Modelling of the Auditory Satisfaction Function for the Automobile Door Opening Quality

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ABSTRACT

This study aims to determine the affective response that occurs when the driver listens to door opening sound of vehicles by analyzing the relationship of sound parameters and the affective satisfaction. For the purpose of this study, we conducted an experiment with 26 vehicles and 30 subjects. The subjects evaluated the door opening sounds of the vehicles on affective satisfaction by answering a standard affective evaluation. Through multiple regression analysis, the result of evaluation was utilized to create a model that can presume the satisfaction of door opening sound. As the result of the regression analysis, ‘SharpnessZ’, ‘Short-term loudness’, and ‘Roughness’ turned out to be the sound parameters that have significant impact on improving the satisfaction of vehicle door opening sound. Moreover, the affective adjectives ‘Unstable’, ‘Quiet’, and ‘Clear’ were confirmed to be the affective variables that influence the auditory satisfaction in the door opening quality. Through statistical analysis on the satisfaction of the opening sounds, we expect that a satisfaction model of vehicle door opening sounds can be developed based on the auditory parameters and the affective adjectives of vehicle door opening quality—to further aid designing procedure of vehicle door opening quality for improving affective satisfaction.

Keywords: Affective engineering, Affective sound quality, Vehicle door, Door opening sound, User satisfaction model

1. Introduction

There have been many efforts to improve user satisfaction for the driver in the area of affective engineering. The gap between vehicles’ quality in performance and function has been reduced. Also, because driving has become important in daily life, consumers pay more attention on affective quality. Therefore, considering consumer’s affect in vehicle design is an important factor for product development and sales [1, 2].

Consumers place value on both vehicle’s functions and design factors which satisfy their affective needs [3]. Thus, the affective engineering, which translate consumer’s affection and needs on functions and designs of product into the domain of product design, have to be implemented in product development process [4].

There are a growing number of researches about the influence of vehicle sounds [5, 6, 7] on human affection using sound parameters. In the early days, they were mostly about engine sounds among the noises. Gonzalez *et al.* [8] developed Active Noise Control (ANC) to control the engine sound and investigated its effectiveness using psychoacoustic parameters. Also, Coen *et al.* [9] determined which sound quality parameters affect comfortability of users from engine sound using Automatic Relevance Determination (ARD) and rated the parameter ranking based on its effectiveness.

There are also studies about other various parts of vehicle sound. Parizet *et al.* [10] divided door closing sounds of vehicles into groups with representative sounds of each group based on subjective similarity and investigated the relationship between the representative sounds and perceived quality, and subjective affection. Nykänen and Sirkka [11] defined perceptually

prominent attributes of Power Window sound and suggested a guideline to maximize subjective overall product quality using acoustic metrics. Also, Leite *et al.* [12] developed a model to predict subjective response of users to Heating, Ventilation, Air conditioning (HVAC) system sounds using significant attributes of sound parameters.

However, these researches are not sufficient to identify the relationship between satisfaction of drivers or passengers and sound from moving parts of vehicle (e.g., front door, rear door, trunk, etc.). Especially, there has been a lack of studies investigating the relationship between the satisfaction and door sound of vehicle.

In addition, the affective engineering research of door sound was focused to develop a model of user satisfaction based on affective adjectives perceived from door closing sound [10, 13]. There is no research about developing an affective model that considers sound parameters and satisfaction of door opening sound.

The study aims to investigate the relation between the satisfaction and door opening sound of vehicle. An affective model was developed through assessments of affective variables which influence the satisfaction. In addition, sound parameters which affect the satisfaction of users were identified to suggest a design guideline for maximizing the satisfaction.

2. Method

2.1 Affective variables in door opening sound

For the research, at first, 15 adjectives were selected through literature surveys and expert reviews for subjective evaluation. Pilot test was conducted based on the selected adjectives to prescreen and choose suitable affective variables. Finally, Choose the 7 affective variables was followed; 'unstable', 'quiet', 'tight', 'sharp', 'rough', 'heavy', and 'satisfaction' (Table 1).

Table 1. Selected affective variables of vehicle door opening sound

Affective variable	Description
Unstable	Not stable; likely to change or come to an end

	suddenly
Quiet	Making or characterized by little or no noise
Clear	Not hoarse; distinctly perceptible to the ear
Sharp	Having or emitting a high-pitched and sharp tone or tones
Rough	Not sounding soft or gentle, and often rather unpleasant or angry
Heavy	Full and loud and deep; heavy sound
Satisfaction	Giving or affording satisfaction

2.2 Sound parameters in door opening sound

Ten sound parameters were selected based on existing research findings. Then, five significant design parameters were chosen through expert evaluations and pilot tests on seven vehicles; the removed five parameter-values showed no difference among the sample vehicles (Table 2).

Table 2. Selected sound parameters of vehicle door opening sound

Sound parameter	Definition	Reference
Loudness	Attribute of auditory sensation in terms of which sounds can be ordered on a scale extending from quiet to loud	[14]
Sharpness	Among other things, can be regarded as a measure of tone color	[15]
Roughness	Governed by temporal variations of a sound and reaches a maximum for modulation frequencies around 70 Hz	[16]
Long-term loudness	Method for combining a series of individual (per-frame) level estimates, obtained using any of a variety of method	[14]
Short-term loudness	Derived by smoothing the instantaneous loudness with respect to time using various psycho-acoustically motivated time constants	[17]

2.3 Evaluation questionnaire for door opening sound

A survey to evaluate the subjective response on the opening sounds was composed of three sections; questions about personal information, explanation about experiment methods and steps, and questions for subjective evaluation

on each sound. The personal information questions consisted of gender, age, driving experience, and type of owned car. The experiment was explained to subjects with an instruction of each step and methods. Lastly, the subjective evaluation was assessed on 7-point Likert scale for the affective variables and on 100-point scale for the satisfaction.

2.4 Selected vehicle door opening sound in evaluation

In this study, the experiment was conducted for door opening sounds of vehicles. The vehicles in the experiment were composed of 26 sedans and the opening sounds were recorded in anechoic room of Hyundai NGV research center to minimize the effect of noise (Figure 1).

Figure 1. Recording sound in anechoic chamber in Hyundai-NGV research center

2.5 Research procedure and participants

Total 30 subjects (male: 17, female: 13) were recruited in this experiment. Before begin the test, the instructions and explanations were given to the subjects. To avoid bias and distortion of data, recorded samples were randomly organized for each subject. The subjects listened to the each sample five times and evaluated the affective questions. YAMAHA-MSP7 speaker was used for subjects to listen the sounds. 52A of TES Company, which is measuring device of sound level meter, was used for the same decibel test-environment to provide equivalent sound volume to the subjects (Figure 2).

Figure 2. Speaker using experiment (left), measurement equipment of SPL (right)

3. Results

3.1 Analysis of relationship between ‘Satisfaction’ and demographic characteristics

The relationship between demographic characteristics of subjects and user satisfaction of door opening sounds was analyzed by using ANOVA. There were significant differences between the satisfaction and each characteristic gender, age and years of driving (Table 3). Tukey’s HSD test was applied for post-hoc analysis based on ANOVA results to identify difference of satisfaction among the characteristics (Figure 3). The results show that significant difference was found between 30’s and the other groups. In case of driving year, there were significant differences between 5~10 years and the others. And in case of automobile ownership, there were significant differences between domestic middle and domestic full.

Table 3. Summary of ANOVA for demographic variables ($\alpha=0.05$)

Independent variable	df	F	P
Gender	1	6.444	.011
Age	3	9.563	.000
Driving Year	2	15.602	.000
Automobile Ownership	3	13.287	.000

Figure 3. Summary of post-hoc ANOVA for age, driving year ($\alpha=0.05$)

3.2 Regression analysis of relationship between ‘Satisfaction’ and affective variables

Regression analysis was applied to identify the relationship between satisfaction and other affective features. The results shows that satisfaction is negatively affected by ‘unstable’ and ‘rough’ variables, and is positively related to ‘quiet’, ‘tight’, ‘sharp’, and ‘heavy’. The relationship between satisfaction and affective variables which influence the satisfaction are derived by the regression analysis as below Eq. (1)

$$y = -3.12 \times \text{unstable} + 2.08 \times \text{quiet} + 4.16 \times \text{clear} + 2.17 \times \text{sharp} - 1.16 \times \text{rough} + 2.08 \times \text{heavy} + 46.14 \quad (1)$$

In the variables, the significant variables in 90% of confidence interval are ‘unstable’, ‘tight’, ‘sharp’, and ‘heavy’. Especially, ‘tight’ and ‘unstable’ are found as the most important affective variables for consisting of the user satisfaction of door open sound (Table 4).

Table 4. The result of regression analysis between satisfaction and affective variables ($F(6,17)=58.678$, $p=0.000$, $R^2=.954$)

Model	unstandardized		standardize	t	Sig.
	B	Std. Error	beta		
(Constant)	46.135	15.552		2.966	.009
unstable	-3.116	1.596	-.405	-1.953	.067
quiet	2.077	1.401	.351	1.483	.156
tight	4.159	1.686	.363	2.466	.025
sharp	2.165	1.130	.205	1.917	.072
rough	-1.159	2.222	-.163	-.521	.609
heavy	2.080	.993	.206	2.094	.052

3.3 Analysis of relationship between affective variables and sound parameters

In order to identify which sound parameters affect the satisfaction of door opening sound, regression analysis was applied, and Eq. (2) was derived. In the result, Variance Inflation Factor (VIF) was greater than 10 among loudness, short-term loudness, and long-term loudness. Thus, short-term loudness, which has highest R^2 value in the regression model, was only selected to the model, and the other two parameters were removed.

In the variables, ‘SharpnessZ’ has been positive effect in satisfaction, and ‘Short-term loudness’, ‘Roughness’ has been negative effect in satisfaction

$$y = 3.16 \times \text{SharpnessZ} - 2.01 \times \text{Short-term Loudness} - 7.50 \times \text{Roughness} + 81.27 \quad (2)$$

Table 5. The result of regression analysis between satisfaction and sound parameters ($F(3,16)=7.453$, $p=0.002$, $R^2=.583$)

Model	unstandardized		standardize	t	Sig.
	B	Std. Error	beta		
(Constant)	81.269	6.443		12.614	.000
SharpnessZ	3.160	3.263	.166	.969	.345
Short-term Loudness	-2.008	.783	-.906	-2.564	.019
Roughness	-7.495	4.433	.165	-1.691	.107

4. Conclusion

This study aimed to develop an affective model of user satisfaction by investigating the satisfaction of door opening sound. Through literature study and expert reviews, seven affective adjectives and three sound parameters, which affect satisfaction of user when listening to door opening sounds, were selected. The experiment was conducted to 30 subjects, and an affective model was developed by investigating satisfaction, the affective variables, and the sound parameters. The model explains the relationship between satisfaction of door opening sounds and the affective variables, and sound parameters.

At first, there is significant difference between satisfaction of door opening sounds and each demographic characteristic. For this reason, these demographic characteristics have to be considered to design the vehicle door sound.

The affections that consist of satisfaction of the door opening sound are figured out; 'unstable', 'quiet', 'tight', 'sharp', 'rough', and 'heavy'. The affections 'unstable' and 'sharp' are identified as the most important affections. Further, short-term loudness is the most influential sound parameters among the threes from the regression model which maximize the satisfaction of door opening sounds.

In this study, significant affections influencing user satisfaction of door opening sound are identified. Also, a compelling model of sound parameters is derived to maximize the significant affections of users. Hence, this study is expected to help designers to optimize door opening sounds which satisfy affection of users.

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