Sound Quality of Starting Electric Railbound Vehicles - Dimensions of Hearing and Relevant Psychoacoustic Quantities

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1. Introduction

In order to investigate the psychoacoustic optimisation potential of starting electric railbound vehicles, sound-generating parameters have been introduced in another paper at this conference [1]. This contribution focuses on traction-noise perception. The question is if conventional descriptors like A-weighted level, loudness or sharpness are appropriate for psychoacoustic evaluation. There are some arguments for a more detailed look at these quantities:

- The link between sensation and physical descriptor can be product-dependent [2],
- some new product-dependent quantities might be appropriate, like "dieselness" in the field of automobiles [3].

Thus it is a useful strategy to study the dimensions of perception first and physical descriptors afterwards.

2. Dimensions of hearing

2.1 Test A: Semantic-differential test

For a psychoacoustic study of a relatively unknown type of sound, a well-known approach is the semantic differential with subsequent factor analysis. Both stimuli and adjective pairs must be chosen very carefully because the results depend on this choice.

17 stimuli of 2 s length were selected from binaural recordings inside starting vehicles. The short length of 2 s was necessary because it is not wanted that sound characteristics vary in time. They comprised different sound types according to [1], varying in types of motors and converters:

- 1 × driveless car (just broad-band noise),
- 1 × DC motor (the following are all induction machines),
- 2 × thyristor with phase-sequence switching,
- 4 × GTO with PWM and constant switching frequency (f_S),
- 1 × GTO with PWM and increasing f_S,
- 1 × GTO with DTC,
- 4 × GTO with synchronous switching,
- 3 × IGBT with PWM and constant f_S or RCFM.

Many sets of adjective pairs have been elaborated in various studies before, but they are mostly adapted to a certain product. Since no set was found for railbound-vehicle traction noise, adjective pairs for environmental sounds from Johannsen and Prante [4] were chosen for this study and slightly modified after a pilot test. The listening test itself was carried out with

- Stax Lambda headphones, presentation in original loudness,
- a 7-step category scale from –3 to +3,
- 16 normal hearing subjects,
- an explanation phase of stimuli, adjectives and context before,
- and statistical evaluation with SPSS for Windows.

The test yielded the following results for 22 adjective pairs:

- good suitability of factor analysis due to a KMO value of 0.90,
- four factors explaining 68.4% of total variance.

Figure 1 shows the squared factor loadings and one part of the related adjectives. All factors are named after the highest loading. The fourth factor, however, was changed from "dynamic" to "temporal activity" in order to avoid confusion with dynamic loudness.

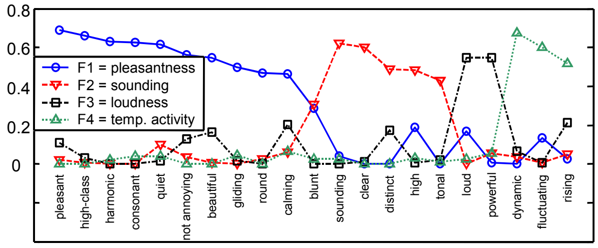

Figure 1: Squared factor loadings and related adjectives

To conclude, traction noise is perceived mainly in these four dimensions. Even a silent sound can thus be unpleasant. Sharpness and roughness are not visible as separate dimensions as it was the case in [4], but it can be assumed that they are part of the pleasantness factor. A complete listing of factor values would be too extensive, so that the most prominent factor values are listed instead:

- most pleasant sounds: DC motor (1.08), IGBT+RCFM (0.91),
- least pleasant sounds: GTO+DTC (-1.40), thyristor (-1.01),
- most sounding sound: thyristor (0.86),
- least sounding sound: driveless car (-1.46),
- highest temporal activity: GTO with fast increasing f_S (0.66),
- lowest temporal activity: GTO with constant f_S (-1.70).

The finding of physical descriptors for the factor values will be explained in Sec. 3. It can be assumed that the most important "pleasantness" factor F1 depends on more than one quantity, but unfortunately, high inter-correlations between the descriptors made a multiple-regression analysis impossible. Therefore, the pleasantness factor was investigated in a second test, see next section.

2.2 Test B: Rating-scale test for pleasantness

Correlating pleasantness with psychoacoustic quantities has been subject to various studies before. Again, it is assumed that these dependencies are product-dependent [2] so that a new test was carried out with the following features:

- A category partitioning (CP) scale [5] with 5 main adjectives (very pleasant – pleasant – medium – unpleasant – very unpleasant) and 10 sub-categories each,
- a higher number of 30 stimuli, length again 2 s, presented by headphones like in test A,
- types of converters and motors distributed similar to test A, whereby two of the new stimuli include PCFM [1],
- loudness of all stimuli was adjusted to 17 soneGD, in order to avoid a high influence of this parameter [2],
- preceding tests of collinearity: inter-correlations of assumed psychoacoustic quantities did not exceed 0.4,
- one anchor stimulus that made the test more convenient, and
- 19 normal hearing subjects.
- Results: see Sec. 3.2.

3. Psychoacoustic descriptors

It is evident that both A-weighted level and loudness [6] show significant correlations with the "loudness" factor F3 from test A. Therefore, it is more interesting to investigate the "pleasantness" and "sounding" factors. Note that a suitable descriptor for the "temporal activity" (F4) has not been found yet. All of the following calculations are arithmetic means between right and left ear.

3.1 Tonality

It can be assumed that the "sounding" factor F2 can be explained by the physical descriptor tonality alone, since the correlation with sharpness was negative and very low (–0.27). However, it is not so easy to find an appropriate model. In this study, two German guidelines are compared, which are DIN 45681 (draft 2002), basing on the tone-to-noise method, and VDV 154 - a guideline designed especially for trams and light-rail vehicles [7], involving the prominence-ratio technique and an approximation of critical bands by third octaves. In both cases, the (physical) level differences ΔL are taken, and averaging times are T = 2 s (DIN 45681) and T = 1 s without overlap (VDV 154). The second method yields two ΔL values for each second, so that the higher value will be taken.

In principle, both methods are difficult to apply in the case of starting railbound vehicles. The following two examples, typical for traction noise but with suppressed broad-band components, should yield a very high tonality. Prominence-ratio methods, however, indicate too low values if harmonic complex tones are distributed over neighbouring critical bands (or third octaves [7]). In Figure 2 (left), the indicated tonality of 3 dB is much too low. Furthermore, tone-to-noise methods tend to evaluate sweeps improperly if they increase too fast or if the averaging time is too long. In Figure 2 (right), especially for the sweep around f_2 a tonality of about zero dB is obtained, since it increases exactly within one critical band.

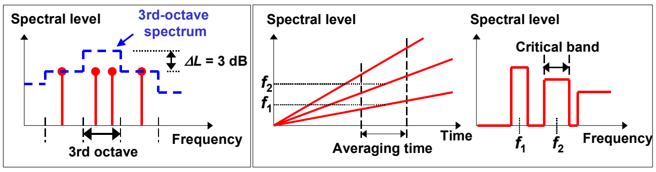

Figure 2: Examples for bad detection of tones by different tonality models

Hence, correlations are not high for both methods:

- correlation F2 / tonality (ΔL) by VDV 154: 0.50*
- correlation F2 / tonality (ΔL) by DIN 45681: 0.63**

It is sometimes useful to adapt psychoacoustic quantities to a special type of sound. Apart from other developments towards a more sophisticated model of tonality [8], a special manual procedure was elaborated within this study: All stimuli that contain sweeps are made quasi-stationary in frequency by means of order analysis (constant acceleration assumed), and ΔL [dB] is calculated by DIN 45681 afterwards. Some stimuli that have both constant and increasing tones are evaluated with and without this procedure, taking the higher tonality value into account. With these modified signals, a more satisfying result is obtained:

- correlation F2 / modified tonality (DIN 45681): 0.75**

The second factor of the listening test can therefore clearly be explained by tonality.

3.2 Descriptors for pleasantness

Since it is assumed that pleasantness depends one more than one quantity, a stepwise multiple-regression analysis is carried out with mean judgements from test B (Sec. 2.2) as criterion. One must be aware that the category-subdivision scale is not automatically an interval scale (as used in [5]). Furthermore, Beta weights and regression coefficients can depend on the chosen set of stimuli. The interval-scale assumption, however, is necessary for a multiple-regression analysis, but in this case results should rather be considered as tendencies. Hence, only Beta weights, but no regression equation will be presented. With two predictors, a corrected R^2 = 0.64 and the following Beta weights are obtained:

- sharpness (von Bismarck [6]): β-weight = 0.70 ($p < 0.001$),
- modified tonality (Sec. 3.1): β-weight = 0.60 ($p < 0.001$).

To conclude, sharpness and tonality are relevant psychoacoustic descriptors for pleasantness of railbound-vehicle traction noise apart from loudness, whereby high values indicate a high unpleasantness. It seems to be contradictory that tonality is both an individual factor (Sec. 3.1) and a predictor of another factor (pleasantness). This might be explained by the fact that subjects were trained to judge independent dimensions in test A and a rather "global" pleasantness in test B.

But since only 64% of the variance is explained, it is possible that additional predictors for pleasantness exist which are no "classical" quantities. For example, traction noise is often composed of characteristic musical intervals [1]. Although roughness values are low (≈ 0.1 asper) for most stimuli, it should be investigated if consonance has a relevant influence. Results of these studies will be presented in a further publication.

4. Conclusion

Several techniques were applied in order to investigate the perception of a relatively unknown type of noise. It was found that railbound-vehicle traction noise is perceived mainly in four dimensions, and that the most important factor called pleasantness depends on physical descriptors like sharpness and tonality. It was also shown that modifications of models or stimuli are sometimes useful. In future studies, some of the technical parameters found in [1] will be varied in a sound-synthesis model, and these optimisation measures will be evaluated by the psychoacoustic quantities. These results can also be helpful for revisions of guidelines, since they currently only contain sound level and tonality.

5. References

[1] M. Klemenz, Sound-generating Parameters of Starting Electric Railbound Vehicles and their Influence on Sound Quality. CFA/DAGA'04 (this conference)
[2] T. Hempel, Ph.D. Dissertation, Techn. Univ. Berlin, 2001
[3] C. Patsouras, Ph.D. Dissertation, Techn.Univ. München, 2003
[4] K. Johannsen, H. Prante, Proc. DAGA'98, p. 122, 1998
[5] O. Heller, Psychologische Beiträge 27, p. 478, 1985
[6] E. Zwicker, H. Fastl, Psychoacoustics. Springer Edition, 1999
[7] Geräusche von Nahverkehrsfahrzeugen nach BOStrab. VDV Schriften 154, August 2002
[8] D. Salz, S. Rossberg, Proc. DAGA'03, p. 600, 2003