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Annoyance of railway curve squeal

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ABSTRACT

Trains passing through a curve frequently produce the so-called curve squeal, which comprises salient noise components (typically either tonal or transient) covering a wide frequency range. Although the main underlying acoustical mechanisms are known, due to the large variety of curve squeal characteristics, their effects on acoustic parameters and in particular on the perception are difficult to quantify. The work aims at investigating the effects of acoustically described curve squeals on the perceived annoyance, tested in the laboratory with 30 listeners. Passby measurements in three narrow curves at distances of 7.5, 25, and 50 m were obtained. By means of so-called frame multipliers, time-variable salient features were manipulated and combined with a number of clean rolling noise samples to simulate squeals with parameters obtained from existing emission measurements. As a result, annoyance ratings showed that the perception of curve squeal can be considerably altered compared to that of regular passby noise. A model was developed for the

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annoyance equivalent level adjustment from a clean rolling noise based on the contrast of high and mid-frequency energy. The model predictions can serve as basis to establish rating levels predicting the perceived annoyance of railway curve squeal.

1. INTRODUCTION

When transversing in particular tight curves, rail bound vehicles can produce additional high frequency and/or tonal noise components as compared to the rolling noise on straight tracks. These noise components are called curve squeal. The mechanisms as well as the conditions producing such effects were and still are the subject of different investigations [1, 2]. In contrast to the complex mechanisms producing and affecting curve squeal, incorporating the acoustic and perceptive effects into noise mapping approaches seems to be limited to relatively simple adjustment terms taking into account only the radius of the curve [3] (Annex II).

On an Austrian national level, in recent years two studies were done investigating the effect of curve radius, speed, meteorological conditions, and conditioning of the railhead using extensive long-term measurements [4, 5]. The aim was to find relevant influencing factors like the train type, curve radius, speed, weather conditions, etc. and to derive more detailed level based adjustment factors for noise mapping based on these parameters. For trains with high noise emissions, for example, the acoustic effect of curve squeal is lower than for trains exhibiting low emissions.

Still, however, this work only included acoustic effects and did not consider perception. For example, tonal components which also occur in curve squeal are well known to produce higher annoyance ratings and are thus taken into account using a tonality penalty [6]. High frequency noise, on the other hand, shifts the spectral centroid to higher frequencies and may thus be perceived as sharper and thus more annoying. However, in the prediction model for railway noise of the European Environmental directive 2002/49/EC [3] (Annex II) squeal is taken into account by adjustment values without clarifying if these values address increases of sound pressure level or if they also incorporate annoyance effects.

As a consequence, the work presented here will focus on the perception effects of curve squeal based on a subjective noise rating experiment based on immission measurements at 25 and 50 m. Using previous emission measurements representative parameters for curve squeal were derived and used as a basis to modify the immission measurements. The manipulation of the stimuli was done using frames, i.e. a spectro-temporal representation and frame multipliers [7] which allow the modification of the stimuli in that domain. The details were reported previously [8]. 30 normal hearing listeners were asked to judge the annoyance of a large set of noise samples and a model for was derived for a annoyance equivalent level adjustment.

2. METHODS

2.1. Measurements

The acoustic measurement considered three narrow curves with radii ranges from 299 m to 332 m. On each of these sites the measurements were carried out on three days with dry weather conditions and little wind. The immission sound pressures were recorded in 25 m and in 50 m from the center line of the track and 2.2 m above the ground. Used were 1/2” free field microphones (G.R.A.S.

46AE). To compare the measurements results with previous measurements, a further microphone was situated in the standard emission measurement point in 7.5 m distance and 1.2 m above the top of the rail. All passbys were recorded with a video camera to identify the train type offline. Axle speeds were determined with the means of two light barriers across the track. In total, 214 train passbys of different train types (e.g. cargo trains, high speed train, regional trans or suburban trains) were recorded with passby speeds mostly between 70 and 80 km/h. In addition, also track decay rates and rail roughness were measured on all three sites. Mainly, the roughness of the inner rails exceeded the limit of the EN ISO 3095 [9] at higher wavelengths. One site stands out with clearly increased roughness amplitudes also in mid wavelength range, which also produced the highest noise emissions measured. However, track decay rates varied around the limit curve according to EN ISO 3095, and thus not have a significant effect on the emissions.

2.2. Sample selection

The duration of the samples for the annoyance rating was set to 4 seconds to allow for a large variety of noises to be tested. All methods and results for the remainder of this manuscript are based on this sample duration. For the experiment, clean rolling noise samples had to be selected. These rolling noise samples formed the basis for all stimuli presented. For each of the three sites rolling noise samples for a cargo train and the most typical passenger train were selected. To achieve this, for each of these six categories the median of the passby spectra was calculated. Only trains with a speed in the range from 75 km/h to 82 km/h were used. Six 4-second segments with the lowest quadratic norm of the distance between the median and the measured spectrum in the range from 50 Hz to 2 kHz were pre-selected. This frequency range was chosen, as it covers the main parts of the signal not or only slightly affected by squeal. For the two immission distances the same passby segments up to a minor correction of the segment boundaries due to the increased distance were used to allow for a direct comparison. Even though the algorithms developed in [4] were used to distinguish clean samples from tonal or broadband squeal samples, a manual selection had to be done to find the sound sample with no or only minimal non-typical rolling noise components for the recordings at 25 and 50 m. The main reason is that the algorithm works on emission measurements at 7.5 m distance and the recordings of the same segment in 25 m and 50 m contain noise from a much larger portion of the train. For the tonal squeal, recordings of all 19 detected tonal events for all distances were listened to and the instance with the most constant and cleanest tonal squeal was chosen for further processing (see below). For broadband squeal only recordings of the passenger trains of two sites were used, as the rolling noise of cargo trains and the passenger train of the third site exhibited to high rolling noise components to be used for all recordings. To allow for maximum flexibility at later processing stages, broadband squeal covering at least 85% of the 4 seconds were used. Only three suitable instances were found. One was relatively constant in amplitude, one was audibly varying and one exhibited also some tonal quality. The first instance was used for a systematic variation of spectral parameters whereas the latter two were also included for a comparison of different broadband squeal. One instance of a high frequency tonal squeal was also included in the experiment (center frequency of around 8 kHz)

2.3. Sample modification

Modification of the stimuli has been described elsewhere [8]. In brief, to produce a set of stimuli comprising a systematic variation of squeal parameters, measurements were modified and combined based on data from a previous measurement campaign. Extraction, manipulation, and combination of different components was done directly in the time-frequency-domain. For this, so called frame multipliers [7] were used which modify the analysis coefficients of the time-frequency representation of a signal. To extract the tonal squeal, a semi-automatically generated mask was used. After the extraction, the squeal was modified using a phase vocoder [10] to produce different fundamental frequencies of the squeal. Using the time-frequency representation of the isolated and modified squeal and of the rolling noise a binary mask was generated which was one for bins with higher energy in the squeal and zero for bins with higher energy in the rolling noise. To avoid artefacts from single isolated spots and holes, the binary mask was subjected to a morphological closing and opening operation. The inverse mask was used for the clean rolling noise. For broadband squeal, isolating the noise component is extremely difficult and thus the approach was to first use a lower frequency cut at 1.5 kHz with a slope of 24 dB/octave to isolate the main frequency region of the squeal above that frequency. Then, the broadband noise was modified in the time-frequency domain to achieve a certain third-octave band spectrum target defined for frequencies from 1.25 to 12.5 kHz. Then, as in the case of the tonal noise, an energy comparison was done to generate a squeal and a rolling noise mask to then combine the two signal portions. The high frequency tonal samples were processed as the other tonal squeal samples, with the squeal frequency transposed to 10 kHz.

2.4. Perception tests

For the perceptual evaluation, 30 normal-hearing listeners (16 female, 14 male, age 27.5±4 years) participated in the study. Recordings and synthetic signals were played back via headphones (HD 650, Sennheiser). The annoyance rating comprised a free magnitude estimation (see e.g. [11]). While the listeners were free to choose their range of ratings, the ratings had to be proportional to the perceived annoyance and only positive-valued ratings were allowed. Listeners had to rate the annoyance of 4 seconds long segments. The set of stimuli consisted of 234 different audio signals. Each signal was presented a total of 3 times. A full set of stimuli was split into two runs resulting in 6 runs with a minimum break of 5 minutes in between.

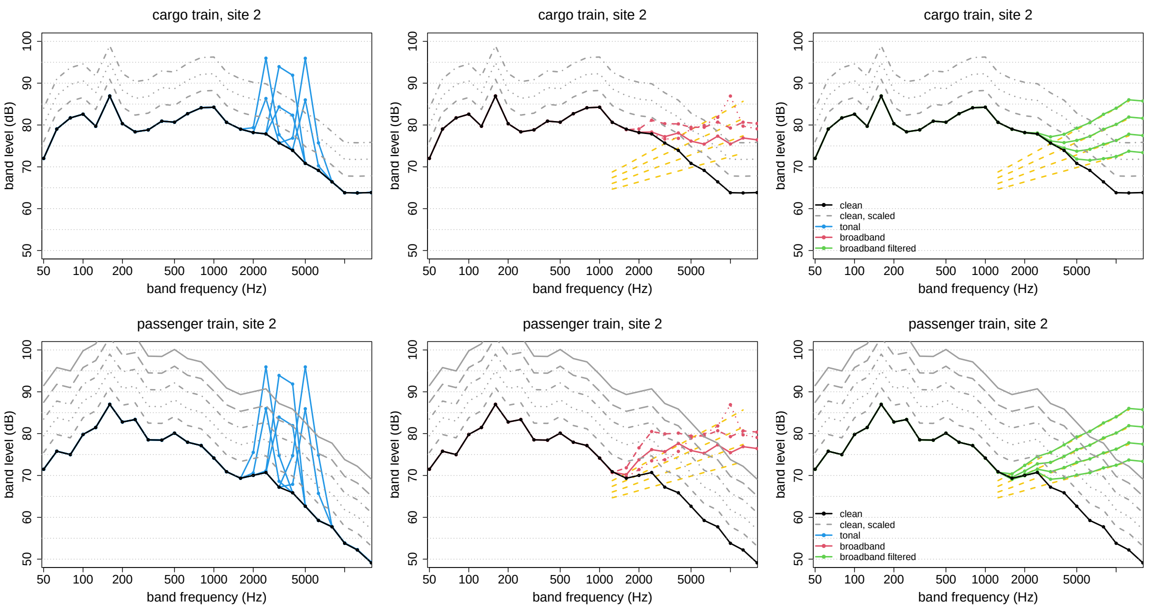

Figure 1: Spectral content of squeal at a distance of 7.5 m. Upper panels show the cargo train, lower panel the passenger train of one site. The black line shows the clean rolling noise and gray lines show amplitude scaled versions of it. Yellow dashed lines show the spectral slants derived from a previous study. Blue lines show 6 tonal squeals with 3 different frequencies and 2 amplitudes, red lines the 3 different original broadband squeal spectra used, and green lines the modified squeal with 4 different intensities.

The stimuli comprised of a set of reference rolling noise samples for each of the three measurement sites, with two trains of different type (a passenger and a cargo train) and two distances (25 and 50 m). The black lines in Fig. 1 show the rolling noise spectra averaged over the 4 seconds. These rolling noise samples were also scaled in steps of 4 dB (gray lines in Fig. 1) up to a level increase of 12 dB (20 dB for the passenger trains at the two of the three sites with lower levels) to provide a reference for pure amplitude scaling. Instances of tonal squeal were presented at two amplitudes (original and -10 dB) and frequencies of 2.5, 3.5, and 5 kHz (left panels in Fig. 1). The main portion of the broadband squeal samples was presented for all site/train combinations and was based on a single sample with a temporally constant squeal (dashed red line, middle panels in Fig. 1). This squeal was presented as is but also spectrally manipulated to simulate squeal of different intensity (green lines in right panels, Fig. 1). The target spectra (yellow dashed lines, right panels) derived from a previous study [4] are also shown. For a single site, additional samples were presented: for a high intensity a temporal windowing was performed to model different durations. Furthermore, two instances of non-stationary squeals (red solid and dash-dotted lines, middle panel) and a number of combinations between tonal and broadband squeals was also presented.

2.5. Analysis

A logarithm of base two was applied to the annoyance ratings and the median across the three ratings per listener and condition. To achieve an average group rating, the overall mean per listener was subtracted from each listeners ratings and then the mean per condition was calculated across listeners. For brevity, these averaged log annoyance ratings will be referred to simply as annoyance ratings.

3. RESULTS

Fig.2 shows the ratings of the unscaled and scaled clean rolling noise as a function of the A-weighted sound pressure level (L_{Aeq}). Both investigated distances, are shown (color coded symbols). The trend can be approximated by a linear regression model showing a good fit for the majority of data points. The residual distribution is shown in the right panel. Adding a distance-dependent slope (i.e. an interaction term comprising level and distance) leads to only a slight improvement in the residual error.

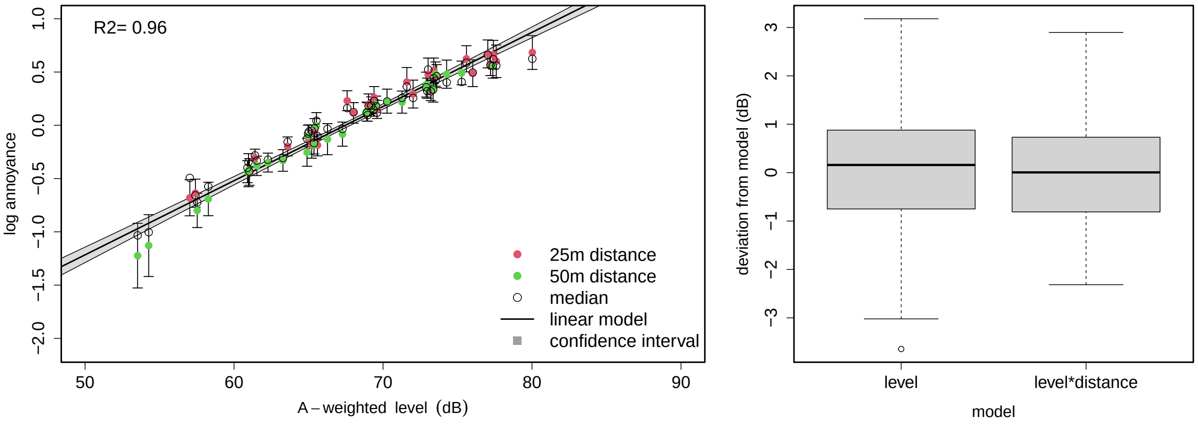

Figure 2: Annoyance of the rolling noise vs. L_{Aeq}. Shown are the scaled and unscaled rolling noises. Immission distance is color coded. Error bars show the standard error of the mean. The left panel shows the linear fit. The right panel shows the distribution of the residual for a constant slope and a distance-dependent slope (left and right boxplot, respectively).

Fig. 3 shows the difference of the perception of rolling noise and squeal noise for one train type and one site. The left panel illustrates the perception of the constant squeal for different spectral target functions as well as for the original spectrum. Clearly, the acoustic changes in L_{Aeq} are relatively small in the range of up to 5 dB even though this train was considered silent. It is clear that the perception significantly deviates for the squeal when considering the L_{Aeq}. For tonal noise (right panel) the changes in overall level are much higher in the range of up to 10 dB. The perception also deviates considerably from regular rolling noise. However, for high amplitudes, the annoyance seems to curve back towards the amplitude scaling function.

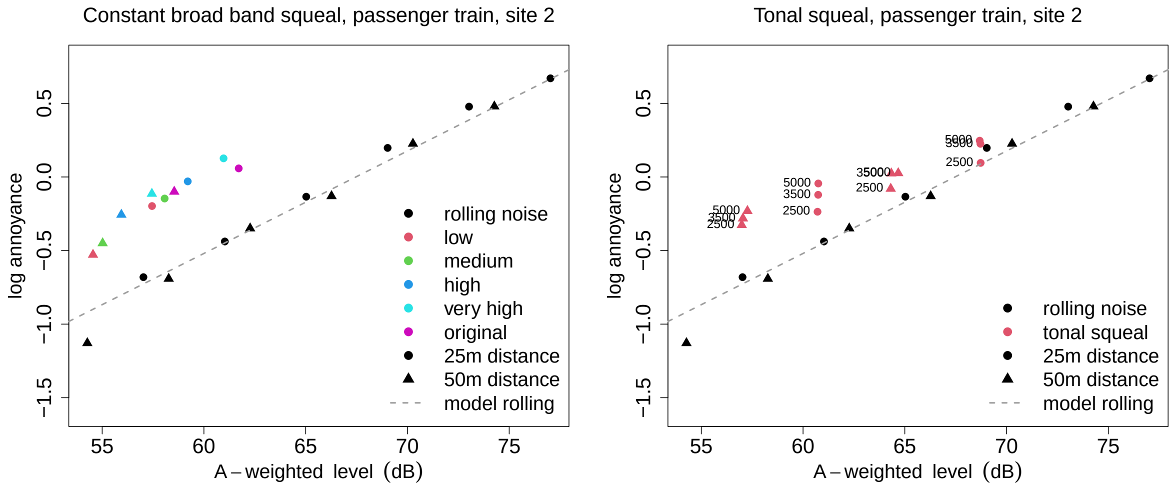

Figure 3: Annoyance of the curve squeal vs. L_{Aeq}. Shown are broadband (left panel) and tonal (right panel) squeal for the passenger train at a single site (colored symbols). Black symbols show the scaled and unscaled rolling noise. Immission distance is coded by a circle (25 m) and a triangle (50 m).

The main purpose of this work was to find a method to adjust noise mapping level estimates for the presence of squeal noise. The approach chosen was to find an annoyance equivalent L_{Aeq}, i.e. the level for which the annoyance of the noise with squeal and that for the scaled rolling noise are equivalent. In Fig. 3 this is simply the horizontal displacement between the squeal and no squeal conditions. This will be termed the perceptive adjustment term, as the changes in overall level due to squeal are not included. Fig. 4 illustrates the different adjustment terms in more detail.

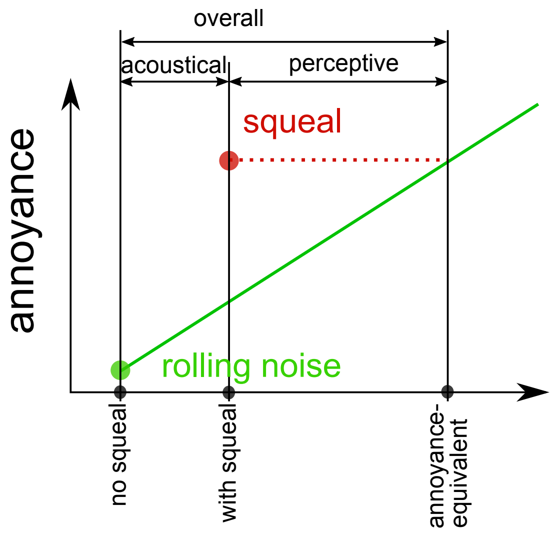

Figure 4: Definition of adjustment terms. The drawing illustrates the different adjustment terms: acoustical, perceptive, and overall.

For this, the linear model of the rolling noise was used to determine the perceptive adjustment term of the squeal noise samples. Adding the acoustical adjustment term (i.e. the increase in A-weighted level due to the presence of squeal noise) leads to the overall adjustment term.

The modeling approach was based on a correlation between either the perceptive or the overall adjustment term and the difference between high frequency noise level and the noise level at lower frequencies to model the rolling noise. The high frequency noise was chosen to incorporate the range starting at the 1.6 kHz band up to 12.5 kHz. The energy of this frequency range was calculated. For the rolling noise different octave bands up to 1 kHz center frequency were investigated. The highest correlation for the acoustic adjustment term and the difference of high and mid/lower frequencies was found for the 1 kHz octave (correlation coefficient 0.9). For the perceptive adjustment term the correlation ranged between -0.4 and 0.1.

Fig. 5 illustrates the relation between the high to mid-frequency contrast for the 1 kHz octave and perceptive adjustment term (left panel) as well as the overall adjustment term (right panel). As already indicated by the correlation coefficient, only the overall adjustment leads to a suitable model. The standard deviation of the error for the linear model was 1.7 dB.

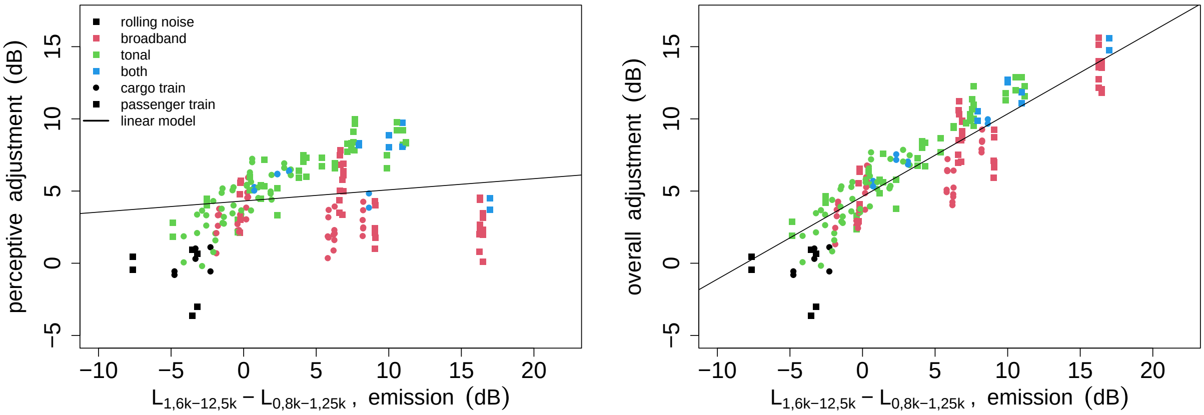

Figure 5: Different adjustment values vs. spectral contrast. The left panel shows the relation between the high frequency content vs. the 1 kHz octave and the perceptive adjustment of the 4 second stimuli at the emission point. The right panel shows the same for the overall adjustment. The black line indicates the respective linear model.

4. CONCLUSIONS

The aim of the study was to investigate the perception of salient acoustic components that occur specifically for railbound vehicles when transversing a curve. This so called curve squeal strongly affects the acoustics of railway passby noise. The measurement campaign produced suffcient data to design a experiment enabling a systematic investigation of different types of curve squeal. Experimental conditions were produced by manipulating recordings according to parameters derived from an earlier study [4]. The manipulation method was described previously [8]. Perception data illustrated large significant deviations of curve squeal from pure rolling noise and amplitude scaling. These deviations were quantified using a perceptual adjustment, i.e. an annoyance equivalent level adjustment based on the amplitude scaling function for pure rolling noise. Using a high-frequency to mid-frequency contrast, the overall adjustment including the level changes induced by curve squeal was described as a linear model. In the future this simple and practical model can be applied for more precise railway noise prediction in curves, which addresses sound pressure increasement as well as annoyance effects. To achieve this, however, suitable ways to include the mean frequency of occurrence of squeal according to different external factors like curve radii or mean meterological conditions, need to be derived. In addition, whether the dose-response relations (e.g. [3], Annex III) which are used to quantify the noise effects on humans already contain squeal data needs to be taken into account.

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