Sound Quality Prediction of Fuel Cell Vehicles Based on Regression Analysis

Zeyu Liu¹, Hai Liu¹, Yanyi Zhang ², Dong Hao², Xiuxiu Sun¹,³, Xiang Ji¹

¹ Tianjin Key Laboratory of Power Transmission and Safety Technology for New Energy Vehicles, School of Mechanical Engineering, Hebei University of Technology, Beichen District, Tianjin 300130, China

² China Automotive Technology and Research Center Co.Ltd, 68. East Xianfeng Road. Dongli District, Tianjin 300300, China

Corresponding Author: Xiuxiu Sun. Email: 2019042@hebut.edu.cn

Abstract. The typical fuel cell vehicle(FCV) was taken as the research object. The noise test of the FCV was carried out in the environment of the semi-anechoic room of the vehicle. The noise samples in the vehicle were collected under the condition of constant speed, which was intercepted and processed with equal time. Noise was subjectively evaluated using a pairwise comparison method. The objective evaluation parameters suitable for evaluating the sound quality of FCV were selected. The objective evaluation parameters were calculated and solved. According to the subjective and objective evaluation results of sound quality, run multiple linear regression analysis to quantitatively solve the correlation between the subjective and objective evaluation results. MAPE results showed that the accuracy of the multiple linear regression prediction model was low, in order to further improve the accuracy of the prediction model of the sound quality of FCVs, The GA-BP neural network prediction model was used to establish the evaluation prediction model between the subjective and objective evaluation results. The weight of the influence of objective parameters on the subjective evaluation results was calculated. The MAPE calculation results showed that the neural network model was more suitable for the establishment of FCV sound quality prediction According to the model, A-weighting and roughness were the most influential to the subjective evaluation results. The two algorithms had the same results.

1. Introduction

Recent discussions on climate change caused by global warming and carbon dioxide emissions have also brought public support for zero-emission vehicles. FCV are seen as the future vision of the automotive industry to replace gasoline engines [1]. The vehicle interior noise is one of the important factors affecting passenger comfort, hearing damage and the ability to identify various sound signals in the vehicle [2]. FCV are different from traditional vehicle noise sources and are unevenly distributed. The noise is small and very irritating.

Therefore, it is very necessary to study the sound quality in FCV. At present, there are few researches on FCV. South Korea's Song MK [3] and others obtained the FCV blower model by EMA (test modal analysis) and FEM (finite element analysis) method, and predicted the radiation noise by using the boundary element method, and reduced the noise parameters of the blower by modifying model. Shen Xiumin from Tongji University in China used a certain fuel cell prototype as the research object. Through the analysis of the experimental data, the indoor noise source and the noise source and
characteristics in the rear part of the low-speed driving vehicle were determined. The internal noise transmission path test of the FCV measured and calculated the acoustic transfer function of different paths, and synthesized the internal airborne noise in combination with the actual excitation data [4, 5]. The linear correlation analysis between the subjective and objective parameters was used to establish the low frequency acoustic diversity. The linear regression sound quality analysis model [6] used the separate operation method to collect the vibration and noise signals under the independent operating conditions of the air assisted system and the hydrogen assisted system. The vibration signal source was identified by modern signal analysis technology to determine the main vibration and noise sources [7, 8]. Liu Hai [9] of Hebei University of Technology in China and others used nuclear principal component analysis (KPCA) to extract key objective features that mainly affect sound quality, to achieve dimensionality reduction targets, and qualitatively analysed the variation of sound quality during acceleration of FCV. Through the above research, the research on FCV focuses on the noise control and objective evaluation of sound quality. However, different from traditional automobiles, FCV have many noise sources and scattered distribution, which have a greater impact on the sound quality of vehicles. The subjective evaluation and prediction research of sound quality in FCV has important guiding significance for guiding the optimization of sound quality in FCV.

In this paper, the interior noise of the FCV at a constant speed was used as a sample. In order to improve the internal sound quality of the FCV, the subjective feelings and evaluation of the interior noise of the vehicle were obtained through testing. The appropriate objective parameters were selected to describe the interior noise. Correlation analysis and regression analysis of the objective parameters and subjective evaluation results of the sound samples in the vehicle to obtain a multiple regression prediction model. Objective parameters were taken as input and subjective evaluation results as output, the prediction model of GA-BP neural network was established. The relationship between the subjective feelings of the hearing examiner and psychoacoustic characteristics was established. By comparing the multiple regression prediction model and the GA-BP neural network prediction model, a more accurate prediction model was obtained. Through weight calculation and correlation analysis, the objective parameters that have the greatest impact on the sound quality in the car were obtained.

2. Subjective evaluation of sound quality in the vehicle

2.1. Sound sample collection

In order to obtain the interior noise of the FCV, the NVH test of the FCV was designed and implemented. The test was carried out under uniform conditions on a drum test stand in a semi-anechoic chamber environment. A total of 17 noise samples were collected. Noise sensors were disposed at the right ear of the seat of the main driving position, at the right ear of the passenger seat, and at the rear seat. The experimental equipment is the LMS 24-channel data acquisition front end of Siemens. The sound signal was collected and recorded by the noise sensor using LMS Test. Lab software. The bandwidth of the sound collection was set to 20480 Hz and the resolution was 1 Hz. The noise measurement points of the test were arranged as shown in Figure 1.

![Fig 1. Noise measurement point layout.](image)

![Fig 2. Subjective evaluation of the experimental process.](image)
2.2. Objective Evaluation of Sound Quality

Subjective evaluation of sound quality is based on human perception, taking into account the formation process of subjective perception in human hearing. A total of 17 sound samples were subjectively evaluated, and the sound samples were processed to a length of 5 s in equal response. There are usually two methods of subjective evaluation of sound: direct scoring and paired comparison [10]. Although the process of paired comparison method takes a long time, the consistency of the obtained results is good, and the requirements of the evaluator are low. Combined with the characteristics of FCV interior noise, a paired comparison method was used to conduct a subjective evaluation experiment. The paired comparison method refers to combining the noise samples according to the arrangement and combination of two and two. The auditor evaluates the sound in turn, the better sound scores 2 points, and the poor voice scores 0 points. If the two were similar, each scores 1 point. The noise samples are arranged and combined by the computer, randomly played, and the auditor evaluates the noise samples until all the noise samples have been played. The trial consisted of 22 people, 14 males and 8 females. The composition of the members is shown in Table 1.

Table 1. Subjective evaluation member composition.

| Gender | Driving experience | Number |
|--------|--------------------|--------|
| Male   | √                  | 9      |
|        | ×                  | 5      |
| Female | √                  | 5      |
|        | ×                  | 3      |

The subjective evaluation test was completed in the listening room with environmental noise compliance. This listening device is a Sennheiser professional noise-cancelling earphone, which provides high quality, high-resolution sound, reducing sound distortion and rendering in the full frequency band, and it has excellent effects on isolating the noise outside the headphones. The listening software is self-programming. The auditing experiment process is shown in Figure 2. Before the experiment begins, the experimenter will explain the test principles and steps to the evaluator help the evaluator to be familiar with the sound sample, and ensure that each evaluator correctly understands the test content. Then subjective evaluation experiments are beginning. The test time of each evaluator is controlled within 30 minutes to avoid the evaluator's fatigue, thus effectively ensuring the quality of the evaluation. The data coincidence degree and the data consistency coefficient [11] were used to test the subjective evaluation results. The data with 2 coincidence coefficients below 0.6 and the consistency coefficient below 0.7 were excluded. The total effective data was 20, subjective evaluation. The results of the normalization of the score are shown in Table 2.

3. Objective evaluation of sound quality

The objective evaluation method of sound quality is using objective physical parameters as the basis for evaluation. Sound quality objective parameters can be directly calculated and evaluated by using software. The physical parameters used for objective evaluation mainly include loudness, A-weighted sound pressure level, fluctuation, AI, roughness and sharpness [12]. The interior vehicle noise signal of the FCV obtained by the experiment was objectively evaluated. The LMS software of Siemens was used to calculate and analyze the loudness, A-weighted sound pressure level, Fluctuation, Articulation Index (AI), Roughness and Sharpness of 17 noise sample signals. Calculating the objective evaluation parameters of 17 FCVs under uniform speed conditions and the subjective evaluation score. The results are shown in Table 2.
Table 2. Objective parameters of noise and subjective evaluation results.

| Number | Loudness (sone) | A-weighted SPL (dBA) | Fluctuation (vacil) | AI (%) | Roughness (asper) | Sharpness (acum) | Subjective evaluation score |
|--------|----------------|----------------------|---------------------|--------|------------------|-----------------|--------------------------|
| 1      | 10.89          | 57.66                | 1.05                | 93.53  | 0.14             | 0.84            | 0.49                     |
| 2      | 13.24          | 60.28                | 1.09                | 90.09  | 0.15             | 0.95            | 0.79                     |
| 3      | 17.41          | 63.82                | 1.06                | 83.43  | 0.17             | 1.04            | 0.67                     |
| 4      | 21.64          | 66.96                | 1.11                | 71.75  | 0.2              | 1.19            | 0.47                     |
| 5      | 16.44          | 64.12                | 1.05                | 87.95  | 0.16             | 0.87            | 0.29                     |
| 6      | 21.5           | 67.67                | 1.12                | 81.39  | 0.18             | 0.96            | 0.12                     |
| 14     | 22.17          | 67.32                | 1.07                | 69.92  | 0.18             | 1.21            | 1                        |
| 15     | 12.92          | 61.4                 | 1.04                | 91.95  | 0.15             | 0.77            | 0.34                     |
| 16     | 17.14          | 64.54                | 1.07                | 87.61  | 0.16             | 0.85            | 0.4                      |
| 17     | 25.08          | 69.25                | 1.12                | 68.08  | 0.21             | 1.17            | 0                        |

4. Multiple regression prediction model for sound quality in FCV

4.1. Multiple linear regression prediction model

Using multiple linear regression analysis, it was studied whether there was a linear relationship and quantitative variation law between subjective evaluation and the six objective parameters [13]. The loudness, A-weighted sound pressure level, fluctuation, AI, roughness and sharpness were selected as the independent variables of the regression equation. The subjective evaluation result was the dependent variable of the regression equation. The MATLAB program was used to perform multiple linear regression analysis. The multivariate linear regression theory was used to calculate the model regression equations established by objective parameters and subjective evaluation results. The model regression coefficients are shown in Table 3:

Table 3. Model regression coefficient.

| C            | Non-standardized coefficient | Standard error | Standard coefficient | Sig |
|--------------|------------------------------|----------------|----------------------|-----|
| Constant     | -13.364                      | 4.016          | ………                | 0.08|
| Loudness     | -0.232                       | 0.074          | -3.545               | 0.011|
| Roughness    | -14.936                      | 3.544          | -1.059               | 0.002|
| A-weighted SPL | 0.216                  | 0.063          | 2.546                | 0.007|
| AI           | 0.008                        | 0.023          | 0.235                | 0.758|
| Fluctuation  | 1.545                        | 1.284          | 0.160                | 0.257|
| Sharpness    | 4.381                        | 0.715          | 2.027                | 0.000|

It can be seen from Table 3 that the sig value of AI and fluctuation is higher than 0.05, indicating that the correlation between the two psychoacoustic objective parameters and the subjective evaluation results is relatively small. While the loudness, roughness, and A-weighted sound pressure level and the sharpness of the sig value is less than 0.05. It shows that the correlation between the four objective parameters and the subjective evaluation results is relatively high. The square of the R in the regression model is 0.924, so the accuracy of the subjective prediction model is relatively high. The subjective score of the dependent variable is defined \( Y \), the independent variables including of loudness, roughness,
A-weighted sound pressure level, AI, fluctuation, sharpness, respectively are defined as \( A \), \( B \), \( C \), \( D \), \( E \), \( F \). Multiple linear regression analysis was performed using the MATLAB program, and the equation for the multi-regressive prediction model of the sound quality of FCVs was calculated as follows:

\[
Y = -13.364 - 0.232A - 14.936B + 0.216C + 0.769D + 1.545E + 4.381F
\]

The comparison between the subjective score and the subjective prediction model is shown in Figure 3. The average absolute percentage error MAPE index [14] is used to evaluate the error between the subjective evaluation result and the predicted value. The MAPE value is 61.39%. It can be seen from Figure 3 that the subjective score and the predicted value are compared, and the overall trend is basically the same, but there is a large error. Different from the traditional vehicle multiple linear regression analysis results, the FCV noise multiple linear regression prediction model error is large. It can also explain that the FCV noise difference is small, the multiple linear regression model is not suitable for accurate prediction of FCV noise.

![Multivariate regression model predictive score and subjective score comparison chart.](image)

**4.2. Correlation analysis based on Pearson correlation coefficient**

To study the relationship between subjective evaluation of acoustic quality and objective parameters of psychoacoustics, it is necessary to explore which objective parameters have significant influence on subjective evaluation under the conditions of this experiment. Correlating the objective parameter values and subjective evaluation values in Table 2 and calculating the correlation coefficients. The correlation coefficient results are shown in Table 4:

| Correlation coefficient | Fluctuation | AI | Loudness | Roughness | Sharpness | A-weighted SPL |
|-------------------------|-------------|----|----------|-----------|-----------|----------------|
| Pearson correlation     | -0.352      | 0.307 | -0.471   | -0.542    | -0.014    | -0.514         |

It can be seen from the Table 4 that the subjective evaluation results are positively correlated with AI, other parameters are negatively correlated. The subjective evaluation results have the highest correlation with roughness and A-weighted SPL, high correlation with loudness, low correlation with AI and fluctuation, and there is a very small correlation with sharpness.

**5. GA-BP neural network prediction model**

According to the prediction results of multiple linear regression equations, the MAPE index is too high, and the accuracy of the built-in FCV sound quality evaluation model is low. The nonlinear regression analysis method is further used to solve the correlation between the subjective and objective evaluation results. The subjective evaluation scores of the noise samples are nonlinearly fitted with the objective parameter data. The GA-BP neural network prediction model for evaluating the sound quality of the FCV interior is established [15].
BP network is a multi-layer feed-forward neural network with one-way propagation, which main features are signal forward propagation and error backward propagation. In forward propagation, the input signal is processed layer by layer from the input layer through the hidden layer until output layer. The neuron state of each layer only affects the neuron state of the next layer. If the output layer gets the unexpected output, it is transferred to back propagation. The network weights and thresholds are adjusted according to the prediction error, so that the predicted output of the BP neural network is constantly approaching the expected output. However, the disadvantage of BP network is poor stability and the convergence speed is very slow. If the initial value is not selected properly, it may cause non-convergence or convergence to local extreme values. Genetic algorithm originated from the computer simulation study of biological system. It is an adaptive global optimization method formed by simulating the genetic and evolution processes of organisms in the natural environment. Based on this big feature, genetic algorithm can be used to optimize the initial weight of BP neural network. This paper combines the characteristics of GA and BP neural network to form GA-BP algorithm. First, the genetic algorithm is used to optimize the initial weight of the BP network, and then the BP network is trained. This method makes full use of the global optimization ability of genetic algorithm, which can avoid the situation of local convergence and increase the speed of convergence. The flow chart of genetic algorithm to optimize BP neural network is shown in Figure 4.

![Fig 4. GA-BP algorithm flow chart.](image)

5.1. Structure and parameter setting of GA-BP neural network
For the GA-BP network model, the expected error was set to 0.001, and the training cycle was positioned 1000 times. The genetic algorithm parameters were set to a population size of 30, an evolutionary number of 50, a crossover probability of 0.2, and a mutation probability of 0.1. It was solved using the genetic algorithm toolbox in MATLAB, and the solution was used as the initial weight and threshold of the BP network. Loudness, A-weighted SPL, Fluctuation, AI, Roughness and Sharpness were used as...
inputs, and subjective evaluation values were used as outputs. By comparing the training results of different structures, an optimal structure was obtained. The structure of the neural network was determined to be 3 layers. The number of hidden layers was 1, and the number of hidden layer neurons was 7. The topology of GA-BP neural network was 6-7-1, and the topology is shown in Figure 5:

5.2. Connection weights and thresholds
The GA-BP neural network continuously adjusted the connection weight \( h1 \) of the input layer and the hidden layer, the connection weight \( h2 \) of the hidden layer and the output layer, the threshold \( b1 \) of the hidden layer neuron, and the threshold \( b2 \) of the output layer neuron, so that the mean square error of the expected output value and the actual output value of the neural network was 0.0047. The final results of GA-BP neural network connection weights and thresholds are shown in Table 5:

| Implicit layer number | h1   | h2   | b1  |
|-----------------------|------|------|-----|
| 1                     | -1.19| -1.33| 1.74|
| 2                     | -1.54| 0.16 | 0.61|
| 3                     | -0.43| 1.53 | 2.33|
| 4                     | 1.53 | 1.21 | 1.46|
| 5                     | 0.71 | -0.90| -2.80|
| 6                     | 0.17 | 2.35 | 0.71|
| 7                     | 0.87 | 2.17 | 2.01|

The threshold \( b2 \) of the output layer neurons was -1.66.

5.3. GA-BP neural network training results
Using 10 sets of noise samples as training samples, 7 sets of remaining in-vehicle noise samples as test samples. Loudness, A-weighted SPL, Fluctuation, AI, Roughness and Sharpness were taken as input, and subjective evaluation value was taken as output. The score prediction results are shown in Figure 6. The average absolute percentage error MAPE indicator was used to evaluate the error between the subjective evaluation results and the predicted value. The MAPE value is 3.67%. It can be seen from Figure 6 that the comparison between the subjective score and the predicted value of the GA-BP neural network, the true value and the predicted value are basically the same, there are small errors. The MAPE value of the BP neural network prediction result is only 3.67%. Therefore, the GA-BP neural network prediction model is more accurate and more effective. Compared with multiple regression which MAPE value is 61.39%, the prediction result of BP neural network is more accurate.
5.4. Weight analysis
In the GA-BP neural network, the weight value represents the degree of importance of the influence of the input on the output. For the sound quality of the FCV interior, the weight value is the degree of correlation between the objective evaluation parameters and the subjective evaluation results. If the degree of correlation is higher, the weight is larger; if the degree of correlation is low, the weight is smaller. Through weight analysis and calculation as shown in Table 6, the most significant impact on the subjective evaluation results is A-weighting SPL and Roughness, other parameters have less impact, and Sharpness has the smallest impact, which is consistent with the correlation analysis.

Table 6. Objective evaluation parameters influence the weight of subjective evaluation results

| Parameter       | Weight |
|-----------------|--------|
| Loudness        | 0.15   |
| Roughness       | 0.26   |
| A-weighted SPL  | 0.27   |
| Fluctuation     | 0.15   |
| AI              | 0.11   |
| Sharpness       | 0.07   |

6. Conclusions
(1) A pairwise comparison method was used to subjectively evaluate the noise of 17 FCVs. Calculating the objective parameters. Using multiple linear regression analysis to quantitatively analyze the correlation between the subjective evaluation results of FCV interior sound quality and objective evaluation indicators, it can quantitatively simplify the prediction model of FCV interior sound quality. Comparing the prediction results with the subjective evaluation results, the average absolute percentage error MAPE value is 61.39%. The formula is relatively low but quantifiable. The formula is more intuitive, but for accurate prediction of the subjective evaluation results, the multiple linear regression method is not applicable.

(2) In order to improve the accuracy of the prediction model, GA-BP neural network algorithm was used to solve the correlation between the subjective evaluation results and the objective evaluation results to obtain the prediction model. The 7 groups of noise samples were predicted to obtain the prediction results. The calculated MAPE error was 3.67%. It can be known from the comparison of MAPE indicators that the accuracy of the GA-BP neural network prediction model is more accurate.

(3) By calculating the weights between the input and output variables, it is obtained that A-weighting SPL and Roughness have the greatest impact on the subjective evaluation results, which is consistent with the correlation algorithm.

References
[1] Sokolov, Alexander, Ozcan Saritas, and Dirk Meissner 2019 Global Market Creation for Fuel Cell Electric Vehicles Emerging Technologies for Economic Development 131-152 doi: 10.1007/978-3-030-04370-4_6
[2] Genuit and Klaus 2004 The sound quality of vehicle interior noise: a challenge for the NVH-engineers International journal of vehicle noise and vibration 1(1-2) 158-168 doi: 10.1504/ijvnv.2004.004079
[3] Minkeun Song, Sangkwn Lee and Sanghoon Seo 2008 Structural Modification for Noise Reduction of the Blower Case in a Fuel Cell Passenger Car Based on the CAE Technology Transactions of the Korean Society for Noise and Vibration Engineering 18(9) 972-981 doi: 10.5050/ksnvn.2008.18.9.972
[4] Zuo S and Yan J 2006 Experimental analysis for the interior noise characteristics of the fuel cell car Vehicular Electronics and Safety International Conference on IEEE (ICVES) 241-245 doi:10.1109/icves.2006.371-591
[5] Yan J and Zuo S 2006 Experimental Analysis and Control to the Rear Interior Noise of the Fuel Cell Vehicle Noise and Vibration Control 4 doi:10.4271/2005-01-2425
[6] Song M, Lee S and Seo S 2008 Structural Modification for Noise Reduction of the Blower Case in a Fuel Cell Passenger Car Based on the CAE Technology Transactions of the Korean Society for Noise and Vibration Engineering 18(9) 972-981 doi:10.5050/ksnvn.2008.18.9.972
[7] Kim Y, Kim E and Lee S 2010 Strategy for vibration reduction of a centrifugal turbo blower in a fuel cell electric vehicle based on vibrational power flow analysis Proceedings of the
[8] Kang Q and Zuo S 2012 Research Progress of Air Auxiliary system noise in fuel Cell cars 

\textit{Noise and vibration control} 32(1)1-6 doi:10.3969/j.issn.1006-1355-2012.01.001

[9] Feng Q, Zuo G and Chen Y 2007 Prediction of vehicle Interior noise based on FCV Acoustic solid Coupling Model 

\textit{System simulation technology} 4 201-205 doi:10.16812/j.cnki.cn31-1945.2007.04.004

[10] He Y, Tu L and Xu Z 2014 A Review of vehicle Sound quality Research 

\textit{Journal of automobile engineering} 4(6) 391-401 doi:10.3969/j.issn.2095-1469.2014.06.01

[11] Monson and Brian B 2014 The perceptual significance of high-frequency energy in the human voice 

\textit{Frontiers in psychology} 5 587 doi:10.3389/fpsyg.2014.00587

[12] Yuan W, Lin J and Chen N 2013 A noise Classification method based on Energy Distribution in Bark Domain 

\textit{Journal of East China University of Technology: Natural science edition}, 39(4): 472-476, 2013, doi:10.14135/j.cnki.1006-3080.2013.04.006.

[13] Tan G, Wang Dand, Chen S 2012 Sound quality Optimization of vehicle Interior noise 

\textit{Journal of Jilin University: Engineering edition} S1 51-56 doi:10.13229/j.cnki.jdxbgxb2012.s1.101

[14] Du Y, Wang W and Tian Q 2011 Orthogonal Experimental Design of structural Topology Optimization parameters 

\textit{Mechanical design and research} 27(5)14-17 doi:10.13952/j.cnki.jofmdr.2011.05.023

[15] Song Y and Zutong W 2015 Sound Quality Prediction of Vehicle Interior Noise under Multiple Working Conditions Using Back-Propagation Neural Network Model 

\textit{Journal of Transportation Technologies} 5 2 doi: 10.4236/jtts.2015.52013