International Journal of Automotive Technology, Vol. 6, No. 4, pp. 367−374 (2005)

1229−9138/2005/022−08

DEVELOPMENT OF A SOUND QUALITY INDEX FOR THE EVALUATION OF BOOMING NOISE OF A PASSENGER CAR BASED ON REGRESSIVE CORRELATION

J. K. LEE[1)*], Y. W. PARK[2)], J. B. CHAI[3)] and H. K. JANG[4)]

[1)]GM Daewoo Auto & Technology, 199-1 Chungchun-dong, Bupyeong-gu, Incheon 403-714, Korea
[2)]System Engineering, Ajou University, Suwon-si, Gyeonggi 443-749, Korea
[3)]Mechanical Engineering, Ajou University, Suwon-si, Gyeonggi 443-749, Korea
[4)]Institute for Advanced Engineering, 633-2 Goan-ri, Yongin-si, Gyeonggi 449-860, Korea

(Received 19 April 2004; Revised 24 August 2004)

ABSTRACT−This paper proposes a sound quality index to evaluate the vehicle interior noise. The index was developed using a correlation analysis of an objective measurement and a subjective evaluation data. First, the objective set of measurements was obtained at two specified driving conditions. One is from a wide-open test condition and the other is from a constant-speed test condition. At the same time, subjective evaluation was carried out using a score of ten scale where 17 test engineers participated in the experiment. The correlation analysis between the psycho-acoustic parameters derived from the objective measurement and the subjective evaluation was performed. The most critical factors at both test conditions were determined, and the corresponding equations for the sound quality were obtained from the multiple factor regression method. Finally, a comparative work between previous index and present index was performed to validate the effectiveness of the proposed index.

KEY WORDS : Psycho-acoustic parameter, Sound quality index, Correlation analysis, Multiple factor regression

1. INTRODUCTION

In the past, the meaning of improvement process was simply related to reducing the sound pressure level for interior noise in vehicles (Ko *et al.*, 2003). However, a large number of researches on both the quantitative aspect of sound and the qualitative aspect of sound have been performed recently in order to meet the demands of consumers. A research on the qualitative aspect of sound, namely the sound quality, was started from 1960s, a period when psycho-acoustics became a conspicuous field of studies, and widely applied throughout industries in 1990s. Taking a look at researches on it, Otto (1997) evaluated linearity of the sound quality on a powertrain driving in acceleration using loudness, Hussain (1991) and Schiffbanker (1991) analyzed annoyance in vehicles using paired comparison and multiple factor regression analysis. Bisping (1995) standardized preference of the sound quality in vehicles using a semantic differential technique and a factor analysis.

However, most of those researches were developed by the sense of Europeans who considers vividness and powerfulness more important. Therefore, it is not appropriate to apply them directly to Asians who are sensitive to the loudness level of sound. For this reason, Hashimoto (1997) developed a psycho-acoustics model index. Despite the fact that the research provides a good model for evaluation of roughness that includes frequency modulation, it is insufficient to evaluate the overall sound quality in vehicles. Recently, Lee (2003) derived the sound quality index for booming and rumbling noise using artificial neural network. This paper showed a good try to estimate nonlinear relationship between sound metrics and subjective evaluation. Noise and vibration experts of GM-Daewoo used to utilize the psycho-acoustic parameters developed by Zwicker (1990) for the evaluation of human masking. However, the parameters used did not fully support the subjective evaluation of noise and vibration engineers. And this led to search for a different measure.

In this study, a correlation analysis and multiple factor regression analysis on psycho-acoustic parameters adopted by the objective measurement data and on the result of subjective evaluation conducted by a large number of noise and vibration experts were performed. Additionally, the sound quality index most suitable for a

**Corresponding author.* e-mail: jongkyu.b.lee@gmdat. com

fixed driving condition was derived and the effectiveness of the index testing with the vehicle used for deriving the sound quality index was validated. The validation was repeated using different kinds of vehicles also.

2. OBJECTIVE MEASUREMENT AND SUBJECTIVE EVALUATION OF SOUND QUALITY

2.1. Objective Measurement of Sound Quality

2.1.1. Method of Noise Measurement

In order to obtain the sound quality data in the form of binaural data well-known for its good representation of human sense of hearing, driver set one's ear to wear BHM (Binaural Head Microphone) produced by Head Acoustics Co., Ltd., The data were recorded for the right and left of the driver's seat.

The two conditions of test were motion in acceleration for which it was raised from 2000RPM to 6000RPM in full throttle with the second gear fixed at the automatic transmission and the third gear fixed at the manual transmission respectively and motion in constant-speed (60 km/h and 100 km/h).

The motions in both conditions were performed on a flat, straight driving road. Test vehicles were used three vehicles (A, B, C) produced from our company and one other vehicle (D) produced from other company for the test. Table 1 indicates a specification of test vehicles. This study was performed a practical testing on a driving road in order to include both "feel" and "view" which act as significant components in the subjective evaluation.

Figure 1 represents the process of deriving the sound quality index. First, the objective data were measured and the subjective evaluation were carried out at the specified driving conditions. Secondly, a correlation analysis between the objective measurement and the subjective evaluation follow. Through a series of process, the sound quality index of vehicle interior noise developed. Figure 2 represents the process of objective measurement of vehicles.

2.1.2. Investigation of psycho-acoustic parameters

The noise data were collected through Head Measurement System analyzed using the sound quality module invented by LMS International and MTS system corporation. And the index on the basis of sound pressure level and psycho-acoustic parameters was divided and analysis

Table 1. Specification of test vehicles.

Vehicle	Displacement	Transmission
A	1.6 D	A/T
B	1.8 D	A/T
C	2.0 L6	A/T
D	1.1 D	M/T

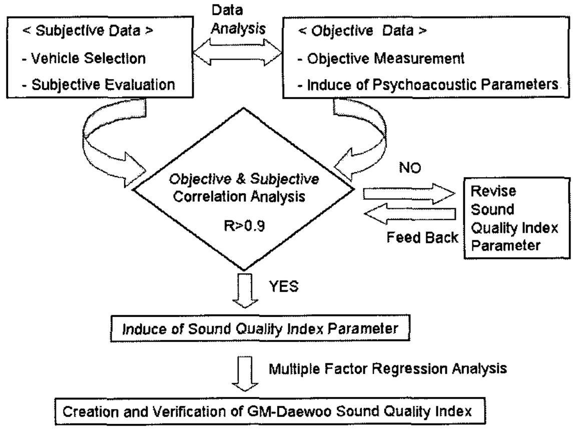


Figure 1. Development procedure of sound quality index.

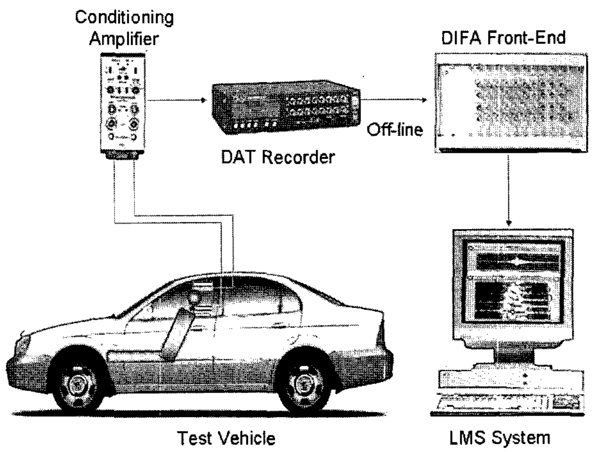


Figure 2. Test setup for the measurement of vehicle noise.

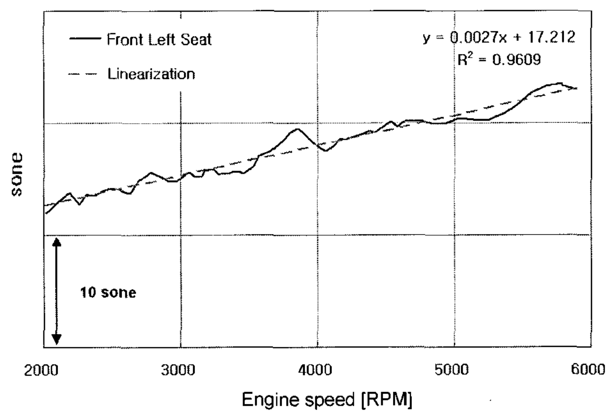


Figure 3. Level of zwicker's loudness.

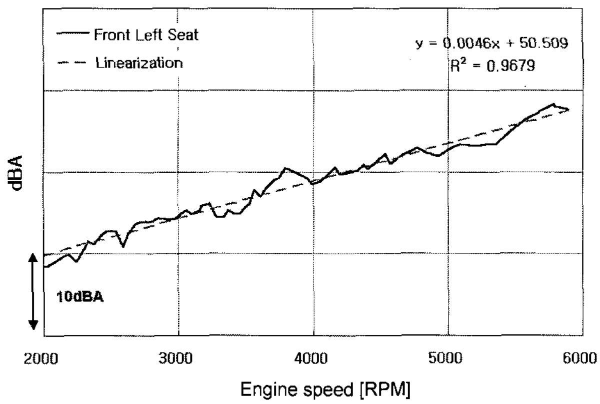


Figure 4. Level of composite rate of preference.

on 130 parameters including frequency factors, weighting factors and statistical factors acquired from the estimated objective measurement was performed. In this study, the loudness factors which are widely used in the analysis of the previous sound quality were examined. Of multiple kinds of loudness, it was adopted zwicker's loudness (1990), which can be applied not only to the free field but also to the diffuse field. This is the value calculated on the basis of the partial loudness on twenty-four critical bands. Also, the one-third octave band spectrum which represents the difference between the levels of interior noise and CRP (Composite Rate of Preference), which represents the difference of level characteristics and takes a high frequency sound into account were examined.

Figure 3 and Figure 4 are characteristic curves of parameters in a high regression correlation of other parameters in clear deviation. Figure 3 represents the loudness of vehicle driving in acceleration and Figure 4 represents CRP under the same condition. The CRP was regenerated by combining values on octave band at SPL (Sound Pressure Level) so as to best fit the sense of hearing. From the observation of Figure 3 and Figure 4 that the trend lines look almost linear. This indicates that the deviation between the trend lines and the respective data can be expressed in any value from the objective data measured. By correcting the slops and the constants of trend lines and the deviation of each data, we can express the transient signal data based on RPM variance as one unique value. This value is an independent variable that will be used in regression analysis and subjective evaluation.

2.2. Subjective Evaluation of Sound Quality

The subjective evaluation was performed using the same method as the objective measurement. It was evaluated was measured interior noise in the range of 2000–6000RPM for both automatic and manual transmission in the test of motion in acceleration. Evaluators used the ten-scale in accordance with SAE J1060 as shown in Table 2. The testing items in the accelerated motion were boom, noise and overall sound. The testing item in the motion of constant-speed was OA (Overall sound). Test place was performed on a flat, straight driving road. The test condition was kept the time as 20 minutes and the distance as 30km. From the subjective evaluation of 17 noise and vibration experts, a statistical analysis of the

Table 2. Rating scale of subjective evaluation.

Subjective Rating Scale	
1 - No operation	
2 - Limited operation	**Bad** ▲
3 - Complained as bad failure by all customers	
4 - Rated as failure by all customers (Poor)	
5 - Rated disturbing by all customers (Border Line)	
6 - Rated disturbing by some customers (Acceptable)	
7 - Noticeable by all customers (Fair)	
8 - Noticeable by critical customers (Good)	▼
9 - Noticeable by trained evaluators (Very good)	**Good**
10 - Not noticeable by trained evaluators (Excellent)	

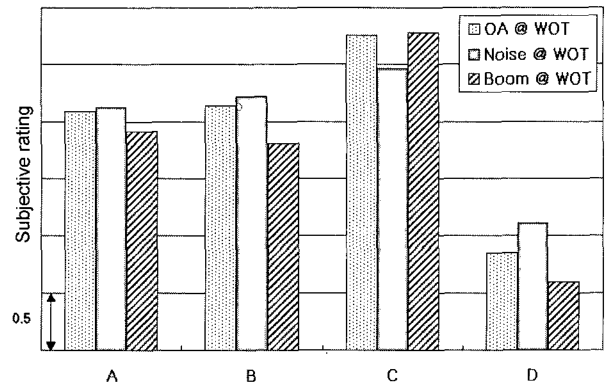


Figure 5. Subjective evaluations of sound at the wide-open test condition.

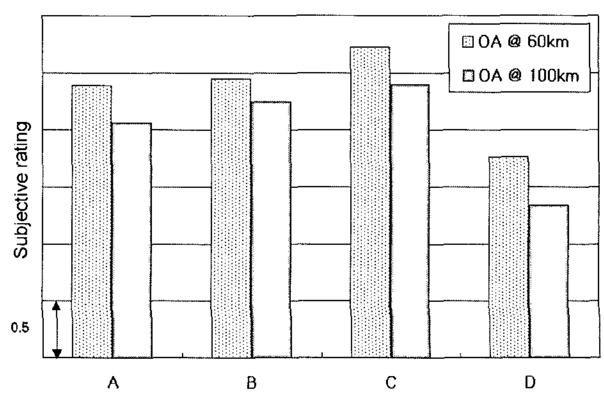


Figure 6. Subjective evaluations of overall sound at the constant-speed.

rated data using MINITAB was performed.

Figure 5 represents the result of the subjective evaluations of sound at the wide-open test condition. on four vehicles. Figure 6 represents the result of the subjective evaluations of sound at the constant-speed. The score represents the average value of the evaluators.

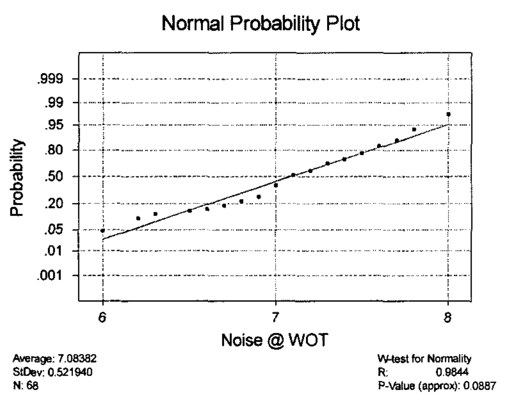
3. DEVELOPMENT OF SOUND QUALITY INDEX

3.1. Normality Test of Subjective Evaluation

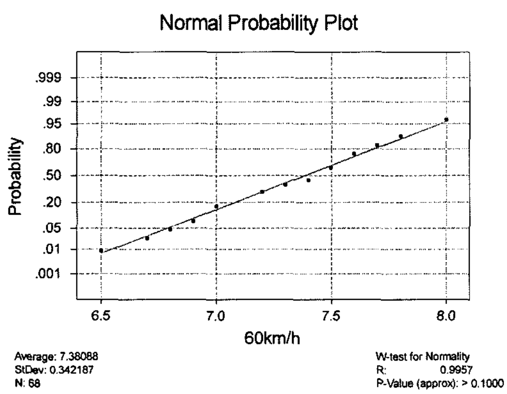
In this section, a normality diagram as in Figure 7 in testing stability and reliability of the subjective evaluation is obtained. The diagram is the result of a normality test obtained by Ryan-Joiner test.

Figure 7(a) is the test of noise in an accelerated motion and Figure 7(b) is the test of overall sound quality in a motion of constant-speed, 60 km/h. Both cases indicate 0.0887 and above 0.1 for P-values.

Here P-value represents the minimum significance level aimed at dismissal of null hypothesis (H_0: follows the normality) in the hypothesis process. The P-values



(a)



(b)

Figure 7. Normality test for the test conditions: (a) at the wide-open test; (b) at the constant-speed of 60 km/h.

Table 3. Correlation of averaged subjective and evaluators of boom at the wide-open test condition.

	M1	M2	M3	M4	M5	M6
Correlation	0.983	0.965	0.978	0.998	0.973	0.998
P-value	0.017	0.035	0.022	0.002	0.027	0.002
	M7	M8	M9	M10	M11	M12
Correlation	0.971	0.984	0.993	0.997	0.951	0.989
P-value	0.029	0.016	0.007	0.003	0.049	0.011
	M13	M14	M15	M16	M17	
Correlation	0.972	0.950	0.965	0.975	0.985	
P-value	0.028	0.050	0.035	0.025	0.015	

are all larger than 0.05 and therefore null hypothesis is not dismissed. Conclusively, the data indicates a normality. The next is about t-test (alternative test) for the test of reliability in case the standard deviation for some average values is not known.

Null Hypothesis (H_0) : $\mu = \mu_0$
Alternative Hypothesis (H_1) : $\mu \neq \mu_0$

Statistical Values $t = \dfrac{(x-\mu_0)}{s/\sqrt{n}}$ $(\alpha = 0.95)$

Here, μ indicates the average value, μ_0 indicates the standard value of the average, s, x and n each represents the variance, the average value and the size of the sample, α indicates 95% of the significance level.

Table 3 represents the correlation between the average values estimated by all evaluators and each evaluator. Here, P-value, the statistical value of t-test, takes a data below 0.05, which is a probability value for statistical test in order to adopt alternative hypothesis (H_1: The two factors are in a linear relationship.) In Table 2, the correlation coefficients to test linearity of the two variables are both higher than 0.95. This implies that the reliability of the data adopted by evaluators to derive the sound quality index is very high.

3.2. Deriving of Sound Quality Index

In this thesis, it was calculated slops, constants, deviation between objective measurement and the trend line using the proposed index and was induced major factors of high correlation throughout the correlation analysis of the subjective evaluation. From the result of the correlation analysis, for the test of motion in acceleration, CRP, loudness, BARK, engine explosion frequency and etc. showed a very high correlation to each other. In the test of motion in constant-speed, AI (Articulation Index), OA, BARK, loudness showed a very high correlation to each other. Also, the regression analysis between subjective evaluation factors and objective evaluation factors was performed. Finally, a linear *GM-Daewoo Sound Quality Index (i.e. GMDSI)* for the correlation function was acquired. The overall correlation was about 97% (R^2=0.97).

$$OA = 15.9 - 0.322 \times LOUD1 - 0.039 \times CRP^* \quad (1)$$
$$Noise = 10.6 - 1.07 \times CRP^* - 0.0418 \times LOUD \quad (2)$$
$$\text{Boom} = 18.6 - 0.177 \times FIR - 0.0082 \times LF \quad (3)$$
$$= 17.9 - 2.16 \times FIR^* - 1.73 \times LOUD^* \quad (4)$$
$$60\ \text{km/h} = 5.99 + 0.0337 \times AI - 0.0396 \times BARK^* \quad (5)$$
$$100\ \text{km/h} = 14.613 - 0.1002 \times OA - 0.0536 \times LOUD2 \quad (6)$$

Here, *LOUD*1 indicates the estimated value of deviation between the trend line and respective data, CRP^* indicates *CRP* level with a correction of slop and constant for the estimate of the trend line, $BARK^*$ acting as a bandpass filter of bandwidth of human sense of hearing is a frequency band for the efficient measurement of bandwidth of a narrow band.

Here, it was adopted *BARK* above 1000 Hz. Also, *FIR* indicates the estimated value on a trend line of the engine explosion frequency, FIR^* indicates the level of sound pressure level with a correction of the slop and constant, $LOUD^*$ indicates the level of loudness on a trend line with a correction of slop and constant of the estimated values. *LF* indicates the level of unweighted (i.e. below 125Hz) 1/1 octave band, *LOUD*2 indicates the average value of loudness in all fields.

The reason why we corrected the slop and constant was that the transient signal sound is for its characteristic difficult to be expressed in one dimension. In this stduy, it was corrected the sound source in order to express linearity and loudness in one dimension. And when it choose for the GMDSI on boom, we take the equation (3) for the case the regressive correlation on engine explosion frequency and a trend line is below 0.85, and we take the equation (4) when the regressive correlation is above 0.85.

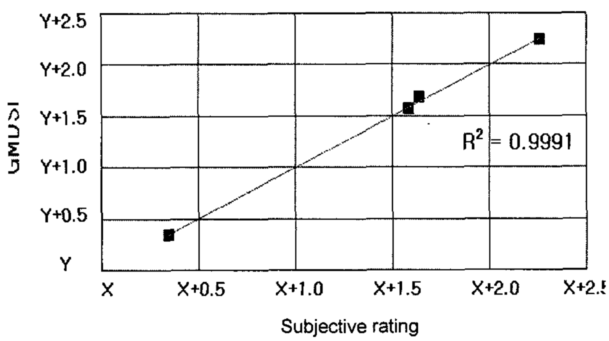


Figure 8. Correlation of subjective evaluation and overall of GMDSI at the wide-open test condition.

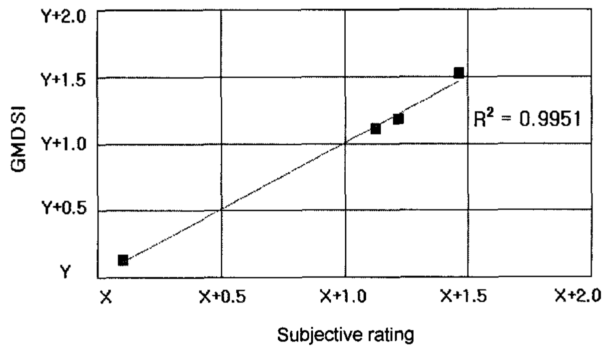


Figure 9. Correlation of subjective evaluation and noise of GMDSI at the wide-open test condition.

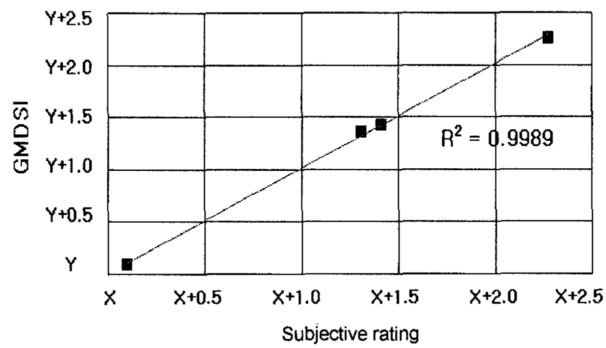


Figure 10. Correlation of subjective evaluation and boom of GMDSI at the wide-open test condition.

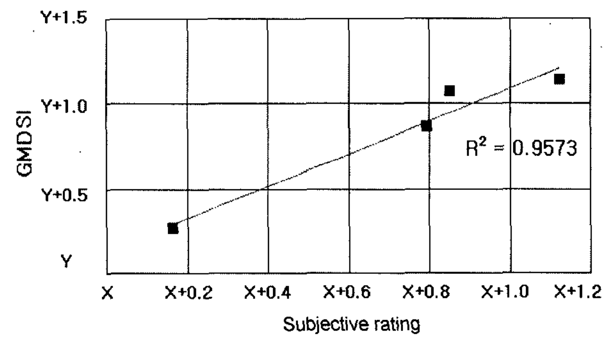


Figure 11. Correlation of subjective evaluation and overall of GMDSI at the constant-speed of 60 km/h.

Figure 8–12 demonstrate the results of the correlation analysis and regressive analysis using the subjective evaluation and the derived sound quality index. It was observed that the subjective evaluation and the sound quality index are in good agreement to each other in both the accelerated and the constant-speed of 60 km/h and 100 km/h. The two factors show a high reliability with the correlation coefficient above 0.95.

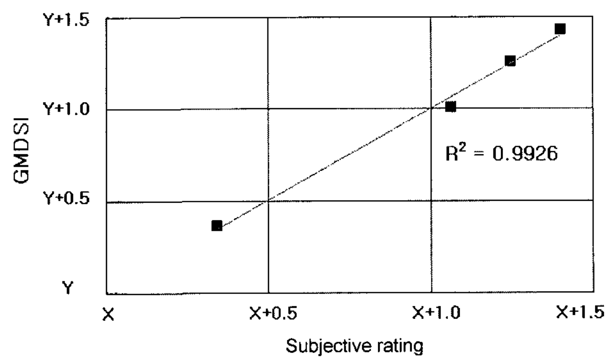


Figure 12. Correlation of subjective evaluation and overall of GMDSI at the constant-speed of 100 km/h.

3.3. Validation of Sound Quality Index

In order to validate the reliability of GMDSI acquired from the data of 4 vehicles, it was substituted the objective measurement estimated to GMDSI using 6 other vehicles and compared the result with those of the subjective evaluation performed by eight noise and vibration experts. Figure 13 indicates a linear regression equation (correlation coefficient is 0.91) on overall subjective evaluation and on GMDSI predicted from the objective measurement in the test of a vehicle driving in acceleration.

Table 4 is the correlation diagram between the subjective evaluation and GMDSI of the vehicle driving in acceleration and in constant-speed. As observed from the Table, the correlation on the subjective evaluation and GMDSI is shown to be 0.9 in all conditions thus showing the excellence in behavior. Figure 14(a) is the comparison between the absolute value of articulation index, which is the representative sound quality index in our company, and the subjective evaluation of noise in the accelerated motion. As observed from the graph, the correlation coefficient of the two factors is 0.73, which is relatively low. On the contrary, Figure 14(b) represents the correlation between GMDSI, which is the predicted value of the subjective evaluation and the practical value of the subjective evaluation all obtained from objective measurement. The correlation coefficient is 0.95, which is an high. This proves that GMDSI is an excellent index in comparison with the previous articulation index.

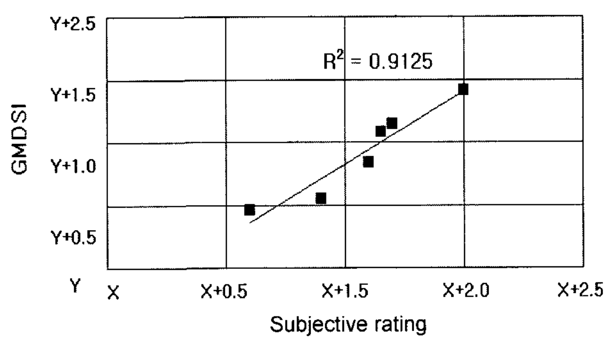
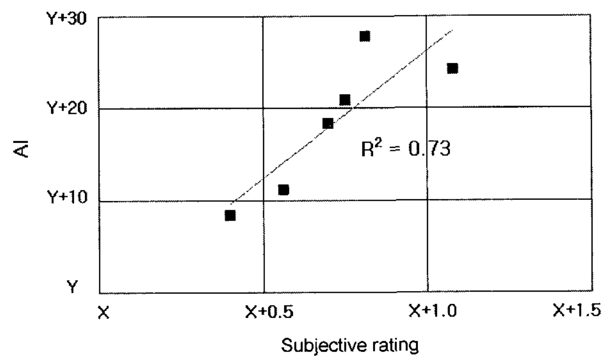


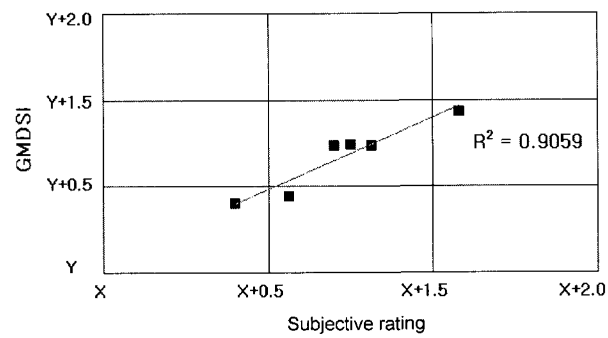
Figure 13. Validation of overall of GMDSI at the wide-open test condition.

Table 4. Validation of GMDSI.

Test conditions	Correlation
Overall at the wide-open test condition	0.91
Noise at the wide-open test condition	0.91
Boom at the wide-open test condition	0.98
Overall at the constant-speed of 60 km/h	0.94
Overall at the constant-speed of 100 km/h	0.96



(a)



(b)

Figure 14. Correlation of each index and subjective evaluation of noise at the wide-open test condition: (a) correlation of articulation index and subjective evaluation (b) correlation of GMDSI and subjective evaluation.

4. CONCLUSIONS

We obtained the following conclusion from the results above.

(1) As it was performed correlation analysis and regression analysis on the results of both the subjective evaluation and the objective measurement, we could derive a highly reliable *GM-Daewoo Sound Quality Index (GMDSI)* achieving its correlation above 97% in motions driving in acceleration and in constant-speed.

(2) For transient signal, unlike steady state signal, it was insufficient to analyze and test the frequency of human ears by combining the previous sound quality index. As a result, it was not related to the subjective evaluation. However, the index derived in this study is an applied index with a correction of its deviation, slop and constant on the trend line. Hence, it supports better for the sense of human hearing and shows a high correlation with the subjective evaluation.

REFERENCES

Alt, N. and Jochum, S. (1993). Sound design under the aspects of musical harmonic theory. *SAE Paper No.* 2003-01-1508, 675–681.

Bisping, R. (1995). Emotional effect of car interior sounds: pleasantness and power and their relation to acoustic key features. *SAE Paper No.* 951284, 1203–1209.

Bisping, R., Giehl, S. and Vogt, M. (1997). A standardized scale for the assessment of car interior sound quality. *SAE Paper No.* 971976.

Hashimoto, T. (1997). Modification of roughness level for higher correlation with unpleasantness - weighted roughness level due to modulation frequencies. *JSAE* 9735132.

Hussain, M., Golles, J. and Ronacher, A. (1991). Statistical evaluation of an annnoyance index for engine noise recordings. *SAE Paper No.* 911080, 359–367.

Ko, K. H., Heo, S. J. and Kook, H. S. (2003). Evaluation of road-induced noise of a vehicle using experimental approach. *Int. J. Automotive Technology* **4**, **1**, 21–30.

Lee, S. K., Chae, H. C. and Park, D. C. (1999). A study on improvement of the power plant vibration for the noise reduction and the sound quality improvement in the Compartment. *Trans. Korean Society of Automotive Engineering* **1**, **2**, 77–88.

Lee, S. K., Chae, H. C., Park. D. C. and Jung, S. G. (2003). Booming index development of interior sound quality on a passenger car using artificial neural network. *Trans. Korean Society for Noise and Vibration Engineering* **13**, **6**, 445–451.

Minitab Inc. (2000). Minitab User's Guide #2: Data Analysis and Quality Tool. New Hampshire.

Noumura, K. and Yoshida, J. (2003). Perception modeling and quantification of sound quality in cabin. *SAE Paper No.* 2003-01-1514.

Otto, N., Cheng, R. and Wisniewski, E. (1997). Linearity of powertrain acceleration sound. *SAE Paper No.* 971982, 887–890.

Otto, N., Eaton, C. and Lake, S. (1999). Guidelines for jury evaluations of automotives sounds. *SAE Paper No.* 1999-01-1822.

Schiffbanker, H., Brandl, F. W. and Thien, G. E. (1991). Development and application of an evaluation technique to assess the subjective character of engine noise. *SAE Paper No.* 911081, 369–379.

Weisberg, S. (1985). *Applied Linear Regression*. Wiley. New York.

Zwicker, E. and Fastle, H. (1990). *Psycho-acoustics - facts and Models*. Springer-Verlag. Berlin.

APPENDIX

(1) Articulation Index (AI, %)

Articulation Index is a method proposed by Beranek as a more precise evaluation of speech disruption than the Speech Interference Level. The Method was later standardized as ANSI S3.5.

AI is calculated from 1/3-octave levels between 160 Hz and 6300 Hz. These weighted amplitude are then expressed as percentages according to the following diagram. The overall AI is calculated as the sum of individual AI. Standard AI is measured as a percentage, where 100% is fully intelligible and 0% is completely unintelligible.

(2) Zwicker Loudness (ISO 532-B, 1975)

Loudness assessment using the Zwicker method (standardized as ISO 532B) starts from 1/3 octave band sound pressure level data, which can originate from either a free or diffuse sound field. It is capable of dealing with complex broadband noises, which may include pure tones.

The method takes masking effects into account. Masking effects are important for sounds composed of multiple components. A high level sound component may `mask' another lower level sound which is too close in frequency. The equal loudness contours are the result of large numbers of psycho-acoustical experiments and are in principle only valid for the specific sound types involved in the test. These curves are valid for pure tones and depict the actual experienced loudness for a tone of given frequency and sound pressure level when compared to a reference tone. The resulting value is called the loudness level.

(3) Speech Interference Level (SIL)

When the comprehension of speech is the goal, background sound or noise has the negative quality of interference. It can cause annoyance, and even be hazardous in a working environment where instructions need to be correctly understood. Therefore, a noise rating called SIL was developed. Beranek originally defined it as the arithmetic average of the sound pressure levels in the bands 600–1200, 1200–2400 and 2400–4800 Hz. Since the definition of the new preferred octave band limits, this definition was changed to the Preferred Speech Interference Level or PSIL, defined as the average sound pressure level in the 500, 1000 and 2000 Hz octave bands.

(4) Low Frequency Factor (LF)
Arithmetic mean of all unweighted octave bands below the firing frequency

$$LF = \frac{1}{N}\sum_{1}^{N} L_i$$

where, L_i: unweighted octave bands below the firing frequency

(5) Spectrum Balance (SB)
Low frequency factor minus SIL

$$SB = \frac{1}{N}\sum_{1}^{N} L_i - SIL$$

(6) Composite Rate Preference (CRP)
The Composite Rating of Preference (in dB) is an empirically established measure of sound quality based on the A-weighted SPL, the Speech Interference Level, and the Spectrum Balance.

The CRP is determined according to the following equation

$$CRP = \sqrt{L_A^2 - 1.5(L_A - SIL)^2 + 0.5SB^2}$$

where, L_A : total A-weighted SPL.
SIL : Speech Interference Level
SB : Spectrum Balance

(7) Critical Band Rate (BARK)
The inner ear can be considered to act as a set of overlapping constant percentage bandwidth filters. The noise bandwidths concerned are approximately constant with a bandwidth of around 110 Hz, for frequencies below 500 Hz, evolving to a constant percentage value (about 23%) at higher frequencies. This corresponds perfectly with the nonlinear frequency-distance characteristics of the cochlea. These bandwidths are often referred to as 'critical bandwidths' and a 'BARK' scale is associated with them as shown in below.

Critical Band (Bark)	1	2	3	4	5	6	7	8
Center Frequency (Hz)	50	150	250	350	450	570	700	840
Bandwidth (Hz)	100	100	100	100	110	120	140	150
Critical Band (Bark)	9	10	11	12	13	14	15	16
Center Frequency (Hz)	1000	1170	1370	1600	1850	2150	2500	290
Bandwidth (Hz)	160	190	210	240	280	320	380	450
Critical Band (Bark)	17	18	19	20	21	22	23	24
Center Frequency (Hz)	3400	4000	4800	5800	7000	8500	10500	13500
Bandwidth (Hz)	550	700	900	1100	1300	1800	2500	3500