Consideration of the frequency characteristics of a sound system in a traveling vehicle

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Abstract: We conducted a subjective evaluation experiment to determine the optimal frequency characteristics for a car audio system during vehicle travel . In this experiment, the car interior noise typically generated when a vehicle travels at a speed of 60 km/h was added to the experimental sound sources, and subjective evaluation was made of the sound passed through filters modifying the frequency characteristics. A total of 10 types of sound sources were used in the evaluation (narration, fusion, classic, J-pop, vocal, healing, nature, jazz, rock, and pop). Five levels of frequency characteristic filter (-5 to -9 dB/oct.), which augmented the bass in response to car interior noise, were used. The evaluation terms were 12 pairs of words related to sound quality, comfort, added value, and safety. Higher evaluation scores were given to items of palatability and safety in the vicinity of the -6 dB/oct. filter level, which augmented the bass to a level slightly below the frequency characteristic curve of the car interior noise (≒-7dB/oct.), and to items of sound quality and added value at the -9 dB/oct. filter level. Factor analysis was also conducted, to identify comfort, sound field, and clarity factors. Based on these factors, the filter results were compared. Higher comfort and clarity factor scores were obtained in the vicinity of the -6 dB/oct. characteristics versus those of other filters. These results confirmed that taking frequency characteristics into account in the performance of a car audio system during travel is effective in improving car interior comfort.

Keywords: car audio system, comfort, car interior noise, subjective evaluation

1. INTRODUCTION

In addition to safety and reliability, basic transport performance features are important requirements for recent vehicles. Among these, the car audio system in particular plays a pivotal role in determining the level of passenger comfort. Car interior comfort, however, is degraded by car interior noise, which typically increases with increasing car speed, due to various noise sources, including engine noise, muffled sound, noise from road surfaces, and wind roar (Figure 1), which detract from the sound reproduction of the car audio system. In response, systems capable of automatically adjusting the reproduced sound, to exceed the interior noise related to car speed, have been commercialized. Many of these systems, however, do not take into account the frequency characteristics of such interior noise, which is critical to improving the overall sound experience.

With the ultimate aim of achieving an optimal car audio system, a subjective evaluation experiment was conducted concerning frequency characteristic correction of reproduced sound, with respect to the frequency characteristics of traveling noise, and the effects of the proposed system were verified.

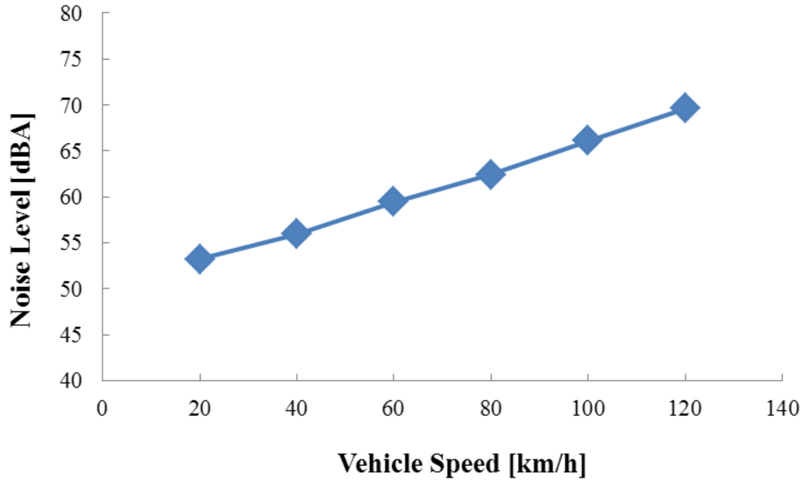

Figure 1: Relationship between car speed and car interior noise (compact car)

2. SUBJECTIVE EVALUATION EXPERIMENT

In this experiment, we created sound sources with the bass augmented by an equalizer in response to the noise characteristics of the car interior, and conducted a subjective evaluation of the respective sound sources with the addition of car interior noise.

2.1. Selection of Adjectives

Adjectives used as evaluation words in the experiment were determined through brainstorming, from the viewpoint of sound quality, palatability, added value, and safety, based on the assumption of car interior noise during car travel. A total of 12 specified adjective pairs are shown in Table 1. Each adjective pair was evaluated by the subjects on an evaluation scale of 1 to 7.

Table 1: Evaluation adjective pairs

Classification	Term	Evaluation adjective pair		
Sound quality	Clarity	Clear	—	Fuzzy
	Spaciousness	Spacious	—	Confined
	Depth	Deep	—	Shallow
Palatability	Comfort	Comfortable	—	Uncomfortable
	Refreshment	Refreshing	—	Unrefreshing
	Palatability	Palatable	—	Unpalatable
Added value	Realism	Realistic	—	Unrealistic
	Classiness	Classy	—	Cheap
	Sharpness	Innovative	—	Conservative
Safety	Wakefulness	Wakeful	—	Soporific
	Concentration	Concentrating	—	Distracting
	Fatigue	Not fatiguing	—	Fatiguing

2.2. Experimental Stimuli

The sound sources (contents) used in the experiment included 10 types of sound: J-pop, fusion, narration, nature, healing, classic, vocal, jazz, pop, and rock (Table 2). To ensure that all the sound sources were heard at the same volume, the ITU loudness level of the respective sources was properly adjusted. The value of binaural loudness was also adjusted, to 14.1 sone, which is equivalent to the road noise at a speed of 60 km/h (recorded with a dummy head). Each sound source was passed through each of five filters, which augmented the bass between 100 Hz and 800 Hz by -5 dB/oct., -6 dB/oct., -7 dB/oct., -8 dB/oct., or -9 dB/oct., in response to the traveling noise of the car. To each sound source was added car interior noise at a speed of 60 km/h. Headphone characteristics were ignored. All sound sources were recorded with a dummy head.

Table 2: Sound sources

Genre	Name of piece	Artist
Narration	Woman's narration + man's narration + BGM	JAS - Impact2
Fusion	Forget Me Nots	Patrice Rushen
Classic	Piano Concerto In A Minor, Op. 54, 2. Intermezzo	Schumann
J-pop	Beginner	AKB48
Vocal	Toire no kamisama	Kana Uemura
Healing	Only Time	Enya
Nature	Sound of nature	Sound Design Japan
Jazz	Mori's Waltz	Yasuhiro Mori
Rock	I Was Born to Love	Queen
Pop	Born This Way	Lady GaGa

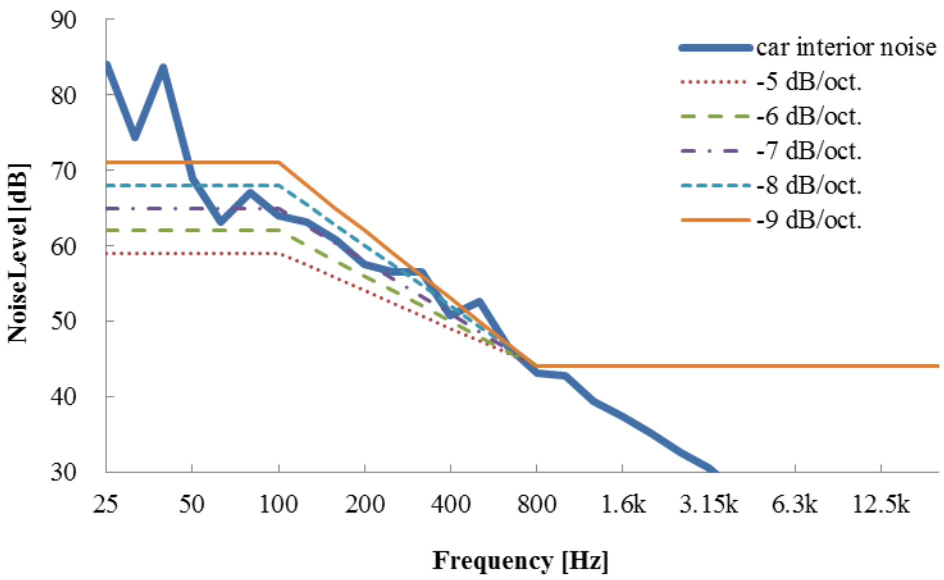

Figure 2: Frequency characteristics of the car interior noise of a compact car traveling at 60 km/h, with five filter types

2.3. Experimental Method

The experiment was conducted in a room less disturbed by noise. Figure 3 shows a schematic diagram of the experiment. Subjects sat on chairs, and the sound sources were presented through headphones (HD 595, SENNHEISER) from a music player (iPod nano, Apple). The subjects were requested to evaluate their impressions of the heard stimuli, using 12 adjective pairs on an evaluation scale of 1 to 7, as shown in Fig. 4. This procedure, counted as one test, was conducted for a total of 50 stimuli, or 5 frequency characteristic filters by 10 sound sources. Subjects were instructed to operate the music player by themselves, and allowed to replay the sound source as many times as desired. The adjectives and stimuli were randomly presented, to eliminate the order effect. The test was repeated 10 times per session, and a total of 5 sessions were conducted; 20 subjects, including men and women with normal hearing capability, were used. To avoid subject fatigue, tests were conducted with at least a one-hour interval between sessions and with a maximum of two sessions per day.

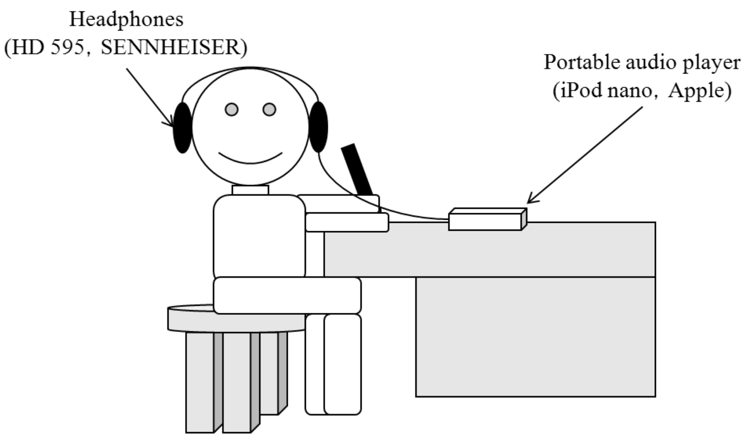

Figure 3: Schematic illustration of the experiment

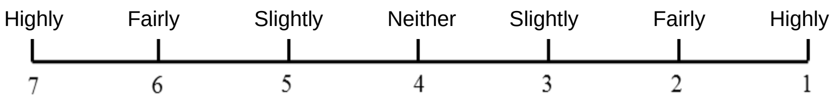

Figure 4: Evaluation scale (1 to 7)

2.4. Experimental Results

The results of the evaluation for the respective filters are summarized in Fig. 5, while the adjectives that showed specific results after a t-test are shown in Table 3. Among these, values with a significance level of 0.05 or less are shown in boldface. In the case of the evaluation items "comfortable" and "not fatiguing," the scores tended to decrease, after peaking at the -6 dB/oct. filter level, as the bass was augmented. In the case of the items "spacious," "deep," and "realistic," roughly increasing scores were obtained, from the -5 dB/oct. filter to a peak at the -9 dB/oct. filter, with increasing bass augmentation. In the t-test, a difference of significance was observed between the -6 dB/oct. filter and the -9 dB/oct. filter for the items "deep," "realistic," and "not fatiguing." In the case of the item "comfortable," a difference of significance was observed between the -6 dB/oct. filter and the -5, -8, and -9 dB/oct. filters, respectively.

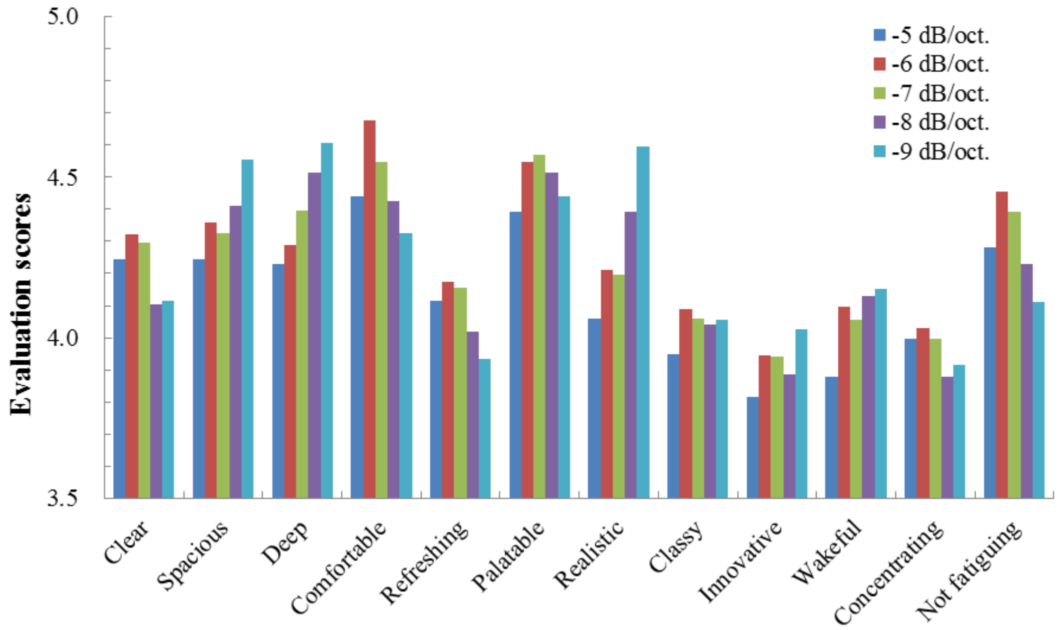

Figure 5: Evaluation scores for the respective filters

Table 3: T-test

Characteristic filter [dB/oct.]	Deep	Comfortable	Realistic	Wakeful	Not fatiguing
-5 vs. -6	0.591	**0.015**	0.211	0.054	0.112
-5 vs. -7	0.149	0.306	0.230	0.119	0.327
-5 vs. -8	**0.015**	0.897	**0.011**	**0.033**	0.676
-5 vs. -9	**0.004**	0.353	**0.000**	**0.015**	0.213
-6 vs. -7	0.377	0.212	0.890	0.723	0.533
-6 vs. -8	0.056	**0.020**	0.131	0.774	0.055
-6 vs. -9	**0.011**	**0.002**	**0.001**	0.626	**0.008**
-7 vs. -8	0.293	0.246	0.091	0.539	0.151
-7 vs. -9	0.066	**0.046**	**0.000**	0.448	**0.017**
-8 vs. -9	0.452	0.329	0.072	0.867	0.326

The results of factor analysis are shown in Table 4. The maximum likelihood method was used to determine the factors. As shown in the table, the first to third components have an eigenvalue of 1.0 or more, and their cumulative contribution ratio is 67%. Analysis of these first to third components, as the principal components, was conducted using the varimax method, and the results are shown in Table 5. As shown there, the first group of principal components showed high loads for evaluation words related to comfort, such as "comfortable," "not fatiguing," "palatable," "concentrating," and "classy." These components are therefore denoted as "comfort factors." The second group of principal components showed high loads for evaluation words related to the added value of the sound field, such as "deep," "spacious," "realistic," and "innovative," and are therefore denoted as “sound field factors.” The third group of principal components showed high loads for evaluation words related to clarity, such as "clear," "refreshing," and "wakeful," and are therefore denoted as “clarity factors.” Factor scores for each reproduction are shown in Fig. 6. The comfort factor had the highest score when the -6 dB/oct. filter was used, while the sound field factor showed increasing scores as the bass was increasingly augmented.

Table 4: Cumulative contribution ratios

Factor	Primary eigenvalue		
	Total	Variance ratio [%]	Cumulative contribution ratio [%]
1	**5.43**	45.24	**45.24**
2	**1.55**	12.87	**58.11**
3	**1.07**	8.87	**66.98**
4	0.78	6.53	73.51
5	0.66	5.53	79.04
6	0.48	3.97	83.01
7	0.44	3.67	86.68
8	0.41	3.39	90.07
9	0.38	3.19	93.26
10	0.32	2.68	95.94
11	0.27	2.29	98.22
12	0.21	1.78	100.00

Table 5: Factor matrix of post-varimax rotation

Adjective	Factor		
	1	2	3
Comfortable	**0.831**	0.289	0.137
Not fatiguing	**0.775**	0.067	0.016
Palatable	**0.739**	0.374	0.162
Concentrating	**0.713**	0.156	0.114
Classy	**0.516**	0.482	0.240
Deep	0.164	**0.701**	0.204
Spacious	0.261	**0.679**	0.210
Realistic	0.202	**0.633**	0.285
Innovative	0.097	**0.250**	0.227
Clear	0.428	0.285	**0.666**
Refreshing	0.527	0.243	**0.612**
Wakeful	-0.067	0.138	**0.268**

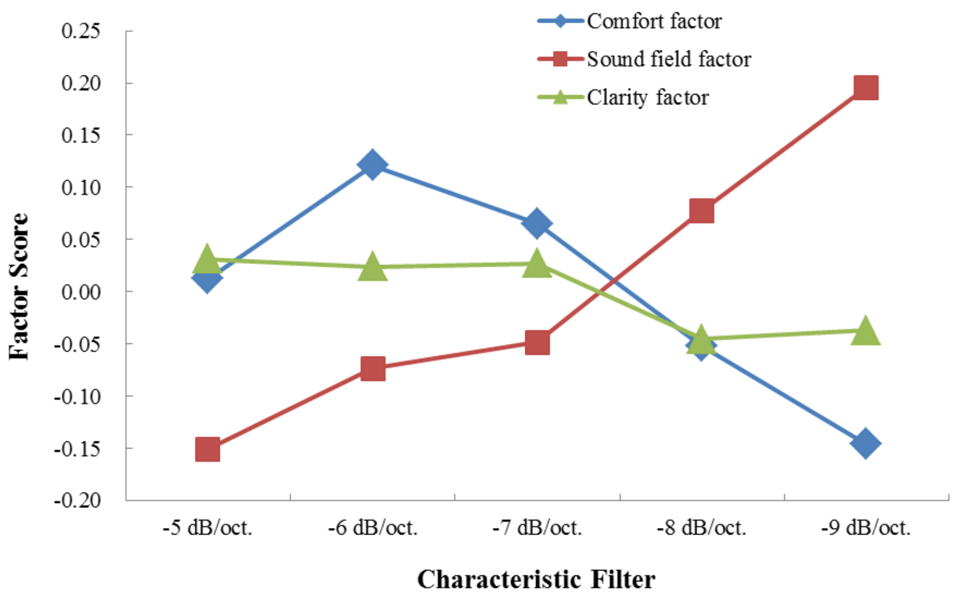

Figure 6: Factor scores

3. DISCUSSION

The experimental results show that in the case of the evaluation items "comfortable" and "not fatiguing," the scores tended to decrease, after peaking with the -6 dB/oct. filter, as the bass was augmented. It is thus apparent that, though augmenting the bass to compensate for car interior noise improves the overall sound, it is important not to overemphasize this augmentation. In the case of the items "spacious," "deep," and "realistic," higher scores were obtained as the bass was increasingly augmented. However, although these items depend on the loudness of the bass, since such items as "comfortable" and "not fatiguing" are important factors for vehicle operation, it is clearly necessary to be careful not to overly augment the lower range.

Among the three factors emerging in the factor analysis, comfort and clarity showed the highest scores with the -6 dB/oct. filter, while the sound factor showed increasing scores with increasing bass augmentation. This analysis suggests that comfort may be improved by augmenting the bass to a level roughly equal to that of the car interior noise.

The above results suggest that taking into account the frequency characteristics of car audio system sound during is effective in improving comfort.

4. SUMMARY

In the present study, a subjective evaluation experiment was conducted concerning reproduced sound, which took into account the frequency characteristics of car interior noise during car travel, and the results were verified.

The evaluation experiment was conducted using experimental stimuli consisting of 10 types of sound source, screened through 5 frequency characteristic filters designed to augment the bass, with typical car interior noise (at 60 km/h) being added to each sound source. The evaluation terms were 12 adjective pairs related to sound quality, palatability, added value and safety. The results of the experiment showed that the -6 dB/oct. filter, which augmented the bass to a level slightly below the frequency characteristic curve of the car interior noise (-7 dB/oct.), had higher evaluation scores for items of preference and safety; and that the -9 dB/oct. filter had higher scores for sound quality and added value items. Factor analysis was also conducted, to identify comfort, sound field, and clarity factors. Comparison based on the factor scores showed that higher scores were obtained in the vicinity of the -6.0 dB/oct. characteristics than those of other filters, in terms of the comfort and clarity factors. Thus, it is suggested that car interior comfort can be improved by augmenting the bass to a level roughly equal to that of road noise.

The above results confirmed that taking into account the frequency characteristics of car audio system sound during travel is effective in improving car interior comfort.

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