Psychoacoustic investigation on sport sound of automotive tailpipe noise

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Introduction

In addition to technical and economical aspects, the emotional component of modern cars gains more and more importance. The sound of the exhaust system is one of these emotional components. Due to the legislative limitation of the pass-by-noise level, it is not possible to emphasise the sportiness by simply increasing the emitted sound pressure level. Therefore, the first part of this investigation dealt with the characterisation of sport sound of automotive tailpipe noise at comparable dB(A)-levels. One of the aims was to find out which physical and psychoacoustic components of the sounds are responsible for subjective evaluations such as powerful, sporty, comfortable, luxurious etc. Hereby, the association between physical (e.g. engine order) and psychoacoustic parameters (e.g. loudness [1]) should be systematically investigated backed up by an appropriate extensive statistical study.

Test sounds and design of the jury evaluation

From the Eberspächer sound data base samples from several passenger cars were selected. These sounds were measured under full load acceleration at roller dynamometers with an artificial head about 2 metres behind the car (**Table 1**). The measured A-weighted sound pressure level differs strongly among the cars which influences peoples subjective evaluation of the sound enormously. However, since this effect should not affect the findings of this study all sounds were postprocessed to have the same A-weighted sound pressure level at 3500 rpm. Furthermore, it is well known among automotive engineers that the ratio of engine orders mainly controls its subjective perception. Several publications on automotive sport sound report on different aspects and come to at least partially different conclusions on what finally determines e.g. the sportiness of a sound [2,3,4,5]. Therefore, two of the original sounds (1 and 3) were further order-filtered to investigate the impact of different ratios of the dominating engine orders according to published rules (**Table 2**).

In the jury evaluation the sounds were reproduced with high-quality electrostatic headphones. To protect the test subjects the overall level had to be reduced in comparison to the original sound but was carefully adjusted to the same level before each listening session. All sounds were played in an arbitrary sequence and at least twice for statistical reasons. Between the sounds there was a pause of about 10 s. The questionnaire contained two parts:

Part A: subjective evaluations (adjective pairs rated between 1 and 10 according to VDI 2563 e.g. not sporty-sporty, uncomfortable-comfortable, unpleasant-pleasant, weak-powerful).

Part B: personal questions (gender, age, car ownership, annual mileage and interest in sports cars).

To avoid any influence of a supervisor the questions and the sounds were presented by an automated PC-program.

Psychoacoustic and statistical analysis

Since more than 100 subjects (mostly students and members of Eberspächer development departments) took part in the jury evaluation there were quit a lot of data to be examined and statistically analysed. After checking the normal distribution and consequently of standard deviations a factor analysis was carried out to describe each sound in a two-dimensional space of the subjective impressions sportiness and comfort (**Fig. 1**).

Apparently, the chosen sounds elicit strong variations in the subjective judgements. The arrows symbolise the alteration of the subjective evaluation due to the engine order manipulation (A1, A2, and B2) while the order filtering B1 did not substantially change the subjective impression of the sound. Since the engine order increase also raised the overall level a reduction of the sound pressure level at 3500 rpm was necessary afterwards. Note that compared to the original sound the final variants A1 and A2 have decreased loudness and sharpness values which is beneficial for comfort and decreases the sportiness slightly. Another effect of engine order ratios can be explained by looking at the different judgements of sound No. 3 and No. 10. While No. 10 contains mainly a dominating 3rd order in No. 3 also a 4.5th order is present. Obviously, this increases sportiness but lowers somewhat the comfort. On the other hand, the comparison of sound No. 3 and sound No. 8 (A2) shows, that a dominating 4th and 6th engine order is superior in comfort but considerably less sporty than a sound with 3rd and 4.5th order.

Apart from the above mentioned analysis the instationary psychoacoustic measures were determined. **Table 3** lists the data which were averaged over the whole speed range. The averaging was necessary to gain a single number value for each category to perform a regression analysis with the also single number value of the subjective rating although clearly some information is lost by this process. Nevertheless, it can be seen, that the loudness differs substantially among the sounds although their A-weighted level was equalised. In most cases the sounds with higher loudness yielded higher sportiness and lower comfort ratings as one might expect (e.g. No. 7 and in the contrary No. 6 and No. 5). The roughness and also the fluctuation strength did not vary a lot since no explicit sports cars with high uneven order content were measured. Thus, an influence on comfort and sportiness could not be observed although it is presumably there. In the contrary, another connection could be statistically proven - high sharpness values spoil the acoustic comfort and are not beneficial towards sportiness (e.g. No. 9 and in contrast No. 8).

Further detailed regression analysis was conducted including the loudness increase over speed range (sone/rpm) which revealed more interesting results. For example, a distinct compensation of high engine orders, their increase over speed and sharpness on the other hand on sportiness and comfort was observed.

The assessment of the questionnaire Part B yielded, that the judgements of the different groups of persons did vary little on sportiness and somewhat more but not essential in the categories determining the comfort. As a consequence, the number of subjects in the tests can be reduced without risking loss of statistical accuracy and hence the validity of final judgements.

Summary of results and outlook

Although the results of the study have many aspects some of the main conclusion can be summarised:

- an extensive jury evaluation with 101 subjects was performed

- a statistical analysis verified relations between physical and psychoacoustic measures as well as subjective ratings
- higher loudness was found to be beneficial for sportiness but detrimental for comfort
- the ratio of engine orders determines also the subjective evaluation of sportiness and comfort
- reducing the firing frequency and increasing the 1st and 2nd harmonic increases the comfort substantially while the impact on sportiness is only minor
- the sharpness has a pronounced negative effect on subjective acoustic comfort.

Future work at Eberspächer will be attributed towards the:
- determination of influence of roughness and fluctuation strength on comfort and sportiness
- relationship between several relevant measures on the subjective evaluation (compensation effects)
- development of a calculation procedure for exhaust noise sportiness and comfort based on measurements and
- validation of the procedure with computations derived from CAE-models and
- realisation of target sounds with optimised exhaust system designs.

References

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Sound No.	Engine / cylinders	Charge	Displacement [cm³]	Power [kW] at rpm
1-A)	Otto/R4	Turbo	1781	165 / 5900
2	Otto/R4	no	1995	105 / 6000
3-B)	Otto/V6	no	2946	140 / 5500
4-A1)	Otto/R4	Turbo	1781	165 / 5900
5	Otto/V6	no	3695	173 / 5600
6	Diesel/R4	Turbo	1896	81 / 4150
7-B1)	Otto/V6	no	2946	140 / 5500
8-A2)	Otto/R4	Turbo	1781	165 / 5900
9-B2)	Otto/V6	no	2946	140 / 5500
10	Otto/V6	no	2800	142 / 6000

Table 1: Overview of the test sounds derived from different engines and their variants (R…inline engine; V…V-engine; A1), A2), B1), B2) …variants of original sound A or B) see Table 2

Variant	Alteration of engine order no.
4-(A1)	1, 3 and 5: increased by 10 dB(lin) 4 and 6: decreased by 5 dB(lin)
8-(A2)	4 and 6: increased by 10 dB(lin)
7-(B1)	dominating 3rd order: increase of 5 dB(lin) per 1000 rpm starting with 102 dB(lin) at 1000 rpm
9-(B2)	dominating 3rd , 6th and 9th order

Table 2: Alteration of the original sound No.1(A) and No.3(B)

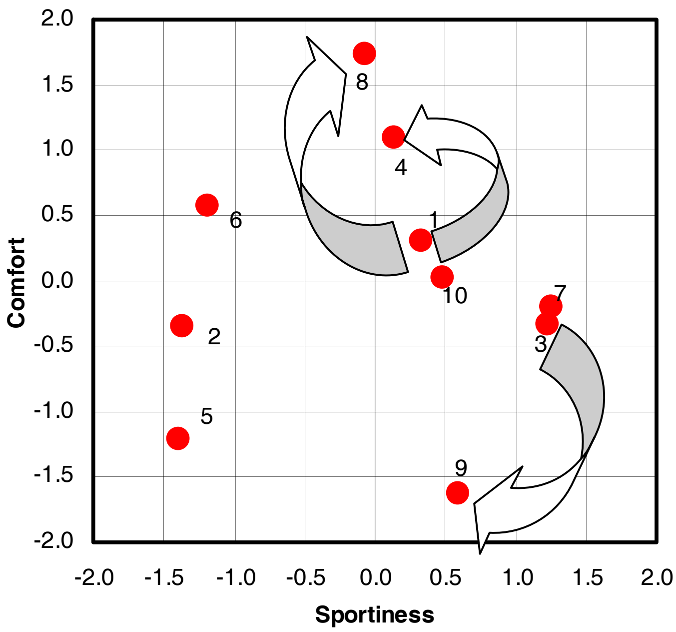

Figure 1: Subjective evaluation of the test sounds

Sound No.	Loudness [sone]	Roughness [asper]	Fluctuation strength [vacil]	Sharpness [acum]
1-A)	91	0.14	0.03	0.88
2	89	0.16	0.03	1.14
3-B)	101	0.13	0.04	1.09
4-A1)	82	0.15	0.04	0.72
5	98	0.13	0.03	1.09
6	67	0.13	0.03	1.23
7-B1)	122	0.12	0.05	0.94
8-A2)	75	0.13	0.05	0.77
9-B2)	89	0.14	0.04	1.16
10	107	0.13	0.03	1.12

Table 3: Average psychoacoustic data of the sound samples