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Sound quality evaluation for vehicle door opening sound using psychoacoustic parameters

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Abstract

The sound of a door opening on a vehicle has a main influence on psychological comfort and affective satisfaction for the vehicle. This study aims to evaluate the auditory pleasantness of the door opening sound and to derive the sound parameters, which can optimize that pleasantness. Fourteen different door opening sounds were selected and recorded. Participants evaluated each recorded door opening sound with the designed questionnaire. Three main results were obtained. First, the questionnaire was developed to evaluate the auditory pleasantness of door opening sound based on five affective attributes: 'loud', 'sharp', 'rough', 'clear', and 'satisfy'. These were selected through previous literature review and expert interviews. Second, 'Loudness', 'sharpness', 'roughness', 'fluctuation strength', and 'tonality' were selected as the psychoacoustic parameters. These parameters were found to be the important dimensions for the perception of door opening sound. Each affective attribute was related to psychoacoustic parameters by correlation analysis. Finally, the authors developed a model to predict subjective response to the door opening sound through regression analysis. In the incidence of 'loud', 'sharp', and 'rough', high R2 values were shown. Multiple regression was used to create a model to predict auditory pleasantness. The psychoacoustic parameter 'loudness' was shown to have a major effect on auditory pleasantness. The parameters 'loudness', 'sharpness', and 'roughness' were shown to affect the attributes of the door opening sound. The result of this study was an optimal model, created through psychoacoustic parameters, to predict the auditory pleasantness of door opening sounds

Keywords: door opening sound, sound quality, psychoacoustic, auditory pleasant model, affective engineering.

INTRODUCTION

Current marketing strategies of automobile manufacturers have been changed to emphasize the emotional satisfaction customers get from their vehicles {Genta, 2014 #55}(Genta et al., 2014). Vehicle customers prefer more comfortable surroundings. Therefore, manufacturers try to design a quieter car and reduce the noise perceptible to drivers (Gonzalez et al., 2003; Leite et al., 2009; Nykänen and Sirkka, 2009; Takami et al., 2008). There are many ongoing studies to reduce the noise level from interior and exterior sources such as engine, warning system, HVAC, and so on.

There are also recent studies of sound perception to ensure that various noises and sounds are pleasant, and as soft as possible, to increase the comfort felt by passengers (Yoon et al., 2012; Zobel, 1998).

Various sound sources (such as hood, door, trunk, fuel door, and sunroof) all produce different and unique sounds when being operated (Kim et al., 2015). Among the moving part sounds, door operating sounds are always heard by drivers and passengers every time they get in and out of the vehicle. Further, it is the first sound that buyers hear after purchasing the vehicle (Shin et al., 2013). To provide better customer satisfaction, it is important to study the relationship between the door operating sound and the feelings of drivers. In a previous research of vehicle door operating sounds, a door closing sound has been actively studied with psychoacoustic parameters to predict human feelings and to model the relationship between specific sounds (Filippou et al., 2003; Hamilton, 1999; Lee et al., 2007; Parizet et al., 2008). The door operating sound is classified as door closing and opening sounds. These have different characteristics and physical parameters from each other. Furthermore, a previous research on door opening sounds was limited to the investigation of physical parameters (Sellerbeck and Nettelbeck, 2004).

Therefore, it is necessary to study door opening sounds in relation to user pleasantness. As mentioned earlier, most studies have researched door closing sounds. Therefore, the door opening sound is studied using psychoacoustic approach based on previous research on door closing sounds. The aim of this study is to identify the relationship between psychoacoustic parameters, affective attributes, and the pleasantness felt by drivers from vehicle door opening sounds, and to build a prediction model of the pleasantness drivers feel for the sound.

The experiments were conducted in three steps: (1) interviews and literature reviews to determine the affective attributes suitable for the description of drivers' satisfaction with, and feelings about, the perceived door opening sound; (2) an auditory affective test based on the verbal attribute Magnitude Estimation (Bech and Zacharov, 2007) for the development of models for prediction of perceived auditory satisfaction based on psychoacoustic metrics; and (3) development of an optimal model for sound quality of door opening sound based on psychoacoustic metrics.

This study will determine the affective quality for the door opening sound by using statistical analysis. Initially, ANOVA was conducted to investigate the significant difference between the demographic variables and the affective attributes for each door opening sound. After the ANOVA, correlation analysis was conducted to investigate the relationship between psychoacoustic parameters, affective attributes, and overall satisfaction. Finally, regression analysis was used to build the prediction model of drivers' satisfaction from the door opening sound for each affective attribute.

METHOD

The procedure of this study is described in Figure 1. First, door opening sounds of 14 vehicles were recorded. Next, the psychoacoustic parameters and affective attributes were selected through a literature review and expert interview. Consequently, the subjective evaluation survey was created based on the selections, and a listening experiment was conducted. Lastly, statistical analyses were conducted in order to develop an auditory affective model of door opening sound.

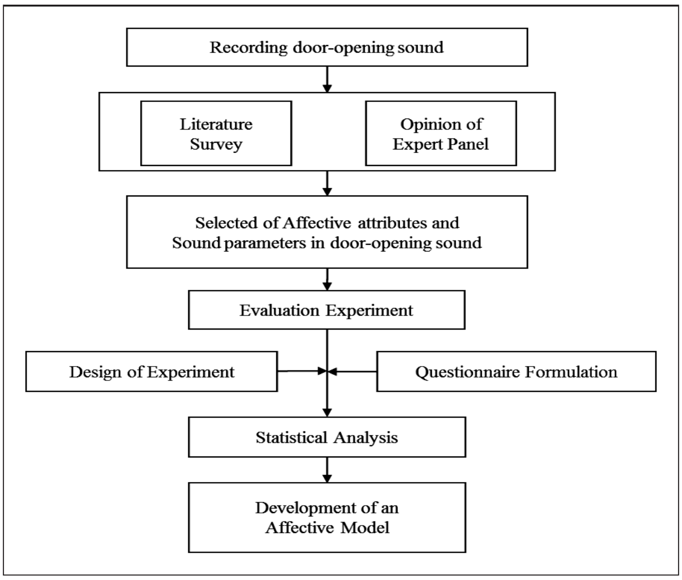

Figure 1. Procedure of the entire research analysis.

Stimuli

In this experiment, fourteen 4-door vehicles from international consumer vehicle manufacturers were used to record door opening sounds. Information about the vehicles used in this experiment is provided in Table 1. The recording was conducted in an anechoic chamber at Hyundai Motors Corporation to minimize noise effects and record the sound in a free filed condition as shown in Figure 2. A B&K recording microphone was installed parallel to the door handle of the driver›s side. It was located 20cm away from the lateral side and 20cm away in a posterior direction. A squadriga II Acoustic Head was used for the recording (based on the front door handle).

A literature review was conducted on psychoacoustic parameters, which had been used in other researches for the operating sound of a vehicle door (Aures, 1985, 1985; Terhardt, 1968; von Bismarck, 1974; Zwicker and Fastl, 2013). Five psychoacoustic parameters were selected based on the review: loudness, roughness, sharpness, tonality, and fluctuation strength. The range of each psychoacoustic parameter was as follows: loudness - 1.19 - 9.47 sone, roughness - 0.04 - 0.61 asper, sharpness - 1.94 - 6.34 acum, tonality - 0.65 - 1.03 tu, and fluctuation strength - 0.63 - 6.19 vacil. The sound parameters used in this study are explained in Table 1.

Table 1. Information of vehicle and stimuli using the experiment.

Vehicle	Mfg. Country	Grade	Model Year	Loudness	Sharpness	Roughness	Tonality	Fluctuation
A_1	Germany	Full-sized	2011	1.19	1.98	0.04	0.65	0.69
B_1		Full-sized	2011	2.15	1.94	0.11	0.72	1.44
B_2		Mid-sized	2011	2.83	2.37	0.26	0.74	1.28
M_1		Full-sized	2009	2.68	2.66	0.2	1.00	0.94
M_2		Full-sized	2010	3.22	2.69	0.19	0.99	1.06
T_1	Japan	Mid-sized	2009	1.42	2.05	0.13	0.84	1.17
T_2		Mid-sized	2011	3.72	2.97	0.23	0.85	1.18
T_3		Full-sized	2012	3.82	2.99	0.26	0.81	6.19
N_1		Mid-sized	2011	4.20	3.09	0.29	1.03	0.63
N_2		Mid-sized	2011	4.21	3.33	0.32	0.93	1.50
H_1	Korea, Republic of	Mid-sized	2013	5.12	4.93	0.36	0.81	0.89
H_2		Full-sized	2010	7.10	4.91	0.38	0.79	5.84
H_3		Full-sized	2012	5.75	6.2	0.48	0.78	1.64
K_1		Full-sized	2012	9.47	6.34	0.61	0.96	5.15

Figure 2. Recording environment in anechoic chamber.

Selection of affective attributes

In this study, twenty affective attributes were selected based on affective adjectives from the literature review to assess feelings when a person listens to the vehicle sounds (Altinsoy and Jekosch, 2012; Cheng et al., 2005; Zwicker et al., 1991). Eleven experts working in the department of Vehicle Test, Door Design, Sound Design, and Noise, Vibration, and Harness (NVH) research at Hyundai Motor Corporation were interviewed to develop prominent variables of door opening sounds among the selected adjectives. The experts had an average age of 36.4 years, and all had more than five years of working experience in the related field. All of the 14 door opening sounds were played to the experts.

The purpose of the expert interview was to find the appropriate affective attributes that describe and express the feelings of people when listening to the door opening sounds. The interviews were carried out in the Namyang Research Center of Hyundai Motor Corporation. The sounds were played by a Carat-Ruby2 amplifier and with AKG headphones for each interviewee. The sounds were played randomly to the interviewees without any information about the sounds. After listening to the sounds iteratively 5 times, the interviewees were asked to answer the following questions. 1. What is a good sound of a vehicle door opening? 2. Which design parameters are related to that good door opening sound? 3. How do you feel about this door opening sound? 4. How do you want to describe or express the sound with affective attributes? 5. List any additional adjectives that should be considered apart from the pair of adjectives selected through the literature review. Each interview was conducted for 60 minutes. As a result of interviews, five-affective attributes were selected: ‘Loud’, ‘Clear’, ‘Rough’, ‘Sharp’, and ‘Satisfy’.

Participants

A total of thirty-one subjects (16 males and 15 females) participated in the jury test. The participants' ages varied from 27 to 45 years old, and their average age was 36.7 years. All subjects were employees at Hyundai Motor Company, and 15 of the participants worked in a related acoustic field. Each subject listened to the 14 sounds of a vehicle door opening five times, each in a random order using the AKG headphones. Their subjective responses to each sound were measured against the five adjectives by a 7-point semantic differential scale based on results of the interviews in Table 2. The sequence of evaluation was followed by playing the recorded door opening sounds 5 times in a random order to the evaluation participants. They evaluated the sound according to their subjective feelings.

Table 2. 7-point semantic differential questionnaire using the experiment.

Comprehensive Evaluation	Point						
	Extremely	Quite	Slightly	Neutral	Slightly	Quite	Extremely
Quiet – Loud	V						
Unclear – Clear		V					
Smooth – Rough		V					
Dull – Sharp			V				
Dissatisfy - Satisfy					V		

Results

Judgements of affective attributes in a jury test

In Figure 3, the mean and 95% confidence interval of the affective attributes are presented for each door opening sound. ANOVA was conducted to verify any significant differences between affective attributes and demographic variables in Table 3. There was no significant difference found between affective attributes and demographic variables (gender, age group, and subjects working with acoustic field and others; $p<0.05$). Thus, it is possible to conclude that the demographic variables may be generalized or even neglected in door opening sound evaluation.

Table 3. Result of ANOVA between affective attributes and demographic variables.

Source	p - value				
	Quiet - Loud	Unclear - Clear	Smooth - Rough	Dull - Sharp	Dissatisfy - Satisfy
Corrected Model	.425	.256	.621	.457	.425
Intercept	.000	.000	.000	.000	.000
Gender	.920	.756	.981	.861	.097
Age Group	.809	.535	.466	.760	.377
Acoustic Field	.425	.082	.762	.178	.530
Gender * Age	.170	.508	.387	.516	.544
Gender * Acoustic	.529	.176	.908	.069	.081
Age * Acoustic	.957	.717	.099	.200	.821
Gender * Age * Acoustic	.131	.741	.693	.974	.601

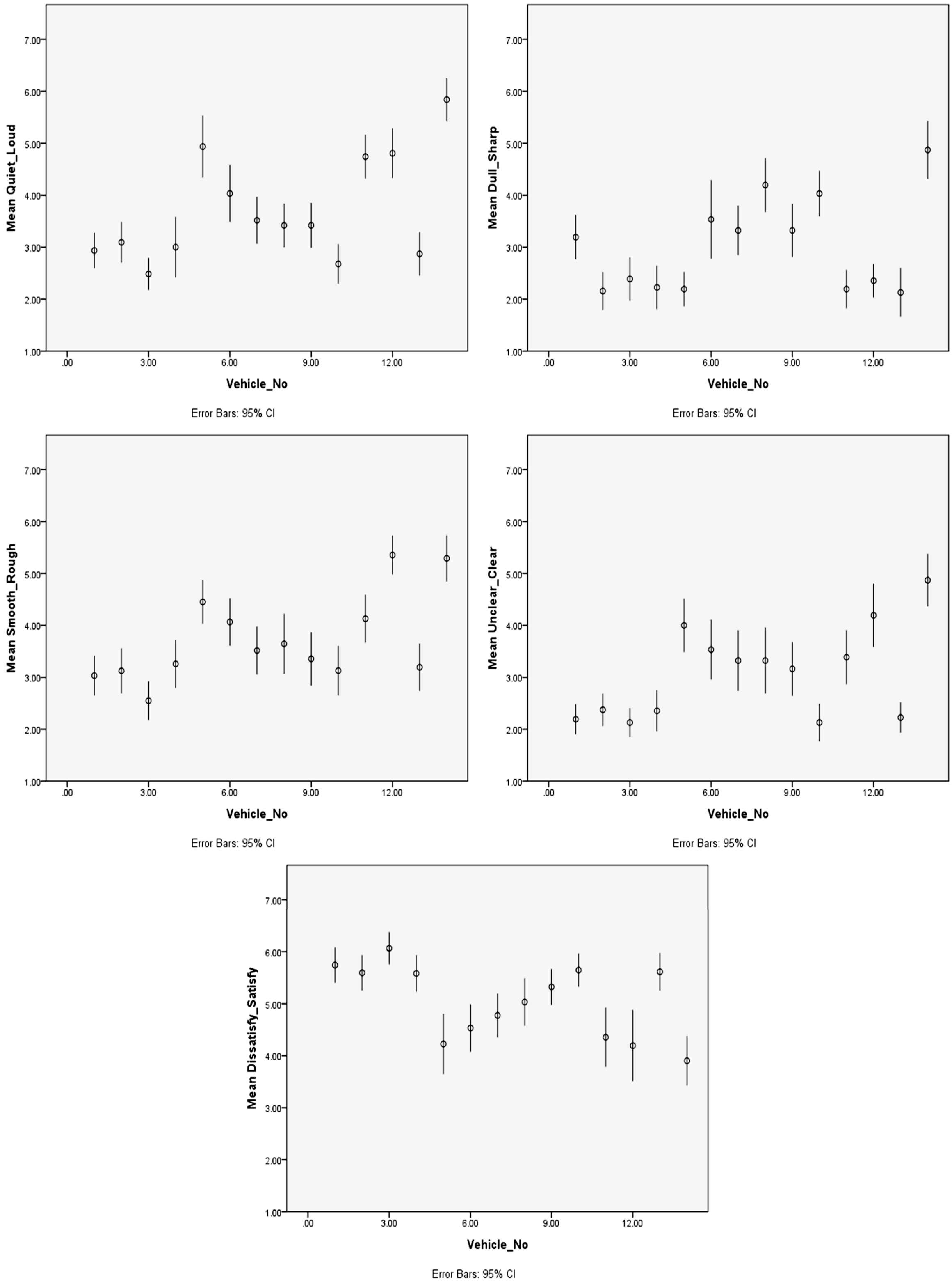

Figure 3. Mean and 95% confidence intervals of judgments of affective attributes for 14-door opening sounds.

Correlation of sound quality evaluation between affective attributes

Correlation analysis was conducted to identify the relationship between the affective attributes. The analysis results of the relationship are based on Pearson's coefficient as presented in Table 4. Three of the affective attributes ('Quiet-Loud', 'Dull-Sharp', and 'Smooth-Rough') are highly correlated to the affectivity 'Dissatisfy-Satisfy'. 'Clear' showed a low correlation with all other affective attributes, especially with the target affectivity 'pleasant'. Therefore, 'Unclear-Clear' was excluded from designing the final prediction model of drivers' affectivity.

Table 4. Correlation of R^2 coefficients between subjective responses for the semantic differential scales.

	Quiet-Loud	Dull-Sharp	Smooth-rough	Unclear-Clear
Dissatisfy - Satisfy	-.958	-.961	-.895	.263
Quiet - Loud		.947	.933	-.343
Dull – Sharp			.943	-.204
Smooth– Rough				-.217

Correlation of sound quality evaluation between psychoacoustic models

The relationship between psychoacoustic parameters was also identified using correlation analysis. The Coefficient results for correlations between the parameters, R^2, are presented in Table 5. The parameters, sharpness, roughness, and loudness are highly correlated to each other, whereas fluctuation and tonality are not. The highest correlation was shown between loudness and roughness (R^2=0.96).

Table 5. Correlation of R^2 coefficients between psychoacoustic models of the sounds under study.

	Roughness	Sharpness	Fluctuation	Tonality
Loudness	.960	.937	.545	.297
Roughness		.939	.492	.301
Sharpness			.444	.141
Fluctuation				-.046

Correlation of sound quality evaluation between psychoacoustic and affective attributes

Table 6 shows the correlation between the psychoacoustic parameters and the affective attributes. From the R^2 values, it is recognized that the affective attributes 'Dissatisfy-Satisfy', 'Quiet-Loud', and 'Smooth-Rough' are highly correlated with the parameters loudness, sharpness, and roughness.

As shown in Table 7, there is more than one psychoacoustic parameter that is highly correlated with the affective attributes. Each psychoacoustic parameter is plotted with the most correlated affective attribute based on the result in Table 7. As shown in Figures 4 (a) and (b), it can be identified that there is no correlation between fluctuation strength and 'Smooth-Rough', and also between tonality and clear.

Table 6. Correlation of R^2 coefficients between subjective responses and psychoacoustic parameters.

	Loudness	Sharpness	Roughness	Fluctuation Strength	Tonality
Dissatisfy - Satisfy	-.943	-.938	-.924	-.224	-.261
Quiet-loud	.961	.961	.937	.345	.220
Dull-Sharp	.960	.968	.946	.377	.174
Smooth-Rough	.927	.959	.965	.245	.168
Unclear-Clear	.173	.095	.252	.014	.226

In Figure 5, the affective attribute scores of 'Quiet-Loud', 'Dull-Sharp', and 'Smooth-Rough' are increasing as the psychoacoustic parameters loudness, sharpness, and roughness increase.

The affective attribute 'clear' has a low correlation with all psychoacoustic parameters. This result implies that 'clear' is not an appropriate affective attribute to test a door opening sound in a vehicle. In contrast, the psychoacoustic parameters 'loudness', 'sharpness', and 'roughness' have high correlation with 'Dissatisfy-Satisfy'. Consequently, fluctuation strength and tonality will be excluded when building the satisfaction model of door opening sound in vehicle.

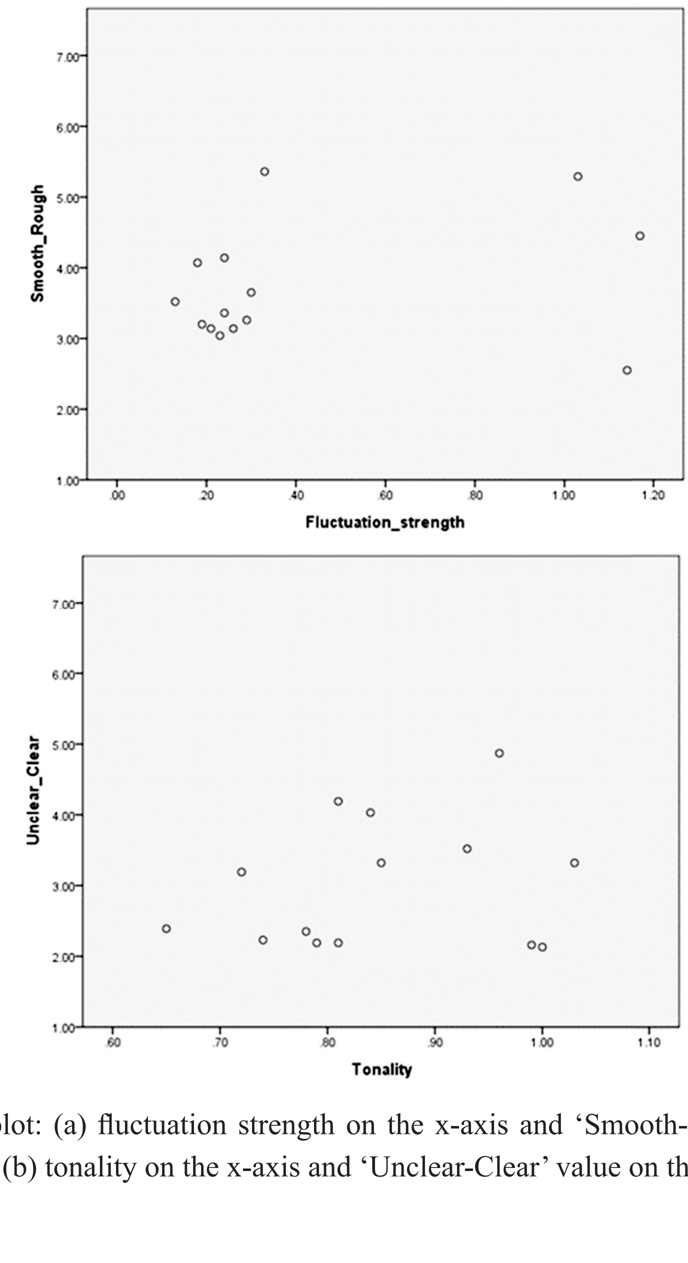

Figure 4. Scatter plot: (a) fluctuation strength on the x-axis and 'Smooth-Rough' value on the y-axis; (b) tonality on the x-axis and 'Unclear-Clear' value on the y-axis.

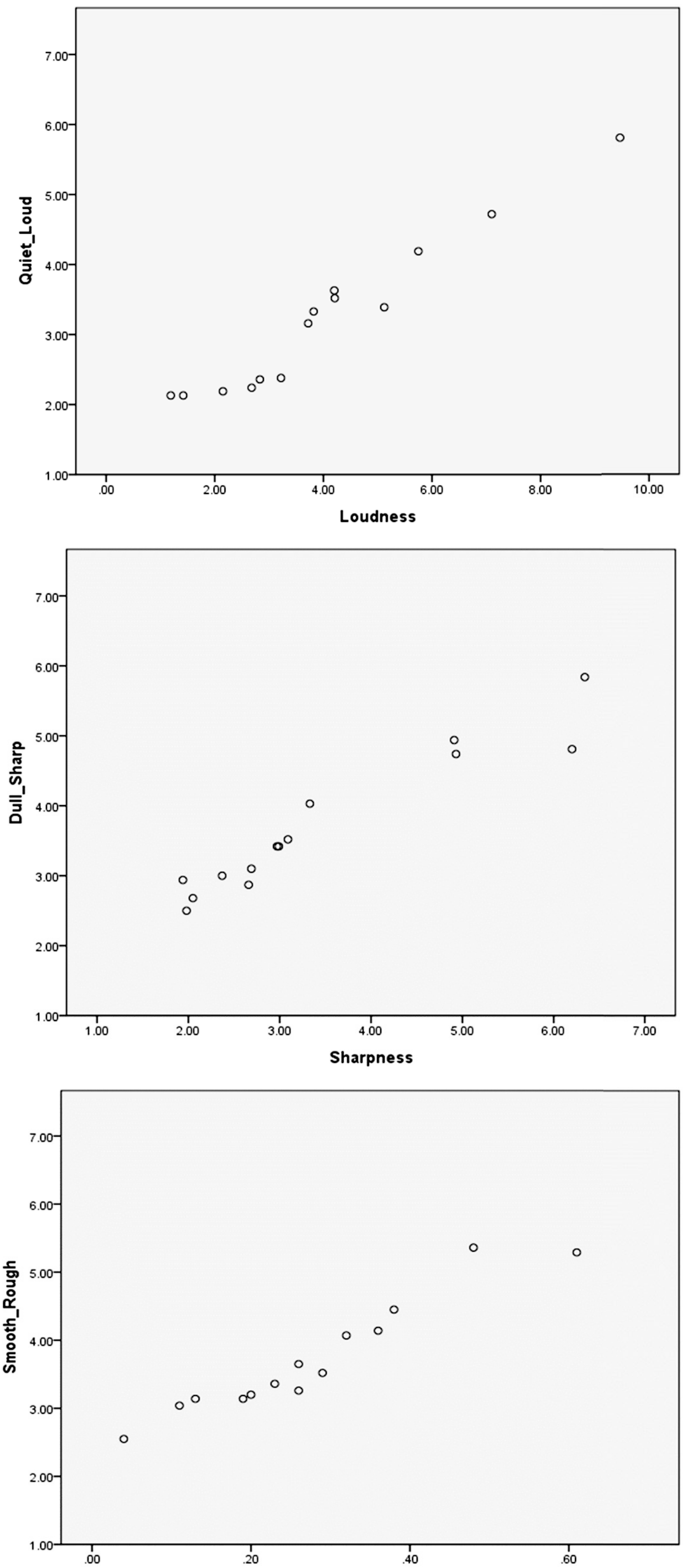

Figure 5. Scatter plot: (a) loudness on the x-axis and 'Quiet-Loud' value on the y-axis; (b) sharpness on the x-axis and 'Dull-Sharp' value on the y-axis; (c) roughness on the x-axis and 'Smooth-Rough' value on the y-axis.

Multiple linear regression of sound quality evaluation

The relationships between each affective attribute and the psychoacoustic parameters were derived from stepwise multiple linear regression (MLR) due to high correlation between ‘loudness’, ‘sharpness’, and ‘roughness’. The tables below show the regression results of the prediction model for each affective attribute against the parameters (Tables 811-). In the case of multiple significant models, regression equations with higher R2 were written.

In Figure 6, the relationship is presented between subjective responses for ‘Dissatisfy-Satisfy’ value and the prediction value from regression analysis. As shown in the graph, it can be noted that there is very little difference between the subjective responses and the prediction value.

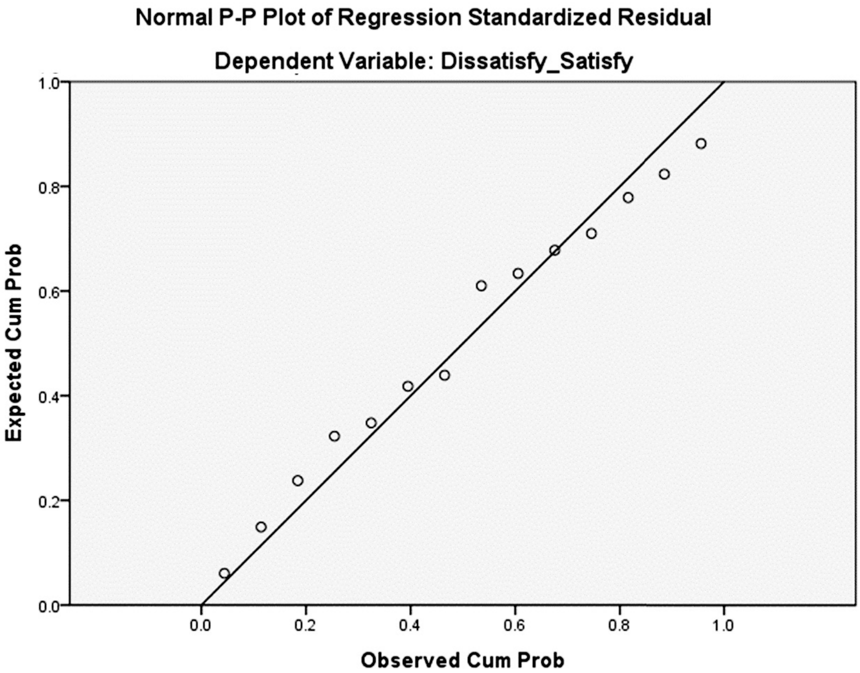

Figure 6. Normal P-P plot of regression standardized residual for ‘Dissatisfy-Satisfy’ and prediction of these responses by Eq. (1). The linear line in the graph means that predicted scores with subjective evaluation and experiment result were equal.

‘Loudness’ and ‘roughness’ have a major effect on the ‘pleasantness’ of the door opening sound (R^2=.955). This result confirms that ‘loudness’ and ‘roughness’ are among the sound parameters that increase ‘pleasantness’. Therefore, this model is appropriate to predict auditory satisfaction of vehicle door opening sounds. The regression equation for this model is presented in Eq. (1):

$$\text{Satisfy} = -.304 \times \text{Loudness} - .248 \times \text{Roughness} + 6.988 \quad (1)$$

In each of the affective attributes, the result of multiple linear regression is presented as follows. First, Eq. (2) refers to the ‘Quiet-Loud’ scale, which can be modeled using loudness (R^2=.915). The variable ‘loud’ is the prediction of the subjective response regarding the ‘Quiet-Loud’ scale.

$$\text{Loud} = .487 \times \text{Loudness} + 1.233 \quad (2)$$

Second, Eq. (3) refers to the dull/sharp scale, which can be modeled using loudness and sharpness (R^2=.961). The variable 'sharp' is the prediction of the subjective response regarding the 'Dull-Sharp' scale.

$$\text{Sharp} = .327 \times \text{Sharpness} + .294 \times \text{Loudness} + 1.439 \quad (3)$$

Finally, Eq. (4) refers to the smooth/rough scale, which can be modeled using roughness (R^2=.926). The variable 'rough' is the prediction of the subjective response regarding the smooth/rough scale.

$$\text{Rough} = .537 \times \text{Roughness} + 1.870 \quad (4)$$

Table 7. Result of MLR between Dissatisfy-Satisfy and psychoacoustic parameters (R2=.923, p=.000, R^2=.955, p=.000).

Model	Unstandardized Coefficients		Standardize Coefficient	t	Sig.
	B	Std. Error	Beta		
(constant)	6.517	.134		48.621	.000
Loudness	-.388	.032	-.961	-12.035	.000
(constant)	6.988	.143		50.939	.000
Roughness	-.248	.137	-.445	-2.394	.036
Loudness	-.304	.103	-.548	-2.948	.013

Table 8. Result of MLR between Quiet-Loud and psychoacoustic parameters (R^2=.915, p=.000).

Model	Unstandardized Coefficients		Standardize Coefficient	t	Sig.
	B	Std. Error	Beta		
(constant)	1.233	.170		7.241	.000
Loudness	.487	.041	.961	11.888	.000

Table 9. Result of MLR between Dull-Sharp and psychoacoustic parameters (R^2=.933, p=.000, R2=.961, p=.000).

Model	Unstandardized Coefficients		Standardize Coefficient	t	Sig.
	B	Std. Error	Beta		
(constant)	1.541	.175		8.801	.000
Sharpness	.567	.042	.968	13.462	.000
(constant)	1.439	.150		9.624	.000
Loudness	.294	.114	.439	2.588	.025
Sharpness	.327	.099	.557	3.288	.007

Table 10. Result of MLR between Smooth-Rough and psychoacoustic parameters (R^2=.926, p=.000).

Model	Unstandardized Coefficients		Standardize Coefficient	t	Sig.
	B	Std. Error	Beta		
(constant)	1.870	.158		11.839	.000
Roughness	.537	.042	.965	12.752	.000

CONCLUSION

This study was conducted based on the statistical method to identify the relationship between psychoacoustic parameters and subjective evaluations of vehicle door opening sounds. Three statistical methodologies (ANOVA, correlation, and regression analysis) were used in this study.

First, ANOVA identified that there are no significant differences in subjective evaluation between each affective attribute and the demographic variables depending on different door opening sounds. As a result, demographic variables should not be used as evaluation indices for further research of the door opening sounds of a vehicle.

Second, correlation was used to show the relationship between affective attributes and psychoacoustic parameters. The results identified that all the affective attributes had a negative effect on 'pleasantness'. The affective attributes 'loud', 'sharp', and 'rough' were highly related to 'pleasant' (R2=.941, .892, .875). The psychoacoustic parameters 'loudness', 'sharpness', and 'roughness' were highly related to 'pleasant' (R^2=.943, .916, .842).

Finally, through multiple linear regression using the stepwise method, the psychoacoustic parameter with the biggest effect on 'pleasant' was identified as 'loudness'. In a previous study on door closing sounds, 'loudness' and 'sharpness' were identified as the major psychoacoustic parameters that affect 'pleasant' as a door opening sound (Cheng et al., 2005). Each affective attribute can be predicted by psychoacoustic parameters as follows: 'loudness' for the quiet/loud attribute, 'loudness' and 'sharpness' for the dull/sharp attribute, and 'roughness' and 'sharpness' for the smooth/rough attribute. Examination of the relationship between psychoacoustic parameters of door opening sounds and 'pleasant' was done through multiple linear regression. The prediction rate of our model was 92.3%. Therefore, if a researcher wants to evaluate and predict the 'pleasantness' of door opening sounds, it would be appropriate to use multiple linear regression based on the parameters in this study.

Recent researches on the feelings and emotions obtained from various products and services (especially vehicles) have indicated various methods to select affective attributes. Examples are literature review, focus group interview (FGI), social network analysis (SNA), and others. SNA and the diary recording method (DRM) were used to select affective attributes based on user experience in (Maguire, 2001; Vermeeren et al., 2010). This study can be developed further by using those methods to select the affective attributes based on drivers' experiences and to conduct comparative analysis with other research.

Additionally, other various contexts or scenarios that door opening sounds occur in should be considered for further experiments. Considering other sound metrics such as kurtosis and sound pressure level (SPL) can benefit the model. In order to improve the accuracy of the model for predicting auditory satisfaction, there are many other parameters and psychoacoustic metrics being developed for research about affective feelings in the field of vehicle sound (Fastl, 2006). These parameters can be utilized as evaluation parameters to further study the door opening sounds of a vehicle.

By applying the three statistical analyses used in this study, the optimal value in the sound quality parameters of door opening noise should be predicted more effectively. This analysis can also be used to establish criteria for useful and meaningful sound quality levels. It can also be further developed as a guideline for building a prediction model of perceived overall satisfaction. This method can be applied to the various other sounds from a vehicle such as engine and HVAC sounds. Finally, this study is also useful for manufacturers and sellers to identify consumers' affective feeling for a vehicle.

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تقييم جودة الصوت
عند فتح باب المركبة باستخدام معلمات Psychoacoustic

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الخلاصة

إن صوت فتح باب المركبة له تأثير رئيسي على الراحة النفسية والرضا الحسي نحوها. تهدف هذه الدراسة إلى تقييم مدى الرضا السمعي نحو صوت فتح باب المركبة واستنباط معلمات الصوت التي يمكن أن تُحسن من درجة هذا الرضا. تم اختيار وتسجيل أربعة عشر صوتاً مختلفاً لفتح باب. وقام المشاركون في البحث بتقييم كل صوت مُسجل وفقاً للاستبيان المُصمم لذلك. تم الحصول على ثلاث نتائج رئيسية. أولاً، تم تطوير الاستبيان لتقييم مدى الرضا السمعي نحو صوت فتح الباب بناءً على خمس سمات حسية: "صاخب" و"حاد" و"غليظ" و"واضح" و"مريح". تم اختيار تلك السمات من خلال مراجعة النشرات السابقة وإجراء مقابلات مع خبراء في هذا المجال. ثانياً، تم اختيار "جهارة الصوت" و"الحدة" و"الغلظة" و"قوة التذبذب" و"الدرجات اللونية" كمعلمات Psychoacoustic. ووجدنا أن هذه المعلمات هي أبعاد هامة لإدراك صوت فتح الباب. وكانت كل سمة حسية مرتبطة بالمعلمات السمعية البصرية عن طريق تحليل الارتباط. وأخيراً، قام المؤلفون بتطوير نموذجًا للتنبؤ بالاستجابة الذاتية لصوت فتح الباب من خلال تحليل الانحدار. ففي سمات "صاخب" و"حاد" و"غليظ"، ظهرت قيم R^2 عالية. تم استخدام الانحدار المتعدد لإنشاء نموذج للتنبؤ بمدى الرضا السمعي. وقد ثبت أن معلمة "جهارة الصوت" لها تأثير كبير على مدى الرضا السمعي. وأظهرت المعلمات "جهارة الصوت" و"الحدة" و"الغلظة" تأثير على سمات صوت فتح الباب. وكانت نتيجة هذه الدراسة نموذج أمثل، تم إنشاؤه من خلال معلمات - Psychoacou tic للتنبؤ بمدى الرضا السمعي نحو أصوات فتح الباب.