PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

The Effects of Weather Conditions and Wheel Wear on Curve Squeal

Thomas MALY[1]; Florian BIEBL[2]; Michael OSTERMANN[3]

[1] Vienna University of Technology, Austria

[2] psiacoustic Umweltforschung und Engineering GmbH

[3] Vienna University of Technology, Austria

ABSTRACT

The mechanisms of curve squeal generation (lateral stick-slip effect on the top of the rail and/or friction of the wheel flange) are well known. Even if various influencing parameters were already investigated mostly on a theoretical level, in real train operation the parameters are in general not measurable in their entirety and their effects due to the complex interdependencies between them are often not predictable. That is why curve squeal generation often seems to have a random character.

As a continuation of previous studies the aim of the work presented was to investigate the influence of weather condition changes over a whole year and wheel profile parameters changes due to wear on the occurrence frequency of curve squeal. For this, measurements of the pass-by noise emissions and the weather conditions in a narrow curve (radius 230 m) of a Vienna suburban railway line were carried out over a period of 11 months. Due to a previously developed algorithm for automatic detection of curve squealing more than 20000 data sets were available for subsequent statistical analysis. In the paper the dependencies of squeal frequency on rain, air humidity, dew point, and rail temperature, as well as wheel parameters are presented in detail.

Keywords: Curve Squeal, Weather Conditions, Wheel Wear

1. INTRODUCTION

In narrow curves, in addition to the ordinary rolling noise, which basically arises from rail and wheel roughness, also noise components with high amplitudes at high frequencies may occur. These components are often a major source of annoyance for people who live near of curved railway tracks. The high importance with regard to noise protection is emphasized by the consideration of the increased emissions in computational models for strategic noise mapping (e.g. European directive 2015/996 for common noise assessment methods (1)).

Components with a dominant tonal characteristic are usually called curve squealing. As the main cause of such emissions lateral creepage at the contact between the wheel tread and the top of the rail head was already identified by Rudd in 1976 (2). Thereby alternating sticking and slipping phases excite the wheel to vibrate corresponding to one of its axial wheel modes. Zenzerovic (3) states, that for the initiating and persisting stick-slip vibrations the falling friction law (decrease of friction coefficient with increasing slip velocity) and/or a geometric coupling of wheel modes will be needed. The observed squeal frequencies range from several hundred Hertz to few Kilohertz (the stated frequency ranges vary widely: for instance Meehan et al. (4) report a frequency range from 600 Hz to 10 kHz, whereas Thompson (5) quantify the range from 250 Hz to 5 kHz).

Apart from to stick-slip squealing, in narrow curves also the contact between wheel flange and rail gauge face may be source of considerable annoying noise components. However, due to wheel flange rubbing a different sound characteristic will be generated: Thompson (5) describes flange squeal compared to stick-slip squeal as more broadband and more intermittent noise with higher fundamental frequencies, which may have lower levels.

Even if the basic mechanisms which are responsible for squeal generation are well known, there are

[1] thomas.maly@tuwien.ac.at
[2] biebl@psia.at
[3] michael.ostermann@tuwien.ac.at

many different influence parameters which may have significant effects. For instance, Dittrich et al. (6) pointed out 18 different parameters related to vehicle, track, and/or environment. This high number of parameters emphasizes the complexity of phenomenon of curve squeal generation. Furthermore, in real-life observations of curve squealing of trains in operation, it will almost be impossible to record all potential influence parameters so that squeal noise generation often seems to be more random rather than deterministic.

In this context, in Austria two granted research projects (BEGEL 2013-2015 and ESB 2015-2018) were carried out to investigate selected influence parameters based on comprehensive sound measurements of pass-bys of trains in operation. Present paper covers a part of these research activities and will focus on the effects of varying weather conditions and of wheel profile changes due to wear.

2. MEASUREMENT DATA

As basis for further evaluations the pass-by noise in a narrow curve with a radius of 230 m of a Vienna suburban railway line were recorded over 11 months (20265 trains). The following sections describe the setup of acoustic measurements, the properties of the pass-bys of selected train types, collected wheel profile parameters, and the way of identifying stick-slip squeal and flanging squeal.

2.1 Pass-by measurements

Sound emissions of train pass-bys were measured in 7.5 m from the center line of the track and 1.2 m above the top of the rail head, accordingly to the position for sound emission measurements of train pass-bys described in DIN EN ISO 3095 (7). The used acoustic railway monitoring system (acramos®) utilize two adjacent microphones to verify their accurate functioning. The recordings were sampled with 50 kHz to be able to analyze the entire audible range up to 20 kHz. Acramos® also determine the time of axle pass-bys in the cross section by inductive axle counters. The recorded axle patterns enable the system to distinguish automatically between different categories of trains and to determine train directions and axle speeds. In addition, meteorology parameters like air and rail temperature, air pressure, air humidity, wind speed and wind direction, dew point and rainfall were measured.

In the cross section the superstructure consisted of rails of type S49 mounted on wooden sleepers. Because of a cant of approximately 90 mm to 95 mm the balanced speed without any lateral acceleration can be estimated at 43 km/h.

For improved interpretation of evaluation results rail roughness and track decay rates were measured in the beginning and at the end of the pass-by noise measurements. Both roughness measurements show that the roughness of the inner rail almost met the limiting curve for type testing according to DIN EN ISO 3095 (7). On the contrary, the roughness of the inner rail exceed this limiting curve in the wavelength range from 6.3 cm to 16 cm significantly (in parts more than 15 dB). The track decay rates mostly fulfill the limiting curve of the DIN EN ISO 3095 (7). Only the lateral decay rate of both rails falls at 1600 Hz under the limiting curve at the initial measurements and the vertical rates of the inner rail show at both measurements (slightly) too low values in the frequency range of 500 Hz to 800 Hz.

The traffic in the measurement section consists of 82.9 % (17097 trains) of the same suburban train type (train type A). Further 15.2 % (3128 trains) of the traffic were of another suburban train type (train type B). Thus, for further evaluations train type A will primarily be considered and type B will only be added if meaningful. The distribution of mean train speeds in the left diagram of figure 1 shows that there is an accumulation point between 55 km/h and 60 km/h and that most of the trains passes the cross section with speeds substantially above the balanced speed where lateral acceleration

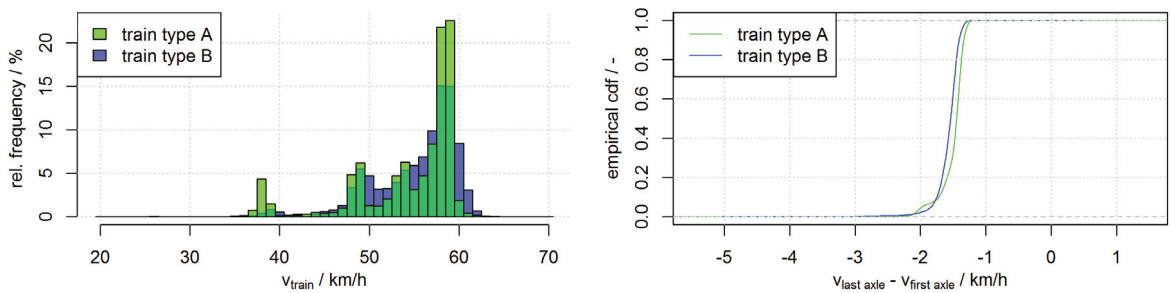

Figure 1 – relative frequencies of mean train speeds (left) and empirical cumulative distribution function (cdf) of speed differences between last and first axles (right) of suburban trains of type A and B

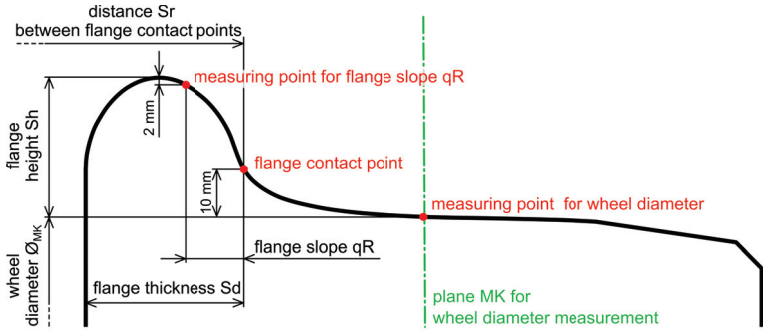

Figure 2 – basic wheel profile parameters used for further evaluation

disappears. An electrically isolated cut point of the catenary in front of the measuring section leads to the absence of any traction in the measurement section (cf. low variation of speed differences between last and first axle in right diagram of figure 1) even if the power units and the auxiliary systems were already powered up in the measurement section.

2.2 Wheel profiles

At each stop for maintenance or inspection of mentioned suburban train types in workshops of Austrian Federal Railways the profiles of all wheels were measured. Thus the profile parameters were collected for all eleven units of suburban train type A which passed the measurement site and of all workshop stops during the whole period of acoustic measurements as well as of the stops right before and after this period. This enables linear interpolation of wheel parameters over time and allows assigning them to the pass-by noise data sets with the aid of unit schedules.

For detailed analysis only those profile parameter were selected, where a considerable impact was presumed (for instance, rim thickness, wheel width, or tread rollover were discarded). Furthermore, hollow tread was also excluded because of its very rare appearance. The remaining profile parameters were illustrated in figure 2. As an additional parameter the maximal diameter differences of wheelsets were derived based on wheel diameters.

2.3 Detection of curve squealing

To analyze the large quantity of recorded pass-bys, an algorithm for automatic detection of the characteristic sound components, which are generated by flange contact with the rail head (broadband flanging noise) or by lateral stick-slip effect (tonal squeal noise), was applied. The empirically developed identification bases on interpretation of third octave spectra over time. Examples of different noise characteristics of pass-bys of type A suburban trains were given in figure 3: left diagram shows a pass-by without any squeal or other disturbing noise, middle diagram shows clearly perceptible time-varying flanging noise with increased sound pressure levels (SPL) in the upper third octave bands, and right diagram shows an isolated tonal noise component with increased SPLs of the neighboring 3.15 kHz and 4 kHz bands as well as slightly increased SPL of the 8 kHz band due to the first harmonic. According to these noise characteristics the already well-tested algorithm assesses the mean value of the upper third octave bands for the detection of flange squeal and peaks of one or two neighboring bands in the medium frequency range for each time sample of the spectra. If the time behavior of such anomalies also met requirements concerning their length of time and in case of tonal

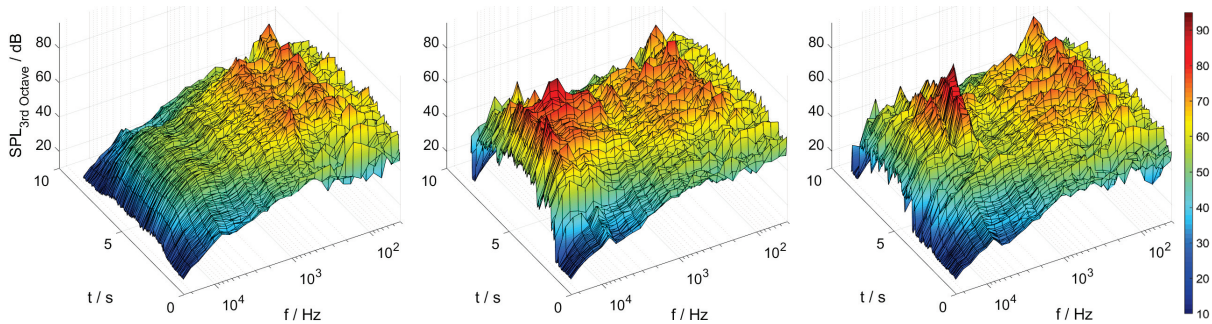

Figure 3 – examples of 3rd octave spectra over time for suburban trains of type A without any squealing (left), with flange squealing (middle) and with stick-slip squealing (right)

components their continuity over time, trains will be classified as broadband conspicuous (representative for flange squeal) or tonal (representative for stick-slip squeal) conspicuous.

An initial evaluation of the overall squealing rates in absence of rainfall reveals a tendency to less stick-slip squeal (~7-8 %) compared to other suburban or regional train types considered in previous investigations, especially in the frequency range lower than 5 kHz. And identified tonal conspicuities often (~90 %) occur together with broadband noise, which might be an indication, that these components arise from flange rubbing or have at least a causal relationship. Flanging noise rate is on similar level (~29 %) compared to the experiences of a former study. Compared to type A, train type B show for both noise types somewhat higher rates (tonal ~13 % and broadband ~45 %).

3. WEATHER CONDITIONS

In order to analyze the influence of various weather conditions, the measured data was separated in increments of 10 as shown in figure 4. The different ranges are always shown with their highest possible value (10 means data from 0.1 to 10). In figure 4 the number of measured data for each weather condition range for the velocity 60 km/h is shown. The colors of the fields should give an easy way to evaluate the reliability of a certain weather condition, depending on the number of measured trains. It ranges from dark green (>50), light green (50-20), orange (20-10) to red (<10). For the evaluation only areas of at least 10 pass-by trains were evaluated.

For the analyses, the data was evaluated for the occurrence of tonal stick-slip squeal and broadband flange squeal. In addition to that, the sound power level was calculated for each single train. This calculation was done using a previous developed calculation method (see (8) in German language) which is based on the Austrian Standard ÖNORM S5026 (9) but only uses one single measurement point in 7.5 m from the rail and in 1.2 m above rail surface.

In the following the influence of the different weather parameters are discussed in detail for the velocity range of 55-65 km/h (highest amount of trains measured, see figure 1).

suburban train type A													
		rain		air humidity [%]								dew point	
		no	yes	30	40	50	60	70	80	90	100	> rail temp	< rail temp
air temp. [°C]	0	569	23		3	23	38	47	51	300	107	458	111
	10	3466	423		29	160	390	837	909	851	290	1346	2120
	20	2673	249	42	166	418	437	638	490	404	78	314	2359
	30	1279	18	9	216	428	355	196	73	2			1279
	40	3				3							3
rail temp.[°C]	-10	54	3			2	14	18	3	11	6	29	25
	0	1373	127		3	35	110	229	249	560	187	918	455
	10	3001	407		29	126	327	723	847	726	223	1015	1986
	20	1832	149	7	70	288	312	495	342	259	59	156	1676
	30	1093	26	29	163	274	309	235	82	1			1093
	40	499	1	15	114	209	143	18					499
	50	138			35	98	5						138

suburban train type B													
		rain		air humidity [%]								dew point	
		no	yes	30	40	50	60	70	80	90	100	> rail temp	< rail temp
air temp. [°C]	0	103	6					6	18	56	23	93	10
	10	798	97		4	34	75	173	207	231	74	377	421
	20	358	49	2	16	34	62	74	79	78	13	59	299
	30	249	5	1	26	104	76	29	13				249
	40	2				2							2
rail temp.[°C]	-10	7								6	1	7	
	0	319	36			1	23	55	71	137	32	227	92
	10	651	87		4	30	61	129	182	178	67	273	378
	20	238	28		9	25	35	68	50	41	10	22	216
	30	158	6	2	20	40	52	27	14	3			158
	40	108		1	11	51	42	3					108
	50	29			2	27							29

Figure 4 – Measured trains (suburban train type A and B) for the velocity range 55-65 km/h with different weather conditions

3.1 Temperature

The measured data shows that for the suburban train type A the frequency of occurrence of all types of curve effects declines with higher temperature (see figure 5). Especially for the broadband effects however, a local maxima at the temperature range of 10-20°C is visible. This maximum is highest for lower velocities and for the suburban train type B it is also visible when looking at the occurrence of tonal effects. Generally the data of the train type B shows a slightly rising tendency with higher

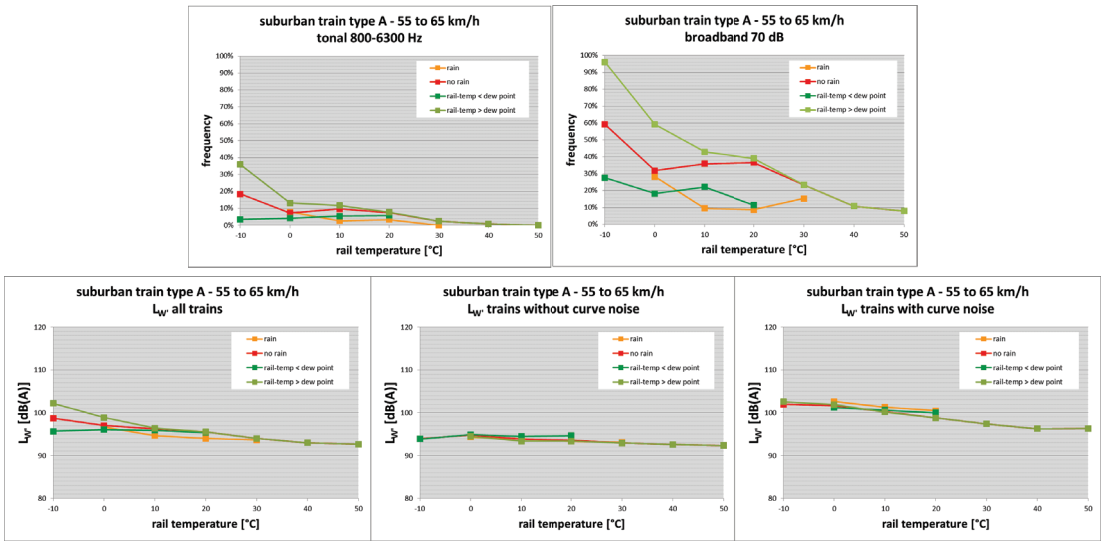

Figure 5 – frequency of occurrence and sound power level – rail temperatures suburban train type A (velocity range 55-65 km/h)

temperature. Only the values for the tonal effects in the frequency range 8 kHz and higher shows declining frequency occurrences.

When looking at the sound power levels, they show falling levels with rising temperature for both vehicle types and for all velocities. When comparing the rail and the air temperature the average values differ slightly, however the general effects are comparable to one another.

3.2 Dew point

In order to evaluate the influence of a wet rail respectively lowered friction coefficients, not only the occurrence of rain had to be monitored, but also the effect of a humid rail due to a rail temperature below the dew point was investigated. The data was separated by the information weather the dew point calculated with the air pressure was higher or lower than the measured rail temperature. The comparison of the frequency of occurrence of tonal and broadband curve noise in relation to the dew point, showed for both train types significant lower probabilities for a pass-by with a rail temperature lower than the dew point. This effect is relatively unchanged by different weather conditions.

3.3 Air humidity

When separating the data according to the air humidity the frequency of occurrence shows a peak for the percentage of 60 % to 70 % with a lower frequency for higher and lower humidity (see figure 6).

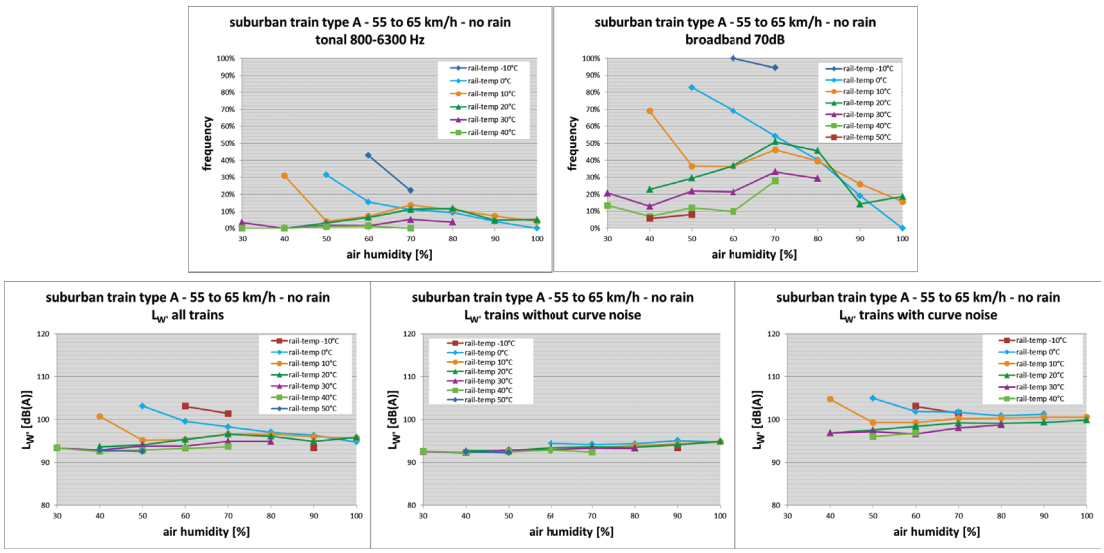

Figure 6 – frequency of occurrence and sound power level – air humidity suburban train type A (velocity range 55-65 km/h)

When only looking at the data in the temperature range below 10°C, the frequency of occurrence is rising for lower humidity, leading to an overall effect of declining frequency of occurrence with rising humidity.

The sound power levels show a slightly rising slope for the train type A. Only the data in the temperature range of 10°C and lower shows the opposite effect. When looking at the train type B the sound power levels give relatively constant levels for all weather conditions.

3.4 Rain

When looking at the pass-bys with rainy conditions, the results show the lowest probabilities for the frequency occurrence of all three types of curve noise. The effect of rain is highest in the temperature range of >0°C to 20°C. The effect of rain is mostly similar to the effect of a rail temperature below the dew point and results in a similar effect. When comparing the sound power levels the data with rainy conditions slightly lower levels, especially in the temperature range between 0°C and 20°C.

4. WHEEL WEAR

Due to the higher number of pass-bys and the lower number of different units, only suburban trains of type A were considered in subsequence statistical analysis of effects of wheel wear. Initially, for each of the eleven train units time plots of squeal rates and of wheel profile parameters, both including times of the workshop visits, were made in order to get a rough overview of time behavior and variations between different units over time.

4.1 Regression analysis

As a consequence of overlaid sound emissions of nearby axles at the measuring point in a distance of 7.5 m, a reliable assignment of acoustic properties of the measured signal to axles is not possible. The time plots of wheel profile parameters (except parameters based on wheel diameter) usually show similar behavior with moderate spread of all wheels of a train unit: reprofiling sets these parameters to initial values and afterwards the profile (and its parameters) wear in a reasonably comparable way. Thus, within the statistical analysis, primarily mean values but also minimum and maximum values of wheel profile parameters were used as independent variables and the identified squeal (flange or stick-slip) were used as dependent variables. Due to the binarity of the dependent variable logistic regression was applied to evaluate dependencies. In face of the absence of the coefficient of determination R^2 in logistic regression analysis, which represents the proportion of variance, three commonly used pseudo-R^2 (McFadden, Cox and Snell and Nagelkerke) were calculated to quantify differences in the goodness of fit between regression results.

As already discussed in chapter 3 weather conditions can influence squeal occurrence. The variation of these dependencies is exemplarily illustrated in figure 7 for the difference $\Delta T_{\text{rail-dew point}}$

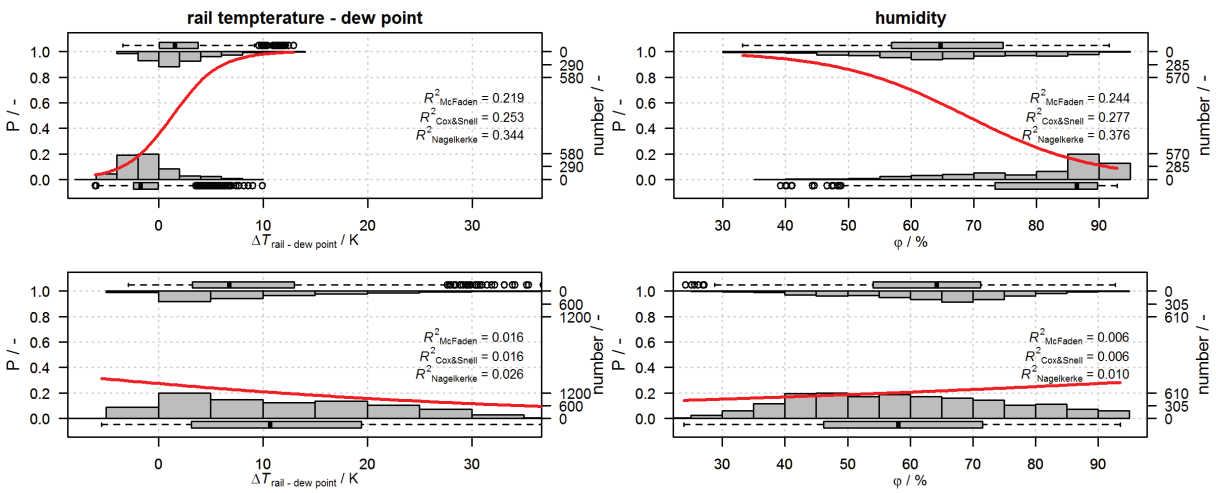

Figure 7 – dependences of squeal on difference $\Delta T_{\text{rail-dew point}}$ between rail temperature and dew point (left diagrams) and on humidity φ (right diagrams) while cold (Nov. 10th, 2016 – Jan. 10th, 2017, 2673 pass-bys of suburban train type A, upper diagrams) and warm (March 10th – Sept. 9th, 2016 with 6762 pass-bys of suburban train type A, lower diagrams) periods without rainfall estimated by logistic regression and related histograms of pass-bys with (upper histograms) and without (lower histograms) detection of squeal noise

between rail temperature and dew point and for air humidity φ: while there seems to be a reasonable dependency during the cold (wet) period, the influence is clearly reduced in the warmer period. Even if it can be assumed, that weather and wheel conditions are uncorrelated, for improving the sensitivity of regressions results to the examined effect, subsequent analysis of the influence of wheel wear was generally restricted to the period from March 10th to Sept. 9th, 2016 and to difference $\Delta T_{\text{rail-dew point}} \geq 5$ K. In addition periods with detected rainfall were ignored, too.

4.2 Results

The pseudo-R^2 indicators of the regressions with wheel profile parameters were generally relatively low, which might be explained by the (necessarily) applied train based approach with aggregated wheel parameters over whole trains. The results of the regressions with all train units of type A are shown in figure 8. Thereby, squeal noise show a low to moderate dependency on the four profile parameters related to the wheel flange and on the diameter difference within the wheelset. The former relation can be interpreted as a decrease of the squeal probability with ongoing wheel wear where the flange contact points (cf. figure 2) move to wheel exteriors and to lower diameters. This trend of highest squeal frequencies at initial parameter values after reprofiling was also observed in the time plots of squeal occurrences. On the contrary, the later dependency with highest predicted squeal probability when diameter differences within the wheelsets tend towards zero was unexpected and seems not to be justifiable by physical relations of the wheel-rail contact. Thus this dependency may be the consequence of a correlation between flange parameters and the diameter difference (all these parameters increase with ongoing wear).

The described dependencies appear also if maximum or minimum instead of average parameters were considered (minimum parameters in parts with reduced pseudo-R^2 indicators). Moreover, the regressions calculated separately for each train unit provide similar trends for ten of the eleven units, whereas the eleventh unit evinces rather independency. And also the regressions after a division of the pass-bys in classes of constant speed or constant humidity emphasize observed trends. On the other hand, the observed dependencies completely disappear between the last months of measurements (September to January) which indicates that the effect of changing weather conditions clearly

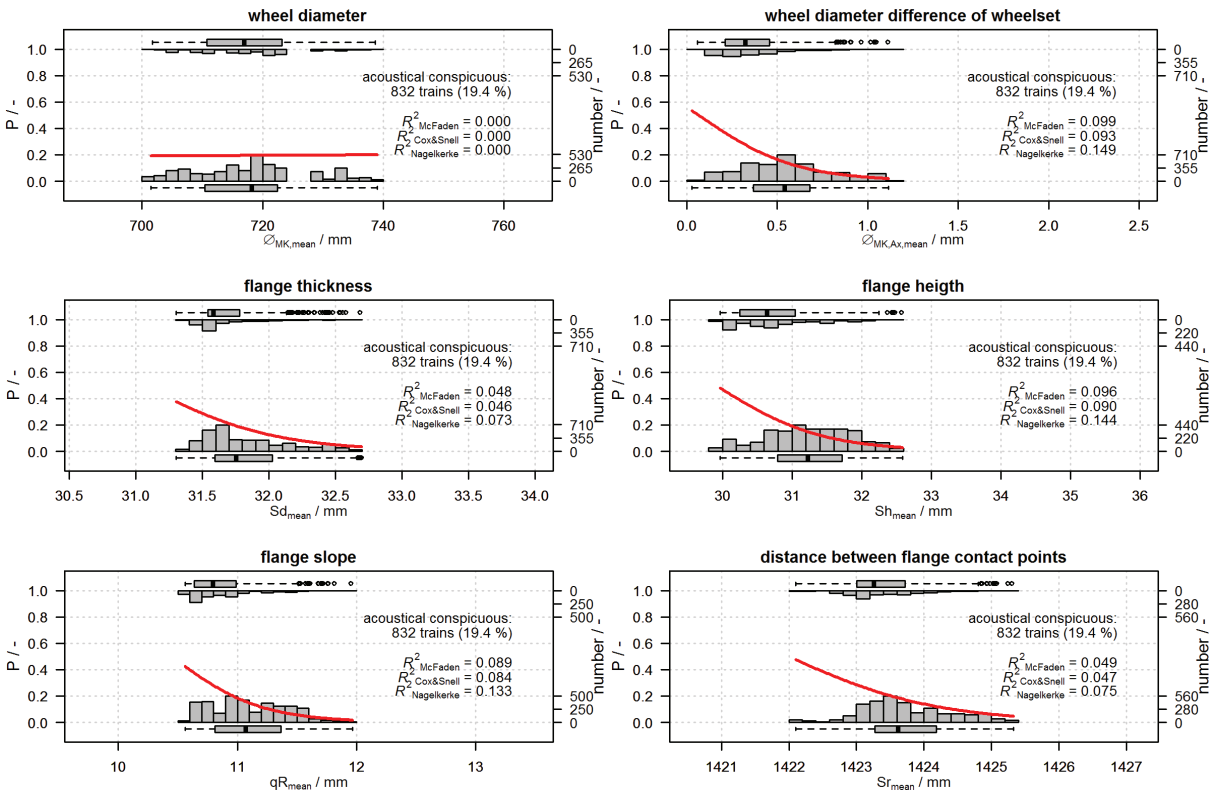

Figure 8 – dependences of squeal on different mean wheel parameters of measurements from March 10th to Sept. 9th, 2016, with differences $\Delta T_{\text{rail-dew point}} \geq 5$ K, and without rainfall (4281 suburban trains of type A) estimated by logistic regression and related histograms of pass-bys with (upper histograms) and without (lower histograms) detection of squeal noise

outweighs the effect of wheel wear under cold and/or moist conditions even under the mentioned restrictions ($\Delta T_{\text{rail-dew point}} \geq 5$ K and no rainfall).

Despite of all these indications for a (weak) dependency in the absence of weather influences it has to be noted, that neither the concrete physical cause for a diminished squeal probability of worn wheels on suburban trains of type A nor the question accounting the generalization of these findings can be clarified sufficiently without further investigations (e.g. axle based and/or including rail profile wear). But on the other hand these findings indicate that at least under certain circumstances wheel profile wear have an impact on curve squeal.

5. CONCLUSIONS

The work presented analyses sound emissions in a narrow curve of a high number of trains in operation with the aim to investigate dependencies of curve squeal on weather conditions and on ongoing wheel wear.

The occurrence of tonal and broadband conspicuous is notably lower at rainy conditions and with rail temperatures below the dew point. Humidity in general shows the highest values at the range of 60 % to 80 %. With rising rail temperatures the occurrences for both types are declining with nearly no occurrences above rail temperatures of 30°C. The sound power level is slightly lower for higher rail-temperatures while showing a slight rise with higher humidity. For temperatures below 10°C, the sound power level shows significant higher sound power levels in the low air humidity range.

Regarding the wear of wheels, a weak dependency was observed. Accordingly, new or reprofiled wheels with initial geometric shape seem to excite more squeal as worn wheels do. But the underlying mechanism and thus the question of a generalization for other train types and/or other conditions could not be studied without further measurements with extended setup (e.g. microphones near the rails), which enables a more in-depth analysis like axle based evaluations and/or assessment of the contact geometry based on rail and wheel profiles.

ACKNOWLEDGEMENTS

This work was supported by the Austrian Research Promotion Agency (FFG, project 850558), the Austrian Ministry for Transport, Innovation and Technology, and the Austrian Federal Railways (ÖBB-Infrastruktur AG).

REFERENCES

1. Commission directive (EU) 2015/996 establishing common noise assessment methods according to Directive 2002/49/EG of the European Parliament and of the Council. May 19th, 2015. Official Journal of the European Union L168/1.
2. Rudd M.J. Wheel/Rail Noise – Part II: Wheel Squeal. Journal of Sound and Vibration; 1976; 46(3). p. 381-394.
3. Zenzerovic I. Engineering model for curve squeal formulated in the time domain. Thesis for the degree of licentiate of engineering. Division of Applied Acoustics, Department of Civil and Environmental Engineering, Chalmers University of Technology; Gothenburg, Sweden, 2014. ISSN 1652-9146.
4. Meehan P A, Bellette P A, Jones P A, and Anderson D. Probabilistic Prediction of Wheel Squeal under Field Humidity Variation. Proceedings of 20th International Congress on Acoustics, ICA 2010, Sydney, Australia, Aug. 2010
5. Thompson D. Railway Noise and Vibration: Mechanisms, Modelling and Means of Control. 1st Edition. Oxford, United Kingdom; Elsevier Ltd., 2009. ISBN 978-0-08-045147-3.
6. Dittrich M, Jansen E, López B M abd Gómez J C. ACOUTRAIN, Deliverable D1.10: Braking noise and Curving noise: corresponding indicators and measurement procedures. Final, update of D1.3, 2014
7. DIN EN ISO 3095 – Acoustics – Railway applications – Measurement of noise emitted by railbound vehicles. 2013
8. Maly T, Ostermann N, Biebl F, Hoisbauer H, Gunacker M, and Djurdev V. Bewertung des akustischen Einflusses von Gleisbögen für die Erstellung von Lärmkarten - BEGEL", report of research project BEGEL (project 840495), supported by Austrian Research Promotion Agency, the Austrian Ministry for Transport, Innovation and Technology, and the Austrian Railways, Dec. 2015.
9. ÖNORM S 5026 - Measurement of noise emitted by railbound vehicles - Sound power level per unit length. March 1996. withdrawn May 2019