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ASSESSMENT OF INTERIOR AND EXTERIOR TRAIN NOISE USING BINAURAL ARTIFICIAL-HEAD RECORDINGS

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ABSTRACT
Newly built railway tunnels have small noise absorption capabilities due to the reflecting surfaces of the tunnel wall and the usage of slab tracks without the sound absorbing ballast. When passenger trains enter the tunnel the noise characteristics change significantly, which is often perceived as very annoying by the passenger. For this reason the Austrian Federal Railways has implemented different measures to increase the noise absorption in the tunnel. To evaluate the achieved changes many binaural artificial-head recordings have been done for a total of five different tunnels over the last five years. Together with psycho-acoustic methods these recordings represent the state-of-the-art technology which is most similar to the human sound and noise perception. There are three good reasons for the use of binaural artificial-head recordings. The effects which occur can be visualised directly from the source signal and easily be interpreted. The recorded signals can also be archived and the experienced sound impression be repeated at any time and any place with a suitable piece of equipment. The most important application can be seen in the possibility to create the link between the technical noise evaluation and the personally perceived annoyance by playing the recordings to groups of test persons.

1 - INTRODUCTION

This paper is a summary of five sound and noise studies inside tunnels where a binaural artificial head was used for recording and it will give an overview of the assessment possibilities of the sound quality.

2 - METHODOLOGY OF STUDY

Due to a current definition noise is unwanted, disturbing and annoying sound and therefore the result of a very complex perception procedure. This fact has especially to be taken into account during the assessment of the sound-quality of technical products − in this case of different track types inside tunnels or on open ground. For the choice of the most appropriate assessment methodology the following aspects have to be considered:

- The target-group onto which these measurements aim − in this case the interior noise of coaches in railway tunnels − is the passenger and not the person who lives next to a track.
- Therefore, the noise, which is the basis of the assessment has to be recorded inside of the coaches.
- The assessment methodology must be able to simulate the sensory procedures as good as possible.

The results of "conventional sound measurement techniques" e.g. the monaural recordings of noise and the evaluation of maximum and equivalent A-weighted sound pressure levels, are insufficient for the assessment of the sound-quality of different slab tracks, because this methodology is unable to display audible differences in the sound characteristics.
The only methodology that covers those aspects is the binaural recording with an artificial head. The main advantages of this methodology are:

- During sound recording, the measurement device also takes into account the direction-characteristics of the ears and the outer-ear transfer function, so the real sound-impression can be reproduced at any time.
- The recorded sound can be electronically manipulated, so it is possible to simulate measurements, which change the nature of the sound (e.g. noise barriers). The manipulated sounds can then be evaluated via headphones.

The interior noise during the ride through the different sections of the tunnel was recorded with an artificial head system and taped with a digital-audio-tape-recorder. For every single measurement sequence, the artificial head was situated in every coach once at the end and once in the middle. The position of the artificial head (height of eyes and orientation) was that of an average passenger.
The interior noise was recorded in both track directions, but the orientation of the head remained the same. The coaches were – except the measurement personnel – free of passengers, doors and windows remained closed and the air-conditioning was set to average.
The test trains, consisting of the test-coaches and a type 1042 engine at the top end the end of the train, passed the tunnels at v_{max}=140 km/h.

3 - TUNNELS AND TRACK TYPES

In the years 1995 to 1999 inside five tunnels artificial head measurements have been carried out. These were the Sittenberg-tunnel (Lower Austria), the Sonnberg-tunnel (Styria), the Tauern-tunnel (Salzburg/ Carinthia), the Galgenberg-tunnel (Styria) and the Römerberg-tunnel (Upper Austria). Within all tunnels artificial head recordings ("Noise") were done and in two of them also vibration measurements ("Vibr.") were done.
Inside the tunnels four different types of track were represented namely ballast tracks with wooden/concrete sleepers ("Schotter"), slab tracks ("FF") with and without absorbing materials, a light mass-spring-system ("LMF") and a heavy mass-spring-system ("SMF").

4 - ROLLING STOCK

The Austrian Federal Railways provided the trains with the following passenger coaches:

- 1. Class RIC-coach (compartment car with air conditioning), type **Amz**
- 2. Class RIC-coach (compartment car with air conditioning), type **Bmz**
- 2. Class RIC-coach (open carriage car with air conditioning), type **Bmpz**
- 2. Class regional coach (open carriage car with half windows to open), type **Bmpz**

All coaches are 26,4 m long. The RIC-waggons are fully air conditioned and have a permitted maximum speed of 200 km/h. The regional coach is partly air conditioned and has a permitted maximum speed of 160 km/h.

5 - RESULTS

The artificial head recordings were evaluated with the binaural analysis. The first step of the analysis was to listen to the recordings and search for unwanted disturbances. These recordings were sorted out. The next step was to cut out an about 21 second long sequence of every recording, which consisted of 10 seconds ride on free track, 1 second of entering the tunnel and 10 seconds of ride inside the tunnel. Those sequences were digitally saved and therefore ready for (psycho-)acoustic analyses and also for subjective assessments. The examples shown below have somewhat other formats in order to emphasize different effects.

5.1 - Visualisation, recognition of problems and effects

From the frequency-time spectrum one can get a visualisation of the acoustical perception, recognise signs of troubles during the measurements, can relate different track or tunnel conditions to the measurement results and can make a first qualitative assessment. The following examples shall illustrate these possibilities:
A) Sonnberg-tunnel: In this spectrum the train is entering the tunnel running on ballast track with concrete sleepers beforehand and on a slab track system afterwards. The artificial head is situated in the alley of the 1. Class RIC-waggon in front of the air condition.
The noise in the side alley of the 1. Class waggon is almost the same as in the 2. Class regional waggon. In both waggons the high frequencies increase very significantly when the train is entering the tunnel.

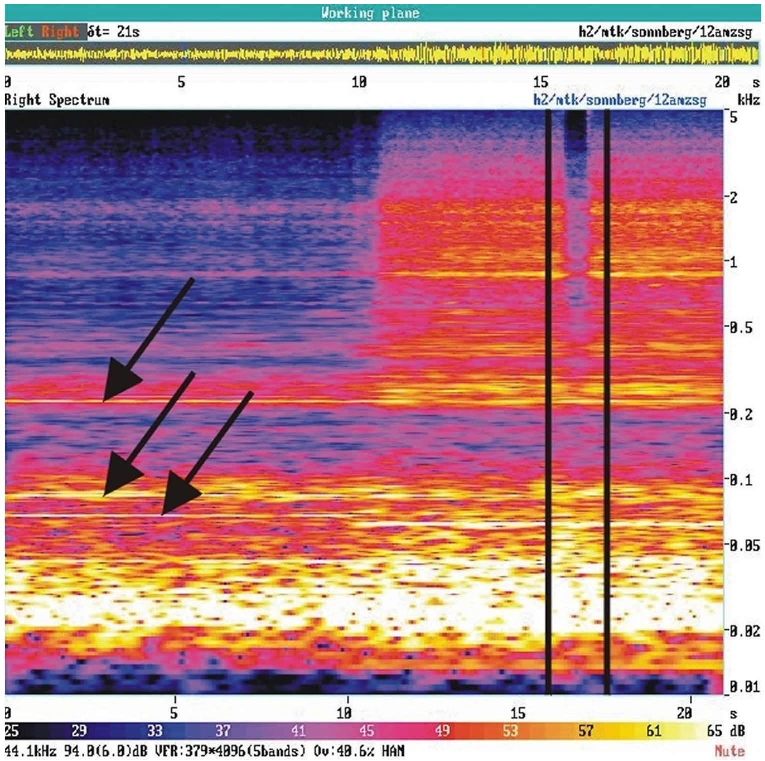

Figure 1: Spectrum of the Sonnberg-tunnel.

This increase is perceived as a strong hiss. During the short closing of the lid of the air condition the sound levels are reduced. The three arrows point to tonality components of the sound at around 60, 80 and 250 Hz, which are also coming from the air conditioning system.

B) Galgenberg-tunnel: In this example the spectrum shows the train already inside the tunnel running over a slab track without any absorbing material (section A and C) and a slab track covered with absorbing material (section B). At the end of the measurement sequence the train starts braking (90^{th} second).

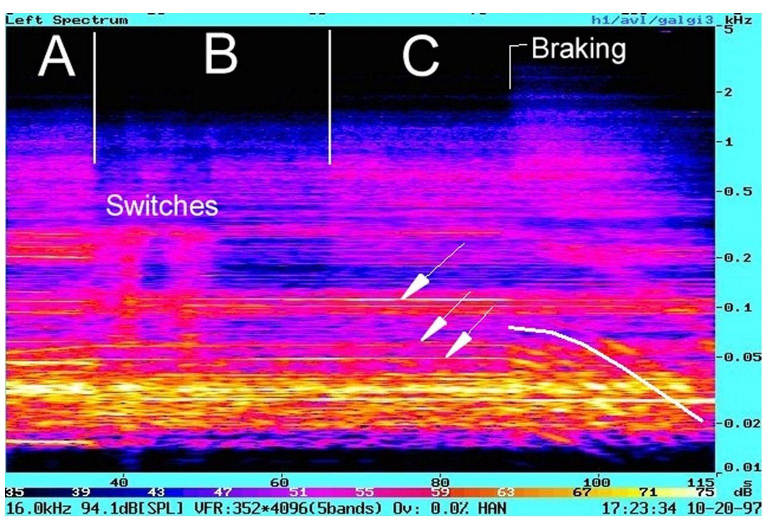

Figure 2: Spectrum of the Galgenberg-tunnel.

Between A and C the track is covered with porous concrete, which has a beneficial influence on the sound level. Especially in the frequency-bands above 150 Hz there are lower sound levels than on the "regular" slab track in A.

Within this section (B) the train is running over two switches, which leads to short level increases in

frequencies between 40 and 300 Hz.
Running onto the slab track (section C) again leads to similar levels as in A. There are also some tonality components visible (50, 60 and 100 Hz).
In the last part of the spectrum after the sharp level increase even to frequencies over 2 kHz, the train has started to brake. This can also very well be identified by the downward curved lines which are the result of reduced speed and reduced number of revolutions. The tonality components at 50 and 60 Hz are bending down as well, which shows that they origin in the speed and/or the rotating wheels. On the other hand the 100 Hz component is more or less continuing unchanged, which means that the origin is independent of speed and can be identified as the air conditioning system.
In terms of customer sound comfort the following points can be made:

- The noise in low frequencies below 100 Hz, which is due to structural sound radiation of the vehicle body, is changing very little inside all studied coaches.
- A significant level increase in frequencies over 200 Hz when the train is entering the tunnel can be stated within all coaches. This increase corresponds with the typical annoying tunnel noise perceived by the passenger.
- The 1. Class coaches have the lowest sound levels as expected.
- Within all coaches there are significant differences in the sound quality between seats over the bogie and in the middle of the coach.

5.2 - RANKING OF SYSTEMS
Generally the acoustical properties of the systems can be ranked with regard to three quite different aspects:

- Qualitatively by means of visual assessment (spectra)
- Quantitatively by means of single value indices
- Representatively by means of listening examples and evaluation of questionnaires

These different approaches haven been done to some extent. They shall be shown for the Tauern-tunnel measurements.
C) Tauern-tunnel: The three spectra represent three different track types inside the tunnel. Type 1 is a conventional ballast track, type A and B are two different slab track systems.

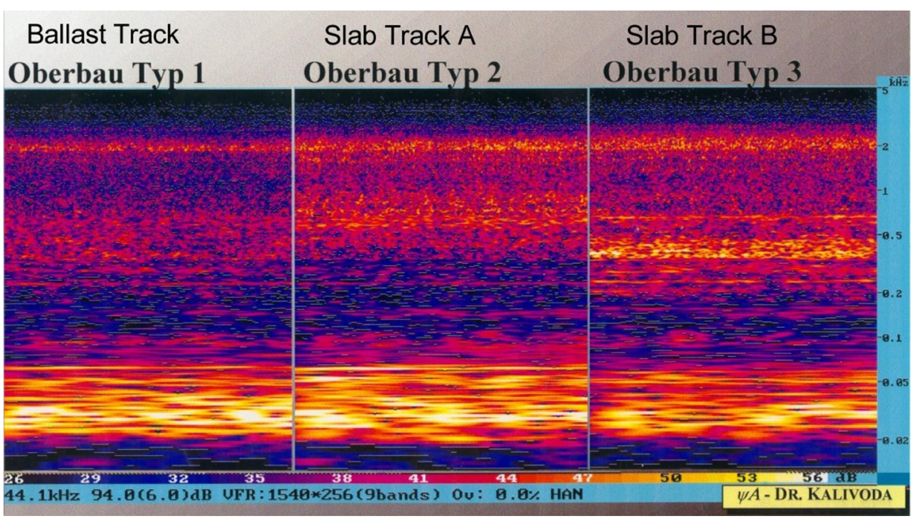

Figure 3: Spectra of the Tauern-tunnel.

As can be seen in the first spectrum (Fig. 3) the sound inside the train running on ballast track is much better balanced and has lower levels over 100 Hz than the other ones. The corresponding subjective impression is that the ballast track is not only more silent but also more pleasant than the others.
It can also be seen that by comparing the A-weighted levels (Fig. 4) there is practically no difference for the three types, whereas there are big differences in the perception of the sound qualities. The overall

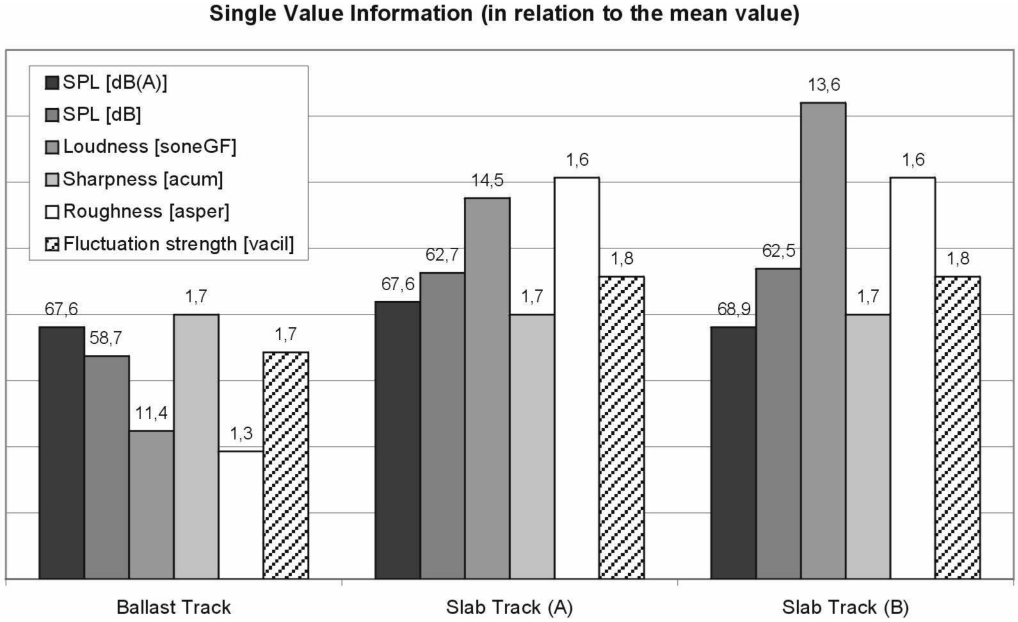

Figure 4: Different indices for three track types inside the Tauern-tunnel.

Ballast Track

Slab Track A

Slab Track B

Figure 5: Ranking of the tracks due to the Questionnaire analysis.

loudness of the ballast track (11,4 soneGF) is also lower by about 25% compared to the slab tracks (14,5/13,6 soneGF). Depending upon which index is chosen, different track orders are produced.
Also listening examples of the three track types have been produced and presented with head phones. The listener always had to choose between two examples and had to mark the one which he perceived as more pleasant. In Fig. 5 the order of the tracks starting with the most pleasant one is shown. The ballast track was perceived as more pleasant than the slab track A by 57% of the test group, slab track A compared with slab track B by 69%. The comparison of the ballast track with slab track B showed 86% favouring the ballast track. It agrees very well with the loudness numbers.

6 - CONCLUSION

The studies have shown that the differences in sound quality, which are not represented in the dB(A) levels, can be expressed in terms of spectra, loudness and other psychoacoustic parameters as well as evaluated by analysing questionnaires. Furthermore a database was created, which can be expanded by future measurements and can be used to assess other types of coaches and/or tunnels. Due to the binaural recordings these data are also a valuable source for listening studies.

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