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# Reliability improvement of a sound quality index for a vehicle HVAC system using a regression and neural network model

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ABSTRACT

The reduction of vehicle interior noise has long been the main interest of noise and vibration harshness (NVH) engineers. A driver's perception of vehicle noise is largely affected by psychoacoustic noise characteristics and SPL. Among the various types of vehicle interior noise, the sound of the heating, ventilation, and air conditioning (HVAC) systems is a source of distraction for drivers. HVAC noise is not as loud as the overall noise level; however, it affects a driver's subjective perception and may lead to feelings of nervousness or annoyance. Therefore, vehicle engineers work not only to reduce noise, but also to improve sound quality. In this paper, HVAC noise samples were taken from many types of vehicles. Objective and subjective sound quality (SQ) evaluations were obtained, simple and multiple regression models were generated, and these were used with the Semantic Differential Method (SDM) to determine what characteristics trigger a "pleasant" response from listeners. The regression analysis produced diagnostic statistics and regression estimates. In addition, neural network (NN) models were created using three objective numerical inputs (loudness, sharpness, and roughness) of the SQ metrics and one subjective output ("pleasant"). The NN model was used primarily because human perceptions are very complex and often hard to estimate. The estimation models were compared via correlations between SQ output indices and hearing test results. Results demonstrated that the NN model is most highly correlated with SQ indices, which led to determination of suggested methods for SQ metrics prediction.



## 1. Introduction

In the automobile industry, the end product has long been conceptualized as a simple machine that is evaluated on its performance alone. However, customers prefer comfortable surroundings in their vehicles, especially since the automobile has become a cultural object in which people spend much of their time [1,2]. For this reason, many previous studies have dealt with noise level reduction. Many ongoing studies aim to meet the needs of customers in ensuring that the noise is pleasant and as soft as possible. It has become common for drivers to listen to music or make telephone calls using hands-free systems or their vehicle's speakers. Some people also upgrade their vehicle's audio equipment, which may increase interior noise levels. Therefore, a vehicle's interior noise level must be considered in vehicle development. Noise transmitted from exterior sources such as the engine, road, tires, and wind, has been decreased dramatically in recent years. Noise that comes from the interior has become more significant to driver comfort. The major contributor to this interior noise is the HVAC system, which is the focus of this report [3]. People hear sound in an emotional and subjective way and thus it is difficult to express it numerically. It is clear that a new measure is needed, in addition to or in place of current objective measures of noise, such as dB(A).

HVAC noise is not loud compared to the general interior noise level, but it has been found to have subjective effects on the driver's emotions. In a previous study, HVAC noise was shown to be a combination of the radiated noise caused by driving, noise from the blower motor, and vibrations of the vehicle body [4]. Thus, noise caused by driving is becoming more important among the factors that influence the SQ of the HVAC system. Improvement of interior SQ sources has also become necessary to realize "Brand Sound," which expresses the particular characteristics and images of an automotive company. In one study, a calculation model for hearing elements was established to improve SQ, and many other studies have striven to construct a model that is more attuned to human hearing by comparing hearing models [5,6]. Hearing models have also been created using regression and neural network models, but studies that apply both models simultaneously have so far been inadequate.

A regression model has the advantage that its estimations are easy to explain, so it is used in a wide variety of applications. However, it also has several disadvantages, especially its assumptions of homoscedasticity, independence, and normality, and its

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problems with multicollinearity and sensitivity to specific values. Additionally, there is also uncertainty in the selection of the optimum regression model, and this can create difficulties for the qualitative evaluation of HVAC vehicle noise characteristics. Neural network models can be used for analysis even if the input variables are imperfect or the range of fluctuation is wide. Additionally, limited or irregular data can be used because the model reduces error through recursive learning. The ability to estimate subjective SQ evaluations accurately and effectively using the neural network model with imported HVAC SQ characteristics and then comparing them to the regression model would be a landmark in the construction of a robust SQ index. Therefore, in this study, we perform SQ evaluations of the HVAC noise of various vehicles using both objective and subjective methods, and we select the SQ metrics with highly correlated objective and subjective evaluations. Then we focus on prediction and comparison of subjective SQ characteristics using regression and neural network models.

## 2. Sound quality evaluation for construction of a sound quality index

### 2.1. Objective and subjective evaluation for sound quality index

The HVAC noise used in this experiment was produced by HVAC systems in vehicles manufactured by a Korean auto company. The operating conditions during evaluation were controlled in one to four steps in an idle engine run-up with 18 different vehicles. The noise data for SQ evaluation were recorded at the driver's ear position using Noise-Book made by Head Acoustics.

Four SQ metrics – loudness, sharpness, roughness, and fluctuation strength – were calculated by Artemis from the recorded data. The results of the objective evaluation were widely distributed. The range of loudness was 5.48–47.1 sone, sharpness was 1.62–3.72 acum, roughness was 0.26–6.95 asper, and fluctuation strength was 0.0221–0.1452 vacil.

Twenty-three men and eight women with normal hearing ability participated in the hearing tests. The ages of the participants were between 20 and 40. The 10 persons of participants were in the 20s and the others were in the 30s. Subjective responses were measured by the Semantic Differential Method (SDM). Five pairs of adjectives that can represent HVAC noise were specified on a seven-point scale, as shown in Table 1. Tests were conducted by playing the recorded sounds with the duration of 10 s in a random order via headphones to the study participants, who rated the sounds according to their subjective feelings.

### 2.2. Correlation analysis between objective and subjective evaluations

Correlation analysis revealed the strength of association between the objective and subjective data sets. These results are shown in Table 2. Except for the fluctuation strength, most of the indices were highly correlated, enabling the SQ indices to be constructed. To represent the most desirable SQ index, we selected "pleasant."

**Table 1**
Pairs of adjectives for SDM.

| Positive adjective | Point | | | | | | | Negative adjective |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| Quiet | | √ | | | | | | Loud |
| Soft | | | | | | √ | | Sharp |
| Smooth | | | | √ | | | | Rough |
| Pleasant | | | √ | | | | | Unpleasant |
| Expensive | | | | | √ | | | Cheap |

**Table 2**
The coefficients of correlation between sound metrics and subjective ratings.

| | Loud | Sharp | Rough | Expensive | Pleasant |
|---|---|---|---|---|---|
| Loudness | 0.964 | 0.922 | 0.940 | 0.925 | 0.958 |
| Sharpness | 0.892 | 0.919 | 0.928 | 0.905 | 0.927 |
| Roughness | 0.919 | 0.874 | 0.925 | 0.882 | 0.934 |
| Fluctuation | 0.212 | 0.295 | 0.377 | 0.274 | 0.263 |

## 3. Regression and analysis of sound quality evaluation

Regression analysis is a statistical technique used for modelling the relationship between predictor and response variables. A simple regression model portrays how a single predictor is related to a single response, while a multiple regression model involves more than one predictor variable for a dependent variable. In this study, in order to create a model that predicts subjective values of SQ from the objective SQ metrics of loudness, sharpness, and roughness, we used both simple and multiple regression models to analyze the data. MINITAB was used as a statistical analysis tool.

### 3.1. Estimation of sound quality index by the simple regression model

The simple regression analysis using three parameters more than 0.9 in Table 1 result in linear Eq. (1). According to these equations, increase of "loudness", "sharpness" and "roughness" degrades the results of subjective SQ evaluation. In case of "loudness", it was established that the simple regression model with the highest coefficient of the determinant ($R^2$) of 0.918. That is, 91.8% of the reliability in this model is explained by the "loudness" parameter.

However, because each of "sharpness" and "roughness" also has the high coefficient of the determinant of 0.860 and 0.872, it is necessary that "sharpness" and "roughness" in addition to "loudness" are considered, in order to improve SQ of HVAC.

$$\begin{aligned} &\text{Pleasant} = 2.47 + 0.822\ \text{Loudness}\ (R^2 = 0.918) \\ &\text{Pleasant} = 1.54 + 3.37\ \text{Sharpness}\ (R^2 = 0.860) \\ &\text{Pleasant} = 2.99 + 0.454\ \text{Roughness}\ (R^2 = 0.872) \end{aligned} \tag{1}$$

### 3.2. Estimation of sound quality index by the multiple regression model

A stepwise procedure was used for the multiple regression model in which the parameter with the highest correlation between the objective SQ metrics and subjective SQ value was reflected first in the analysis. This is illustrated in Table 3. The first stage of the stepwise procedure starts with no variable in the model. Then objective SQ metrics were selected in order according to which had the highest remaining correlation with the "pleasant" subjective SQ value.

Subsequent selections were based on partial correlations, given the variables already selected. Partial correlations measured the associations between a "pleasant" reaction and the objective

**Table 3**
Multiple regression models for "pleasant".

| Step | The estimated multiple regression models | $R^2$ |
|---|---|---|
| 1 | L + S + R | 0.237 |
| 2 | L + S + R + L * S | 0.339 |
| 3 | L + S + R + L * R | 0.482 |
| 4 | L + S + R + R * S | 0.751 |
| 5 | L + S + R + L * S + L * R + S * R | 0.950 |

L: Loudness.
S: Sharpness.
R: Roughness.