A Comprehensive Evaluation Model of Electric Bus Interior Acoustic Comfort and Its Application

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In this paper, 64 noise samples from eight electric buses are acquired and their corresponding acoustic comfort ranks (ACRs) are obtained by subjective evaluation tests with the method of rank score comparison (RSC). To overcome a current problem that the overall sound quality of an electric bus cannot be measured by single noise sample, a comprehensive evaluation model for interior acoustic comfort is established using fuzzy comprehensive evaluation and analytic hierarchy process (FCE-AHP). The model is based on a three-level evaluation index system with two conditions of air conditioning on and off, two observation positions of driver and rear seat, and two constant speeds of 30 km/h and 50 km/h. AHP is used to calculate the weight coefficient of each evaluation index. In addition, the ACRs of 64 noise samples are brought into the established model to gain overall sound quality order of eight electric buses. As a result, based on the subjective evaluation tests and calculation results, the application of the established comprehensive acoustic comfort model is ultimately realized.

1. INTRODUCTION

With the continuous improvement of people's health awareness, vehicle performance indicators not only include vibration reduction, low noise and energy saving, but also higher interior comfort. An electric bus has the advantages of energy saving and emission reduction, forming good economic and environmental benefits, and its interior radiated sound pressure level has met the limit requirement of the domestic standard of GB/T25982-2010. However, the conventional performance homogenization to the same class buses between different manufacturers is becoming serious, and what users most directly feel is the vehicle interior sound quality which describes human ears' subjective perception to noise, so an excellent interior acoustic environment with auditory comfort is one of the key factors affecting bus procurement.[1,2] It is an obvious fact that electric bus noise control has changed from noise reduction to sound quality, which has gradually formed an emerging research field and is of great practical significance.

Current research on vehicle sound quality mainly focuses on subjective and objective evaluations,[3–6] modeling and prediction,[7–11] optimization and control,[12–14] etc. One of the key basic links is subjective evaluation, it can more directly reflect vehicle sound quality, and commonly used evaluation methods primarily include simple order, rank score, paired comparison and semantic differential.[8,15–17] These evaluation methods usually score, compare and rank single or two noise samples, but cannot evaluate the whole vehicle sound quality. This is because, in practice, the optimized sound quality of noise samples is generally better than that before optimization, but there are also individual samples with potentially poor sound quality. Therefore, it is necessary to establish a comprehensive evaluation model of electric bus interior acoustic comfort considering multiple influencing factors.

At present, the comprehensive evaluation methods widely used include techniques for order preference by similarity to ideal solution (TOPSIS),[18] grey relational analysis (GRA),[19] principal component analysis (PCA) and fuzzy comprehensive evaluation (FCE).[15,20] The first two methods are used to solve the problem of multi-objective decision making, and PCA is used to transform multiple indicators into several comprehensive indicators using dimension reduction idea, while FCE is used to solve the problem of judgment ambiguity and uncertainty. Obviously, acoustic comfort is people's subjective judgment on vehicle noise, and its overall perception is affected by many factors such as working condition, observation point and speed. Therefore, the method of FCE is adopted in this case. As is known to all, FCE is used to transform qualitative evaluation into quantitative evaluation with the help of the

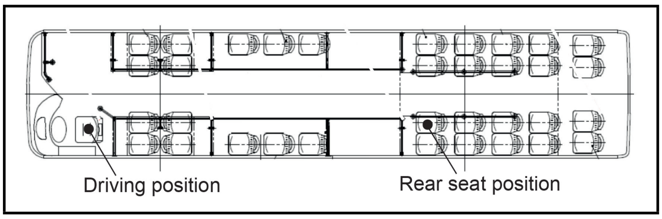

Figure 1. Distribution of two measuring points.

membership theory of fuzzy mathematics, that is, to make an overall evaluation of the things or objects restricted by various factors.[20–22] For example, He and Zhang proposed a diesel engine sound stimuli subjective comprehensive perception model based on improved analytic hierarchy process (AHP).[23] Wang and others investigated a fuzzy comprehensive evaluation of vehicle interior noise annoyance, which can provide a reference for synthetic judgment.[24] In our previous report,[16] the multi-level FCE has been effectively used to forklift annoyance modeling, while the comprehensive evaluation research on electric bus sound quality is still in blank.

Therefore, in this paper, the method combining FCE and AHP was applied to explore and establish a comprehensive evaluation model of electric bus interior acoustic comfort, to overcome the limitation of vehicle sound quality without being measured by the current mainstream subjective evaluation methods.

2. SUBJECTIVE EVALUATION TESTS

2.1. Noise Sample Acquisition

To research vehicle interior sound quality, eight different electric buses, randomly numbered A to H, were determined as noise test objects. According to permissible levels and test methods of bus internal noise (GB/T25982-2010), select on-air and off-air conditioning as two working conditions, the driving and rear seats are two measuring positions displayed in Fig. 1, and 30 km/h and 50 km/h are two constant speeds. During the test, the vehicles were run separately on a professional runway, and after the vehicle operated stably, a handheld portable Squadriga II binaural acquisition system and a head-mounted BHS II were utilized to collect interior noise signals. What needs to be added is that the signal acquisition system had eight channels with the main data acquisition information involved including sampling rate of 48 kHz, response frequency range of 20–20 kHz, sampling resolution of 24 bits and recording format of HDF.[8] Fig. 2 shows the test scene and instruments. Ultimately, a total of 64 noise samples were obtained.

2.2. Subjective Evaluation Tests

All noise samples were edited for a duration of 5 seconds because a prolonged subjective evaluation test can make people's hearing easily tired and irritable, causing inaccurate evaluation results.[16] A jury composed of engineers, drivers and acoustics experts with rich experience in the field of bus noise, was organized to participate in subjective evaluation tests. Since motor noise and transmission abnormal sound have both a medium and high spectrum, and their characteristic order is higher, close to the sensitive frequency band of human ear to noise,

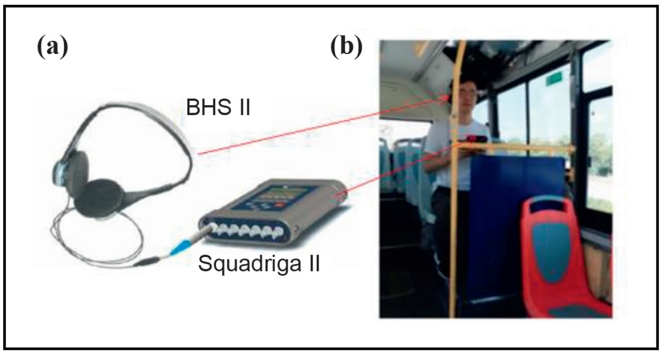

Figure 2. Test scene and acquisition instruments.

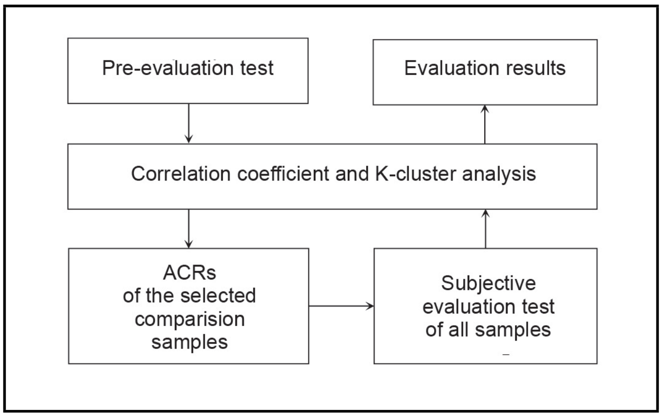

Figure 3. The evaluation process of RSC.

which was easy to cause auditory discomfort. Therefore, in this case, acoustic comfort was identified as a subjective evaluation index. In addition, because of the large number of noise samples to be evaluated, it was appropriate to adopt the rank score method and divide the acoustic comfort into ten standard ranks from 1 to 10, as described in Table 1.

The next work was to carry out the subjective evaluation tests using the proposed method of rank score comparison (RSC),[8,16] illustrated in Fig. 3. First, two of the 64 noise samples were randomly selected as comparison samples, and through the pre-evaluation test performed by the jury, their corresponding comfort ranks were calculated after data statistics of Spearman correlation coefficient and K-mean clustering analysis in SPSS 20.0 (Statistical Package for the Social Science). Secondly, the subjective evaluation test was carried out on 64 noise samples, and during this process, the evaluator could repeatedly play back the current sample to be evaluated and the two comparison samples and determine the sample's acoustic comfort rank (ACR) according to auditory perception until all evaluators completed the evaluation. Finally, the ACRs of 64 noise samples were obtained based on the above data statistical analysis and listed in Table 2. In this case, the correlation coefficients of subjective evaluation data are all greater than 0.7, indicating that the proposed method has high evaluation effectiveness, to overcome the deficiency of traditional rank score method in grasping grade difference.

Table 1. Classification and rank of acoustic comfort.

Poor comfort		Accepted comfort		Satisfied comfort		Good comfort		Excellent comfort	
1	2	3	4	5	6	7	8	9	10

Table 2. ACRs of 64 noise samples after subjective evaluation tests.

Order	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
ACR	5.17	3.33	6.42	5.33	4.67	3.25	2.58	3.42
Order	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
ACR	5.75	5.25	4.58	4.83	4.42	4.67	2.33	5.42
Order	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
ACR	3.17	7.25	2.92	7.08	4.92	2.08	5.33	3.84
Order	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
ACR	2.33	3.08	3.92	2.5	4.25	5.08	3.92	2.5
Order	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
ACR	2.42	4.25	1.75	7.5	5.08	1.42	2.58	6.75
Order	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**
ACR	6.92	2.5	4	5.17	2.33	3.84	4.83	3.08
Order	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**
ACR	7.67	4.12	3.67	2.58	2.67	4.25	5.58	1.92
Order	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**
ACR	5.33	3.58	2.58	5.32	4.33	4.84	1.58	3.13

3. COMPREHENSIVE COMFORT MODELING

3.1. Determination of Evaluation Indexes

The above subjective evaluation of sound quality is usually for noise samples under specific working conditions, position and speeds, and people give subjective judgment on each noise sample through auditory perception. However, the overall sound quality inside an electric bus is the comprehensive action result of these environmental conditions, leading to significant differences in people's auditory perception. In this section, the method of fuzzy comprehensive evaluation and analytic hierarchy process (FCE-AHP) was presented to establish an evaluation model of interior acoustic comfort for the whole electric bus under different working conditions, positions, and speeds.

FCE can be used to obtain the comprehensive evaluation value of sound quality in position or vehicle by weighting calculation. Therefore, based on the above test settings in Fig. 1, the fuzzy comprehensive evaluation index system of an electric bus can be defined and shown in Table 3.

3.2. Fuzzy Comprehensive Evaluation Process

(1) Determine evaluation index sets

Table 3 establishes the following evaluation indexes expressed by mathematical sets, including comprehensive index U, two first-level evaluation indexes $U = \{U_1, U_2\}$, four second-level evaluation indexes $U_1 = \{U_{11}, U_{12}\}$, $U_2 = \{U_{21}, U_{22}\}$ and eight third-level evaluation indexes $U_{11} = \{u_{111}, u_{112}\}$, $U_{12} = \{u_{121}, u_{122}\}$, $U_{21} = \{u_{211}, u_{212}\}$, $U_{22} = \{u_{221}, u_{222}\}$. It should be noted that the acoustic comfort ranks of all noise samples obtained through the subjective evaluation tests were the third-level evaluation indexes.

(2) Establish weight sets

AHP was chosen to determine the weights due to its ability to divide the factors in a complex problem into relevant ordered hierarchies, and it was an effective method to combine quantitative and qualitative analysis.[16,24] According to the fuzzy comprehensive evaluation index system in Table 3, the weight sets of the first-level, second-level and third-level evaluation indexes were respectively described as $\boldsymbol{w_1} = [a_1, a_2]^T, \boldsymbol{w_2} = [b_1, b_2]^T, \boldsymbol{w_3} = [c_1, c_2]^T$. To obtain these index weights, judgment matrices can be constructed by the commonly used method of 1–9 ratio scale, as shown in Table 4.

In the subjective evaluation test of vehicle sound quality, professional engineers and experts with certain acoustic knowledge and many years of experience in the field of electric bus noise were invited to consult and investigate, and judgment matrices were constructed based on questionnaire results.

As for a judgment matrix $\boldsymbol{A}$, where a_{ij} represents the relative importance ratio of factor i to factor j, i.e $\boldsymbol{A} = (a_{ij})_{n\times m} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} (i, j = 1, 2, \ldots, n)$.

The following mathematical equation is to describe the relationship between judgment matrix $\boldsymbol{A}$, maximum eigenvalue $\lambda_{\max}$ and corresponding eigenvector $\boldsymbol{w}$.

$$\boldsymbol{A}\boldsymbol{w} = \lambda_{\max}\boldsymbol{w}. \quad (1)$$

The steps to determine the relative weight by the sum-product method (SPM) are given as follows:

1. Do normalization processing of each column elements in the matrix $\boldsymbol{A}$.

$$b_{ij} = a_{ij} / \sum_{i=1}^{n} a_{ij}. \quad (2)$$

2. Add each column elements of the normalized judgment matrix by rows.

$$\overline{w_i} = \sum_{j=1}^{n} b_{ij}. \quad (3)$$

3. Normalize the obtained sum vector, namely, the weight vector is obtained.

$$w_i = \overline{w_i} / \sum_{i=1}^{n} \overline{w_i}, \quad \boldsymbol{w} = (w_1, w_2, \ldots, w_n)^T. \quad (4)$$

4. Calculate the maximum eigenvalue of the judgment matrix.

$$\lambda_{max} = \frac{1}{n} = \sum_{i=1}^{n} \frac{(\boldsymbol{A}\boldsymbol{w})_i}{w_i}. \quad (5)$$

To make the weight coefficient accurately reflect the objective reality, consistency inspection was needed

Table 3. Definition of comprehensive evaluation index for electric bus interior sound quality.

Comprehensive index	First-level index	Second-level index	Third-level index
Overall vehicle: U	On-air conditioning:	Driving position: U_{11}	Speed (30): u_{111}, u_{112}
	U_1	Rear seat position: U_{12}	Speed (50): u_{121}, u_{122}
	Off-air conditioning:	Driving position:U_{21}	Speed (30): u_{211}, u_{212}
	U_2	Rear seat position: U_{22}	Speed 50): u_{221}, u_{222}

Table 4. Explanation of judgment matrix scale.

Scale	Meaning	Scale	Meaning
1	a_i is of the same importance as a_j	3	a_i is slightly more important than a_j
5	a_i is obviously more important than a_j	7	a_i is strongly more important than a_j
9	a_i is extremely more important than a_j	2,4,6,8	Adjacent intermediate values

Table 5. Average random consistency index.

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

to control the deviation within an allowable range, and the inspection method was based on the relationship between random index RI and matrix order n described in Table 5.

The following formulas are presented to calculate the consistency index CI and the consistency ratio CR, which are expressed as:

$$CI = (\lambda_{max} - n)/(n - 1), \quad (6)$$

$$CR = CI/RI. \quad (7)$$

When $CR < 0.1$ or $\lambda_{max} = n, CI = 0$, it was considered that the consistency of the judgment matrix was acceptable; otherwise, appropriate adjustments need to be made to achieve a satisfactory consistency.

(3) Comprehensive comfort modeling

As mentioned above, the third-level evaluation index was the ACRs of all noise samples obtained through subjective evaluation tests. When the subjective evaluation data and the corresponding index weights have been obtained, the comprehensive second-level evaluation indexes at observation positions can be calculated as:

$$U_{ij} = \sum_{k=1}^{2} U_{ijk} \cdot c_k. \quad (8)$$

Based on the second-level comfort ranks and their weights , obtain the comprehensive first-level evaluation indexes of the working conditions, which is expressed as:

$$U_i = \sum_{j=1}^{2} U_{ij} \cdot b_j. \quad (9)$$

Through the above first-level evaluation indexes and the calculated corresponding weights, the final comprehensive evaluation index, namely an overall vehicle acoustic comfort, can be concluded as follows:

$$U = \sum_{i=1}^{2} U_i \cdot a_i. \quad (10)$$

4. CALCULATION RESULT

Through the FCE-AHP, a comprehensive acoustic comfort model based on three-level evaluation index can be established. When the subjective evaluation test results are introduced into the comprehensive evaluation model, the whole acoustic comfort of each electric bus is obtained successively, so as to compare the sound quality between different electric buses. The ACRs of 64 noise samples in Table 2 are described by mathematical sets and listed in Table 6.

Through the consultation and investigation of engineers and experts from NVH department, it is agreed that: the driver's physical and mental health needs higher vehicle sound quality, so the driving position is the most important; secondly, the influences of noise generated by high speed and on-air conditioning are obviously higher than that of low speed and off-air conditioning. In combination with the 1–9 ratio scale method in Table 4, the judgment matrices of first-level, second-level and third-level evaluation indexes were constructed based on the questionnaire results, and their weight coefficients were calculated by Eqs. (1) to (5). All consistency tests with Eqs. (6) and (7) are satisfactory and their results are shown in Tables 7 to 9, respectively.

The subjective evaluation results in Table 6 and index weights in Table 9 were substituted into Eq. (8) to calculate the second-level comprehensive acoustic comfort ranks, as shown in Table 10.

Taking the comfort data of Table 10 and the second-level evaluation index weights in Table 8 into the Eq. (9) obtains the first-level comprehensive comfort ranks of working conditions, namely: $U_A = \{6.97, 3.66\}, U_B = \{4.91, 4.11\}, U_C = \{3.42, 3.73\}, U_D = \{5.18, 4.86\}, U_E = \{4.41, 3.72\}, U_F = \{4.07, 4.66\}, U_G = \{3.46, 2.75\}, U_H = \{4.35, 3\}$. And then, the comprehensive comfort ranks of the first-level evaluation index and theirs weights in Table 7 were brought into Eq. (10) to acquire the overall vehicle comprehensive comfort of eight electric buses. The calculated results are listed as follows: 5.87. 4.65, 3.47, 5.07, 4.18, 4.26, 3.22 and 3.9. In conclusion, the order of the whole electric bus acoustic comfort is: $A > D > B > F > E > H > C > G$, and it can be seen that the overall sound quality of A bus is the best, D bus is the second, and G bus is the worst.

5. CONCLUSIONS AND FUTURE WORK

Electric buses have been widely used, and the product competition in the industry is becoming increasingly severe. Vehi-

Table 6. ACRs corresponding to noise samples of each electric bus.

A	$U_{11}=\{7.67,7.25\},U_{12}=\{5.75,5.08\},U_{21}=\{5.17,2.5\},U_{22}=\{4.42,4.92\}$
B	$U_{11}=\{5.17,3.92\},U_{12}=\{7.5,7.08\},U_{21}=\{3.84,3.42\},U_{22}=\{5.08,6.92\}$
C	$U_{11}=\{3.84,2.92\},U_{12}=\{5.25,3.08\},U_{21}=\{5.25,3.08\},U_{22}=\{3.67,3.33\}$
D	$U_{11}=\{3.92,5.58\},U_{12}=\{6.75,5.33\},U_{21}=\{4.84,4.83\},U_{22}=\{4.25,5.33\}$
E	$U_{11}=\{6.42,4.25\},U_{12}=\{2.33,2.08\},U_{21}=\{3.58,4.58\},U_{22}=\{1.75,1.58\}$
F	$U_{11}=\{5.32,4\},U_{12}=\{2.58,2.58\},U_{21}=\{4.67,5.42\},U_{22}=\{3.12,2.33\}$
G	$U_{11}=\{5.33,2.42\},U_{12}=\{2.5,4.33\},U_{21}=\{3.17,2.58\},U_{22}=\{2.58,2.67\}$
H	$U_{11}=\{4.67,4.83\},U_{12}=\{3.25,2.33\},U_{21}=\{1.42,4.12\},U_{22}=\{2.5,1.92\}$

Table 7. Judgment matrix and weight of the first-level evaluation index.

Scale	On-air conditioning	Off-air conditioning
On-air conditioning	1	2
Off-air conditioning	1/2	1
Weight	0.667	0.333
Consistency test	$\lambda_{max}=2=n$	

Table 8. Judgment matrix and weight of the second-level evaluation index.

Scale	Driving position	Rear seat position
Driving position	1	4
Rear seat position	1/4	1
Weight	0.8	0.2
Consistency test	$\lambda_{max}=2=n$	

Table 9. Judgment matrix and weight of the third-level evaluation index.

Scale	Speed (30 km/h)	Speed (50 km/h)
Speed (30 km/h)	1	1/2
Speed (50 km/h)	2	1
Weight	0.333	0.667
Consistency test	$\lambda_{max}=2=n$	

Table 10. omprehensive acoustics comfort of the second-level evaluation index.

Vehicle	Comprehensive acoustic comfort
A	$U_1=\{7.39,5.3\},U_2=\{3.39,4.75\}$
B	$U_1=\{4.34,7.22\},U_2=\{3.56,6.31\}$
C	$U_1=\{3.23,3.8\},U_2=\{3.8,3.44\}$
D	$U_1=\{5.03,5.8\},U_2=\{4.83,4.97\}$
E	$U_1=\{4.97,2.16\},U_2=\{4.25,1.64\}$
F	$U_1=\{4.44,2.58\},U_2=\{5.17,2.6\}$
G	$U_1=\{3.39,3.72\},U_2=\{2.78,2.64\}$
H	$U_1=\{4.78,2.64\},U_2=\{3.22,2.11\}$

cle interior sound quality is the most direct subjective feeling for passengers and users, which is one of the key indicators affecting the product macro quality, and thus establishing an overall sound quality evaluation model is helpful to measure the vehicle performance with a comprehensive consideration of various influencing factors.

In this paper, according to the standard noise measurement method of an electric bus, the three-level evaluation index system was established and the comprehensive vehicle interior acoustic comfort model was proposed using FCE. First, the subjective ACRs of 64 noise samples from eight electric buses were obtained by RSC. In addition, the judgment matrices corresponding to three evaluation indexes were constructed through the questionnaire survey, and AHP was adopted to get their index weights, so as to obtain and compare the whole sound quality of electric buses. The integrated acoustic comfort model provides a key technical support in the future for sound quality optimization and standard formulation of electric buses.

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