

Development of a New Software for Objective Evaluation of Interior Sound of Sports Cars

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ABSTRACT

An evaluation method was developed for the interior sound of sports cars. This method was derived from the precise subjective evaluations of 12 sports cars and consists of objective parameters. Further, it was found that there is only a slight difference in perception of sporty sound between Austrians and Japanese. As a result of this research, software for use in development of sound quality was developed and will be useful in the development of sports cars with optimum interior sound.

1. Introduction

The character of interior sound is an important element in enhancing the commercial attractiveness of a sports car. Sports cars have high-quality exteriors, powerful engines, and highly responsive suspensions. Furthermore, the engine sound heard in a cabin during acceleration or during a down-shift conveys information to the driver about the vehicle's response. Therefore, the engine sound during acceleration, for example, must communicate vehicle performance and overall vehicle quality. Given this situation, it is inefficient to attempt development of a sporty sound in the absence of concrete numerical criteria. An enormous number of man-hours have been expended on trial-and-error development efforts involving the fabrication of many prototypes and creation of subjective evaluative criteria for the character of interior sound. The use of objective parameters to express the character of interior sound is essential in the logical development of a sporty sound. If this were possible, it would subsequently be possible to determine target interior sound candidates on a sporty sound map during the development of a new vehicle after considering relative positioning with competitor vehicles and our concept for the new vehicle. As a result, it would be possible to determine the target sound after listening to the target sound candidates created according to their positioning on the map. The adoption of this kind of sound character index for interior sound would not only allow determination of a target interior sound, but it would also enable significant reductions in the man-hours

expended in new-car development overall. Very little research, however, makes reference to the character of interior sound of sports cars.^{(1)–(3)}

This paper reports on a method for creating an index that uses objective parameters to express the interior sound character of a sports car, and presents examples of the practical application of that method. It will also describe the difference in how sports car interior sound character is perceived by Austrians and Japanese. Further, as we developed software to enhance the usefulness of these research results, we will provide an example of its practical application.

2. Method for the subjective evaluation of sports car interior sound character

Fig. 1 shows the flow used to approach the creation of an interior sound character index. The left side of this flow chart represents subjective evaluation, while the right side shows objective analysis.⁽⁴⁾⁽⁵⁾ A comparative analysis of the subjective evaluation scores and the objective parameters for each vehicle is then performed using regression analysis and other methods to generate the sporty sound index. This is a standard method for representing sensory quantities as parameters that can be measured using instruments.

The first thing that must be considered when conducting subjective evaluation is the proper selection of test subjects who match the items being evaluated. Statistical methods were used to select the test subjects in order to obtain highly

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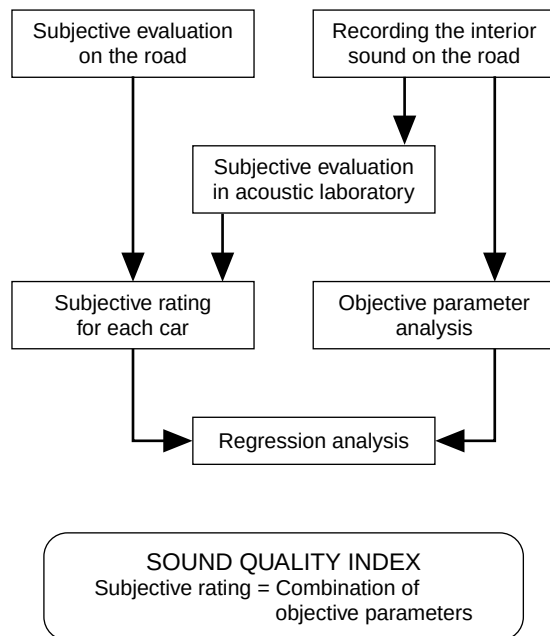


Fig. 1 Overview of approach to create a sound index

accurate evaluation scores that would be usable for comparison with objective quantities. Austrian test subject candidates were presented with questions to identify which of 23 vehicle-related items, such as interior and exterior, specifications, cost, performance, and so on, they considered important. The results were used to select test subjects who were considered capable of evaluating sports car sound. As shown in Fig. 2, the results can be divided into five main clusters⁽⁶⁾⁽⁷⁾ according to their attributes. The test subjects classified under clusters 2 and 3 place importance on the interior sound in sports cars and high-end vehicles (exclusive cars). Therefore, 31 people were selected from these clusters as the final test subjects.

The subjective evaluations were carried out through two tests, an on-road evaluation conducted using actual cars on the road, and an auditory evaluation conducted in an acoustic laboratory by playing back sounds recorded on the road. These tests used the sounds from twelve well-known types of sports cars with different engine types and displacements, as shown in Table 1.

Table 1 List of sports cars tested

No.	Engine type	Displacement [liter]
1	L4	2.0
2	L4	2.0
3	L4 + SC	2.3
4	L6	2.8
5	L4	2.0
6	L4	1.9
7	F6	3.4
8	V6	2.0
9	F6	2.5
10	V8	3.5
11	L4	2.0
12	V8	3.6

3. Subjective on-road evaluations

3.1 Method

For the on-road evaluations, one expert driver operated the vehicles while the test subjects sat in the passenger seat and concentrated on evaluating the interior sound. The tests were conducted on a level road with a dry asphalt surface, and the driving conditions were as follows:

2nd gear Wide open throttle acceleration
 3rd gear Wide open throttle acceleration
 Top gear Constant 150 km/h

No. of People		66	54	68	39	42	total 269 male
		Cluster of driver stereotypes					
		1	2	3	4	5	
Factor Analysis of vehicle main attributes	1 Prestige/Sound						
	2 Performance						
	3 Convenience						
	4 Family						
	5 Noise Quality						
	6 Cost						
Important Attributes	Performance						
	Family						
	Cost						
Unimportant Attributes	Prestige						
Driver Stereotypes		Family Man	Ambitious People	Successful Wealthy	Must buy what is available	Convenience is high priority	

high importance

low importance

Fig. 2 Driver stereotypes

The question posed in the on-road tests was, “How sporty do you consider this interior sound to be for this class of sports car?” The determination was made by assigning a score ranging from 1 point (not at all) to 20 points (completely sporty in character).

3.2 Results

Fig. 3 presents the average scores from 22 test subjects under the three types of driving conditions. The scores for each car diverge widely at wide open throttle (WOT) and the ranking of each car is distinctly defined, indicating that the test subjects were able to differentiate each car from the others. By contrast, the scores from the 150-kph constant speed test were low and they were closer together. This shows that it is more difficult for the test subjects to evaluate sportiness at a constant 150 kph than at WOT.

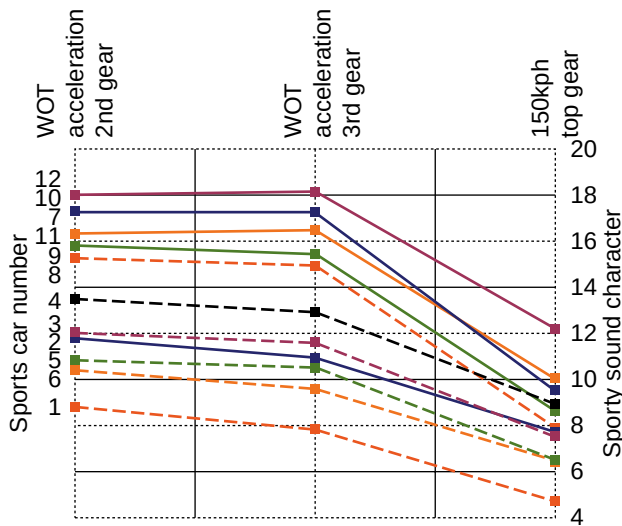


Fig. 3 Results of subjective interior road evaluations of sports cars

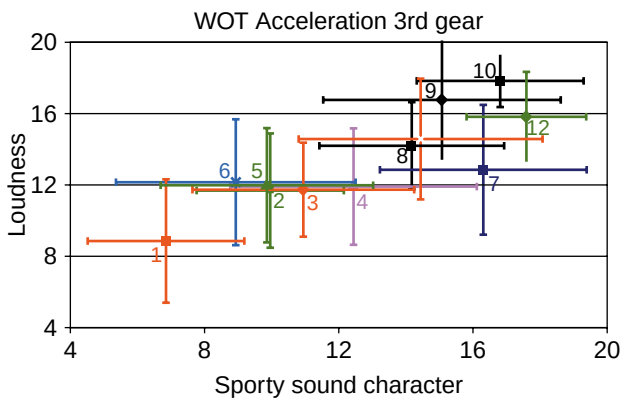


Fig. 4 Results of a subjective interior road evaluation of sports cars at WOT 3rd gear (average judgement of 22 subjects, plus spread of judgements for each car)

Tests were also conducted using multiple types of sensory measurements, with test subjects evaluating loudness and sportiness simultaneously. The results plotted on a two-dimensional map along an axis of score values are presented in Fig. 4. Subjective evaluations were conducted by 22 test subjects under the three driving conditions described above. The results obtained for WOT in third gear are shown as typical. Fig. 4 shows the average scores of all test subjects for each vehicle together with their scatter. Examination of the arrangement of average scores shows that loudness and sportiness appear to be positively correlated. However, there is a very large variance in the scores, exceeding the difference between the average scores, so the results are lacking in accuracy. Thus, the relationship between sportiness and loudness will be further examined, in a later section, by auditory tests conducted in an acoustic laboratory using sample sounds and original sounds tuned to the same sound level.

4. Subjective evaluations by auditory tests

4.1 Method

Recordings were made of interior sounds under the same conditions as for the subjective evaluations on the road. A dummy head microphone was placed in the passenger seat and the same expert driver as in the on-road evaluations operated the test vehicle while the interior sound was recorded. The HMS III made by HEAD Acoustics GmbH, which is capable of digital recording, was used as the dummy head recording system.

The sounds recorded in this way were used to conduct sound evaluations in an acoustic laboratory as shown in Fig. 5. The playback signals are divided into two parts, the low-frequency components of 100 Hz or lower, and the high-frequency components of 100 Hz or higher. The high-frequency sounds are played back through headphones. The low-frequency sounds are played back through a subwoofer so that the test subject can feel the sound through the body while hearing through the ears. The subjective evaluations were carried out using subjective evaluation software made by AVL List GmbH, and the scoring was done using a finer scale (from 1 to 50 points) than in the on-road tests.

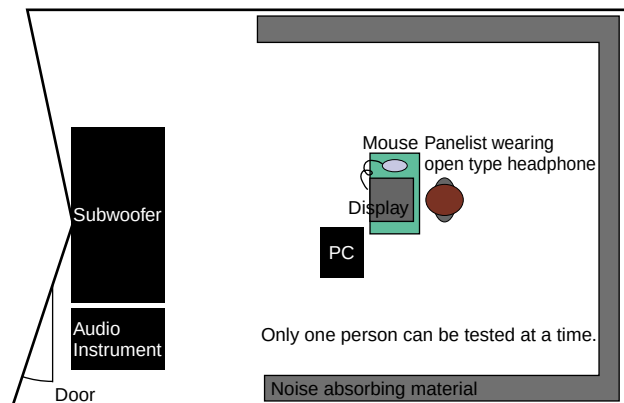


Fig. 5 Layout of psychoacoustic laboratory

4.2 Results

The results from tests on the correlation between loudness and sportiness described in section 3.2 are presented in Fig. 6. This compares the scores for sportiness from auditory tests using samples of the original sound and sounds adjusted to be the same loudness. The data for each car are arranged from left to right in ascending order of engine speed. The original sound from sports car 2 and the sample of the same loudness produced subjective evaluation scores that are completely opposite. This shows that there are cases when sportiness and loudness are not positively correlated. It became clear, therefore, that volume and other parameters of loudness alone cannot represent sportiness.

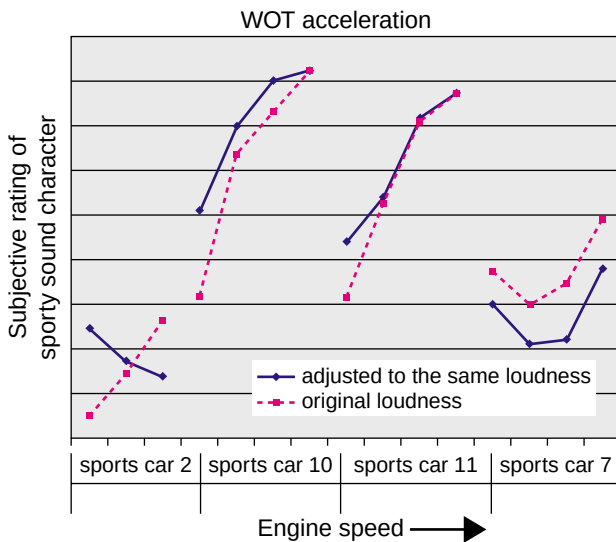


Fig. 6 Comparison of subjective rating between original sounds and sounds adjusted to be the same loudness

5. Comparison of subjective evaluations in the acoustic laboratory and on the road

In order to demonstrate that the sounds played back in the acoustic laboratory are equivalent to the impressions of interior sounds heard on the road, it is necessary to compare the auditory test scores with the on-road scores.

Fig. 7 presents the results from a comparison of the scores from auditory testing in the laboratory and from on-road evaluations. The $\triangle$ symbols indicate comparisons of raw, unadjusted scores. Here the correlation factor is 0.82, which is not very high. This is because the test subjects made their judgments while experiencing the brand image, visual sensations, the stimulation of vibration and acceleration, and so on as well as the sound when they were on the road. Consequently, a comparison was made of the auditory testing and on-road results with consideration of acceleration performance as well as sound.

When regression analysis of the auditory test scores together with the weight/power ratio for each car was

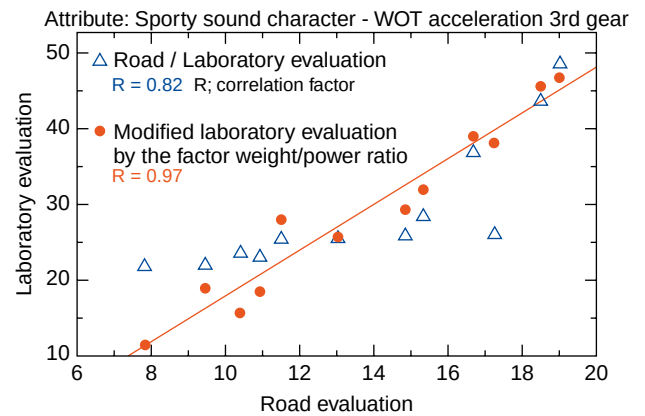


Fig. 7 Comparison of subjective laboratory and road evaluation results for 12 sports cars

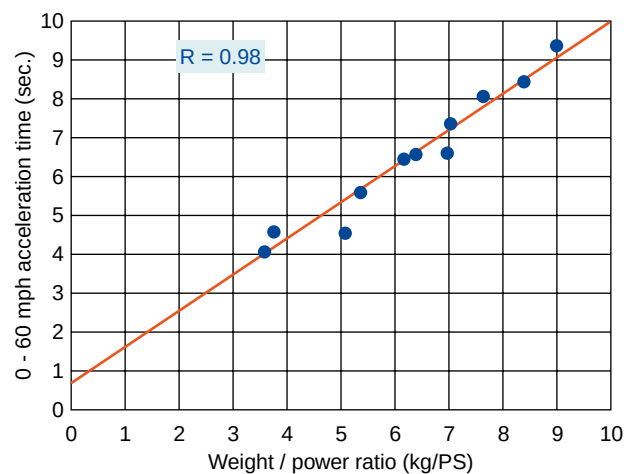


Fig. 8 Comparison between weight/power ratio and 0-60 mile per hour acceleration time

performed, the correlation factor rose to 0.97, as shown by the $\bullet$ symbols. This is an excellent correlation. As seen in Fig. 8, the weight/power ratio is a quantity that is very closely linked to acceleration time. It is apparent, therefore, that the score for sporty sound on the road is formed from evaluation of the interior sound alone and with the evaluation of acceleration. In other words, the auditory testing scores represent the scoring results from on-road evaluation of the interior sound only.

6. Objective representation of interior sound character

Regression analysis of subjective evaluation scores and psychoacoustic measures and other objective parameters was performed in order to determine sportiness, the level of sporty interior sound.⁽⁴⁾⁽⁷⁾ This revealed the involvement of the so-called mid-frequency range. However, it was difficult to obtain a correlation with existing objective parameters sufficient to use this as an index.

As shown in Fig. 9, therefore, we introduced an order component of engine speed to serve as an element of sound

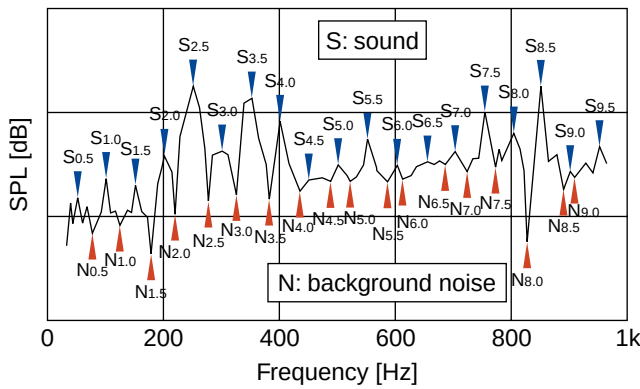


Fig. 9 Definition of sound and noise

character that positively affects sportiness, and background noise other than the order component to serve as an element of sound character that negatively affects the sound character. We then defined the order to noise ratio (ONR) as a new parameter that follows objective procedures to represent the sportiness perceived subjectively using these elements. The ONR is a quantity expressing the extent to which the sound exceeds the background noise. Our research then focused on determining the optimum order domain and weighting.

As a final result we obtained the below expression, which is an objective representation of sportiness:

$$\text{Sportiness} = A \cdot (\text{ONR}) + B \cdot (\text{TP}) + C \cdot (\text{ESP}) - D$$

A, B, C, D: Constants

TP: Tonality

ESP: Engine speed increase rate

Fig. 10 shows the correlation between sportiness on the basis of objective parameters and the subjective scores for each vehicle from the acoustic laboratory. The correlation factor is 0.97, which indicates that there is an extremely favorable correlation.

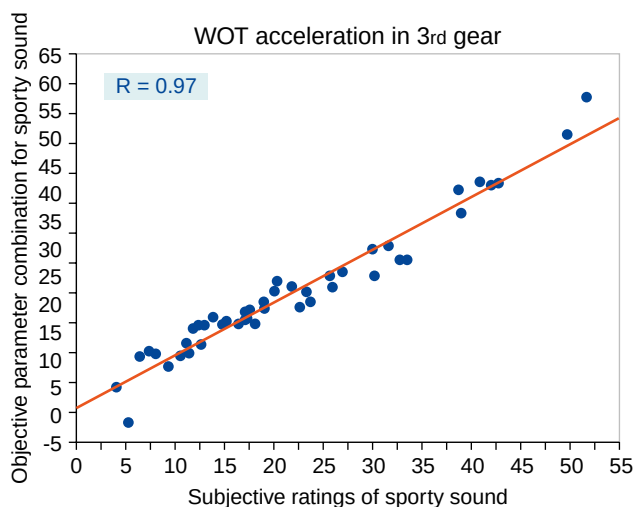


Fig. 10 Subjective rating of sporty sound character compared to objective evaluation results

7. Differences between Austrian and Japanese perceptions with respect to sports car interior sound

The discussion up to this point has dealt with the perceptions of Austrians with respect to interior sound. Japanese subjects were then tested using the same procedures as for Austrians in order to investigate whether there is any difference in the Austrian and Japanese perception of sporty sound. The 32 Japanese test subjects who were selected, however, are people who already own sports cars.

As can be seen in Fig. 11, the scores given each vehicle for interior sporty sound by the Japanese and Austrian subjects showed a correlation factor of 0.98, which is an extremely high correlation. This indicates that the two groups perceive and evaluate sporty sound in a similar manner. A previous study has shown that Europeans and Americans are more tolerant of low-frequency sounds than Japanese, and less tolerant of high-frequency sounds. On first glance, our results may appear to contradict that study.⁽⁴⁾ However, the results of tests with Austrians described in section 6 determined that the frequency range showing a high correlation with sporty sound was the mid-frequency range. Thus, it can be concluded that subject impressions of the mid-frequency range supercede those of the low-frequency range in determining sporty sound, which was why no major differences appeared in the scores from these two groups of subjects.

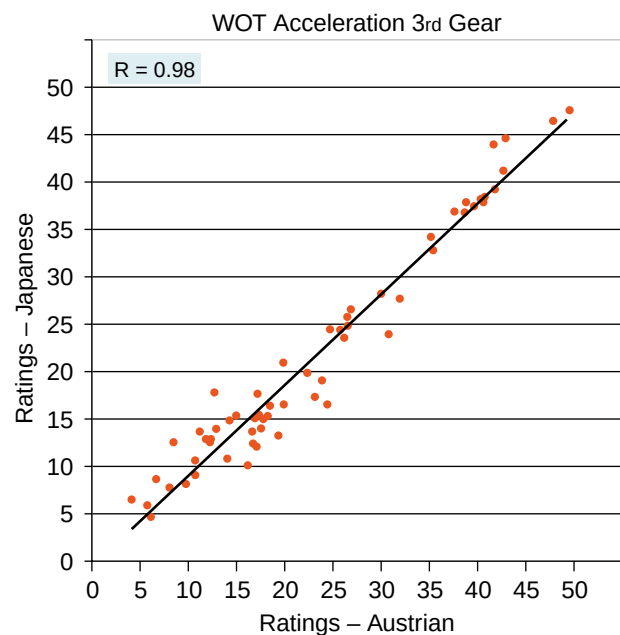


Fig. 11 Comparison of subjective ratings between Austrian and Japanese

8. Sporty sound quality software explanation and application example

As discussed in section 6, it has become possible to use objective parameters, or in other words linear combinations of measurable quantities, to represent the sportiness that is one of the sensory attributes of sports car interior sound character. Consequently, we have developed Sporty Sound Quality Software (SSQS) as a tool that can be applied in sports car development. SSQS not only functions to calculate sportiness, but also provides both database functions and simulation of sportiness using the physical quantities of interior sound. Its basic structure is shown in Fig. 12.

This software was used to improve the interior sound in a certain sports car with a 4-cylinder, 2-liter engine as is shown in Fig. 13. The mid-frequency range of the interior sound contains a component order of engine speed. The vehicle's sportiness increases as this sound becomes larger relative to the background noise. Simply increasing the component order, however, will also end up increasing the loudness itself. Therefore we reduced the low-frequency

component, which has a weaker correlation with sportiness. As a result, not only did this reduce loudness, but we were also able to enhance sportiness.

9. Conclusion

This research yielded the following results regarding the interior sound character of sports cars:

- (1) A method for highly accurate subjective evaluation consisting solely of interior sound alone was developed. The ability to quantify the effect of acceleration on the results of subjective evaluation on the road was also established.
- (2) An expression of sportiness that uses objective parameters to express the character of interior sound in terms of the results from subjective evaluation of interior sportiness was established.
- (3) It was determined that there is almost no difference between Austrians and Japanese in the perception of sportiness.
- (4) SSQS software was developed to enable evaluation and simulation of sportiness as described above for use in automobile development.

We hope that this method proves useful in the creation of future products that will give sports car users greater enjoyment of the sense of sportiness.

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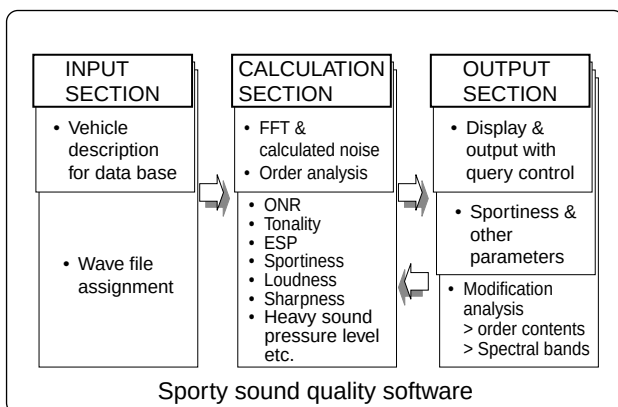
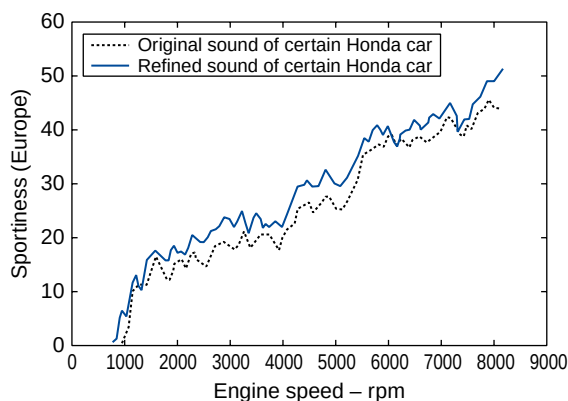
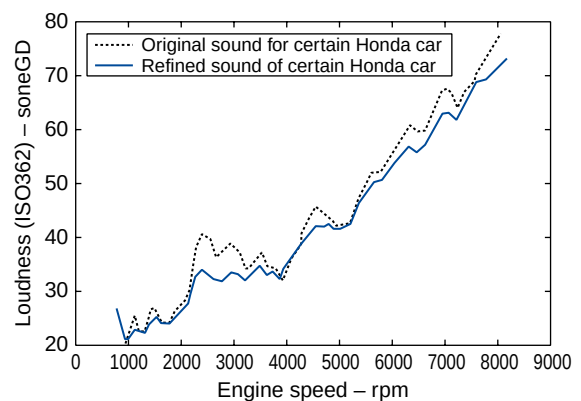


Fig. 12 Schematic flowchart of SSQS



(a) Sportiness



(b) Loudness

Fig. 13 Refinement of sportiness

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