen-Jiugong	Jiugong-Yizhuang Brigde	Yizhuang Bridge-Yizhuang Cultural Park	Yizhuang Cultural Park –Wanyuan Street

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N	1(34) 2(14)	1(46) 2(2)	1(10) 2(36) 3(2)	1(10) 2(38)	1(23) 2(25)	1(35) 2(13)
Station	Wanyuan Street-Rongjing East Street	Rongjing East Street -Rongchang East Street	Rongchang East Street –Tongji South Road	Tongji South Road –Jinghai Road	Jinghai Road - South Ciqu	South Ciqu - Ciqu
N	1(23) 2(25)	1(40) 2(8)	1(13) 2(35)	1(31) 1(17)	1(20) 2(28)	1(6) 2(29) 3(13)

TABLE VIII. THE STATISTICS OF DOWNLINK

Station	Ciqu - South Ciqu	South Ciqu - Jinghai Road	Jinghai Road - Tongji South Road	Tongji South Road - Rongchang East Street	Rongchang East Street - Rongchang East Street	Rongchang East Street - Wanyuan Street
N	1(17) 2(21)	1(35) 2(13)	1(42) 2(6)	1(30) 2(18)	1(27) 2(21)	1(26) 2(22)
Station	Wanyuan Street - Yizhuang Cultural Park	Yizhuang Cultural Park - Yizhuang Bridge	Yizhuang Bridge - Jiugong	Jiugong - Xiaohongmen	Xiaohongmen - Xiaocun	Xiaocun - Songjiazhuang
N	1(16) 2(32)	1(37) 2(11)	1(38) 2(10)	1(29) 2(19)	1(15) 2(33)	1(12) 2(36)

We divide the statistics into a few random events [11]:
Event F_1: passengers feel very comfortable
Event F_2: passengers feel quite comfortable
Event F_3: passengers feel slightly uncomfortable
Event F_4: passengers feel less comfortable
Event F_5: passengers feel very uncomfortable
Event C_1: actually very comfortable
Event C_2: actually quite comfortable
Event C_3: actually slightly uncomfortable
Event C_4: actually less comfortable
Event C_5: actually very uncomfortable

Although different person's perception about comfort are subjective fuzzy, passengers' feeling can objectively reflect the train's real comfort level. Assuming in the case of actually very comfortable, the passengers feel very comfortable with the probability a_1, the probability of feeling quite comfortable is b_1, and $a_1 = 0.8, b_1 = 0.2$, people usually do not feel the other cases, namely [12]:

$$P(F_1 / C_1) = a_1$$

$$P(F_2 / C_1) = b_1$$

Moreover, in the case of actually quite comfortable, the passengers feel very comfortable with the probability a_2, the probability of feeling quite comfortable is b_2, the probability of feeling Slightly uncomfortable is c_1, and $b_2 = 0.8, a_2 = c_1 = 0.1$, namely:

$$P(F_1 / C_2) = a_2$$

$$P(F_2 / C_2) = b_2$$

$$P(F_3 / C_2) = c_1$$

In the case of actually slightly uncomfortable, the passengers feel quite comfortable with the probability b_3, the probability of feeling Slightly uncomfortable is c_2, the probability of feeling Less comfortable is d_1, and $c_2 = 0.8, b_3 = d_1 = 0.1$, namely:

$$P(F_2 / C_3) = b_3$$

$$P(F_3 / C_3) = c_2$$

$$P(F_4 / C_3) = d_1$$

By the Bayesian formula, in the case of passengers' feeling is very comfortable, the probability of actually very comfortable is [13]:

$$P(C_1 / F_1) = \frac{P(F_1 / C_1) * P(C_1)}{P(F_1)}$$

The probability of quite comfortable is:

$$P(C_2 / F_1) = \frac{P(F_1 / C_2) * P(C_2)}{P(F_1)}$$

Similarly, in the case of passengers' feeling is quite comfortable, the probability of actually very comfortable is:

$$P(C_1 / F_2) = \frac{P(F_2 / C_1) * P(C_1)}{P(F_2)}$$

The probability of actually quite comfortable is:

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$$P(C_2/F_2)=\frac{P(F_2/C_2)*P(C_2)}{P(F_2)}$$

The probability of actually slightly uncomfortable is:

$$P(C_3/F_2)=\frac{P(F_2/C_3)*P(C_3)}{P(F_2)}$$

When the passengers' feeling have very comfortable and quite comfortable, and the number of very comfortable is m, quite comfortable is n.

The probability of actually very comfortable is:

$$P(C_1/F_1(m),F_2(n))=C_{m+n}^{m}\left[\frac{P(F_1/C_1)*P(C_1)}{P(F_1)}\right]^{m}*\left[\frac{P(F_2/C_1)*P(C_1)}{P(F_2)}\right]^{n}$$

The probability of actually quite comfortable is:

$$P(C_2/F_1(m),F_2(n))=C_{m+n}^{m}\left[\frac{P(F_1/C_2)*P(C_2)}{P(F_1)}\right]^{m}*\left[\frac{P(F_2/C_2)*P(C_2)}{P(F_2)}\right]^{n}$$

$$\frac{P(C_1/F_1(m),F_2(n))}{P(C_2/F_1(m),F_2(n))}=\frac{C_{m+n}^{m}\left[\frac{P(F_1/C_1)*P(C_1)}{P(F_1)}\right]^{m}*\left[\frac{P(F_2/C_1)*P(C_1)}{P(F_2)}\right]^{n}}{C_{m+n}^{m}\left[\frac{P(F_1/C_2)*P(C_2)}{P(F_1)}\right]^{m}*\left[\frac{P(F_2/C_2)*P(C_2)}{P(F_2)}\right]^{n}}$$

$$=\left[\frac{P(F_1/C_1)}{P(F_1/C_2)}\right]^{m}*\left[\frac{P(F_2/C_1)}{P(F_2/C_2)}\right]^{n}*\left[\frac{P(C_1)}{P(C_2)}\right]^{m+n}$$

$$=\left(\frac{a_1}{a_2}\right)^{m}*\left(\frac{b_1}{b_2}\right)^{n}*\left[\frac{P(C_1)}{P(C_2)}\right]^{m+n}$$

By $a_1=0.8, b_1=0.2$ and $b_2=0.8, a_2=0.1$,

$$\frac{P(C_1/F_1(m),F_2(n))}{P(C_2/F_1(m),F_2(n))}=\left(\frac{1}{2}\right)^{n-2m}\left[\frac{P(C_1)}{P(C_2)}\right]^{m+n}$$

According to the practical statistical results, Beijing Subway Yizhuang line's integral effect is good, we can think:

$$\frac{P(C_1)}{P(C_2)}\geq 1$$

Obviously, when $m>n/2$,

$$P(C_1/F_1(m),F_2(n))>P(C_2/F_1(m),F_2(n))$$

Now we think that is very comfortable or quite comfortable between the stations. When the passengers' feeling have very comfortable, quite comfortable and slightly uncomfortable. Normally, passengers wouldn't feel slightly uncomfortable in the actual very comfortable case, besides, they also wouldn't feel very comfortable in the actual slightly uncomfortable situation, namely:

$$P(F_1/C_3)=P(F_3/C_1)\approx 0$$

So $$P(C_3/F_1)=P(C_1/F_3)\approx 0$$

That means the probability of actually very comfortable and slightly uncomfortable is close to 0, so

$$P(C_1/F_1(m),F_2(n),F_3(q))=P(C_3/F_1(m),F_2(n),F_3(q))\approx 0$$

While the probability of actually quite comfortable is:

$$P(C_2/F_1(m),F_2(n),F_3(q))>0$$

Now the comfort situation is quite comfortable.

According to the above deduced that each station of the comfort level is:

TABLE IX. THE COMFORT LEVEL OF UPLINK

Station	Songjiazhuang-Xiaocun	Xiaocun-Xiaohongmen	Xiaohongmen-Jiugong	Jiugong-Yizhuang Brigde	Yizhuang Bridge-Yizhuang Cultural Park	Yizhuang Cultural Park –Wanyuan Street
N	1	1	2	2	1	1
Station	Wanyuan Street-Rongjing East Street	Rongjing East Street -Rongchang East Street	Rongchang East Street –Tongji South Road	Tongji South Road –Jinghai Road	Jinghai Road - South Ciqu	South Ciqu - Ciqu
N	1	1	2	1	1	2

TABLE X. THE COMFORT LEVEL OF DOWNLINK

Station	Ciqu - South Ciqu	South Ciqu - Jinghai Road	Jinghai Road - Tongji South Road	Tongji South Road - Rongchang East Street	Rongchang East Street - Rongjing East Street	Rongjing East Street - Wanyuan Street
N	2	1	1	1	1	1
Station	Wanyuan street - Yizhuang Cultural Park	Yizhuang Cultural Park - Yizhuang Bridge	Yizhuang Bridge - Jiugong	Jiugong - Xiaohongmen	Xiaohongmen - Xiaocun	Xiaocun - Songjiazhuang
N	2	1	1	1	2	2

Compare the Experimental results with the method of this paper, the result is as follows:

TABLE XI. THE COMFORT LEVELCONTRAST OF UPLINK

Station		Songjiazhuang-Xiaocun	Xiaocun-Xiaohongmen	Xiaohongmen-Jiugong	Jiugong-Yizhuang Brigde	Yizhuang Bridge-Yizhuang Cultural Park	Yizhuang Cultural Park – Wanyuan Street
N	experiment	1	1	2	2	1	1
	calculation	1	1	2	2	2	1
Station		Wanyuan Street-Rongjing East Street	Rongjing East Street - Rongchang East Street	Rongchang East Street –Tongji South Road	Tongji South Road –Jinghai Road	Jinghai Road - South Ciqu	South Ciqu - Ciqu
N	experiment	1	1	2	1	1	2
	calculation	2	1	2	1	1	2

TABLE XII. THE COMFORT LEVELCONTRAST OF DOWNLINK

Station		Ciqu - South Ciqu	South Ciqu - Jinghai Road	Jinghai Road - Tongji South Road	Tongji South Road - Rongchang East Street	Rongchang East Street - Rongjing East Street	Rongjing East Street - Wanyuan Street
N	experiment	2	1	1	1	1	1
	calculation	2	1	1	1	1	2
Station		Wanyuan Street - Yizhuang Cultural Park	Yizhuang Cultural Park - Yizhuang Bridge	Yizhuang Bridge - Jiugong	Jiugong - Xiaohongmen	Xiaohongmen - Xiaocun	Xiaocun - Songjiazhuang
N	experiment	2	1	1	1	2	2
	calculation	2	1	1	1	2	2

From the above table, we can see that the comfort level of experimental results and this paper's method is basically the same, in the uplink process, consistency is 83.33%, in the downlink process, consistency is 91.67%, and the overall consistency is 87.5%.It is proved that this method has a very good applicability.

V. CONCLUSION

This paper uses the data which is easily to obtain in the train operation, adopts acceleration rate to evaluate the train ride comfort. By using the fuzzy system theory, three comfort evaluation models are developed and the parameters of fuzzy sets are determined according to the measured data. Each model can well assess the comfort of the train and the three models have good uniformity. Furthermore, the outputs of the three models are integrated by an ensemble learning method to give a comprehensive evaluation index for the ride comfort. The measured data of the train operation control system in Beijing subway Yizhuang line are used to validate the models. Moreover, we conduct a field experiment, and the experiment result has a good consistency with this paper's methods.

The results show that the three fuzzy models have good uniformity and the ensemble learning can enhance accuracy and robustness of the comfort evaluation. We also have developed comfort evaluation software which has been used in the actual scene and achieved a good effect.

In the future research, we will carry out the model parameters' self-learning methods and better ensemble learning algorithm combining with passenger comfort investigation.

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