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A case study of railway curve squeal radiated from both the outer and inner wheel

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ABSTRACT

This case study is presented after observations were made that partially contrast the prevailing picture of railway curve squeal given in the literature. These are observations with significance both for modelling and condition monitoring. The current case study will be followed by a subsequent investigation focused on the validation and application of a simulation model to investigate root-causes for curve squeal at the Stockholm metro. Curve squeal in a 213 m radius curve on the Stockholm metro is studied. Data includes track characteristics (rail profile, rail roughness and gauge width) and noise measured at the trackside as well as by two vehicles equipped with an on-board mounted noise monitoring system. The current case study contrasts field measurements of curve squeal reported in the literature by a relative shift of emitted noise towards higher frequencies. Wayside noise measurements in the studied curve during a few hours showed squeal generation for all vehicle passages with dominating 1/3 octave band centre frequencies in the range between 6.3–15.8 kHz. Noise data measured during one year of regular traffic of two vehicles equipped with a monitoring system were obtained. The occurrence of curve squeal was analysed through an implementation of the curve squeal detection algorithm in operation at the Stockholm metro. This algorithm was also applied to search for events of squeal noise radiation from the outer wheel. Results show emissions of squeal noise from the inner and outer wheel for 65 % and 8 % of the vehicle passages through the studied curve, respectively. Further, the occurrence of curve squeal radiated from the inner wheel was found to increase by 10 % after rail grinding. In the literature, squeal radiated from the outer wheel is described as having an intermittent character with magnified spectral components in the frequency range between 5–10 kHz. In contrast, the current work presents sustained tonal squeal generated from the outer wheel with similar noise characteristics as typically related to ordinary curve squeal.

1. Introduction

Squeal noise from negotiation of rail vehicles through tight curves is probably the most annoying noise emitted by rail traffic. It is characterized by high-frequency tonality and high noise levels. Its tonal character means that it is more annoying than a broad-band noise at the same level. Noise levels as high as 130 dBA (measured at 2 m distance from the inner rail) in the frequency range up to 10 kHz are reported in the literature [1]. Below follows a literature review that focuses on field studies of curve squeal with particular interest in investigations that consider squeal noise radiation from both the inner and outer wheel. Due to its fundamental importance in the generation of curve squeal, the concept of angle-of-attack is introduced. Moreover, literature on the importance of rail grinding with respect to curve squeal occurrence is presented.

Rudd emphasised the importance of the so-called crabbing motion of the bogie with respect to generation of curve squeal [2]. This corresponds to a transverse bogie steering position caused by the primary suspension that prohibits the wheelsets to align radially. As a result, the leading wheelset develops an angle-of-attack (AoA) that generate large magnitude lateral creepages and creep forces able to excite natural frequencies of the wheel. Note that both wheels of the leading wheelset will be exposed to magnified lateral creep forces [3]. The crabbing motion becomes more severe for increasing bogie wheelbase, l, and

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decreasing curve radius, R. As a rule of thumb, Rudd estimated the minimal curve radius able for a rail vehicle to negotiate without squeal generation to be $R = 100\ l$. Remington found a reasonable good correspondence when this relation was compared towards conditions at the metros of Chicago and Massachusetts [4]. He also presented experiments from a twin-disc roller rig showing that Rudd's result with respect to the ratio between l/R corresponded to saturated contact conditions at a lateral creepage of 0.009. Eriksson et al. presented a statistical analysis for an entire metro line based on data collected by an on-board noise monitoring system during 1.5 years of regular operation by two vehicles [5]. The data covered approximately 380 000 passages through 143 curves with radii up to 1000 m. Inner wheel squeal occurrence showed an inverse proportionality with respect to curve radius for curve radius below 600 m. For radii exceeding 600 m no significant influence on inner wheel squeal occurrence was observed. For the current vehicle with a wheelbase of 2.3 m, this corresponds to a quotient based on Rudd's criterion of $l/R = 0.004$.

Eadie et al. state that industry generally perceives curve squeal from inner wheels to be generated in the frequency range below 5 kHz [6]. This is in correspondence with the field observations reported in the literature and summarized as part of the review by Thompson et al. [7]. Results from curve squeal noise mitigation by friction modification (FM) at 9 different curves located on both light-rail and railway systems are presented in [6]. Curve squeal and flanging noise radiated from the inner and outer wheel are distinguished by their respective frequency ranges being between 0–5 kHz and 5–10 kHz, respectively. This separation in frequency is supported by results obtained from two curves carrying freight and metro traffic, respectively, where FM was applied on the high (outer) and low (inner) rails, independently. At these curves, high rail FM was required to mitigate the squeal noise in the frequency range above approximately 5 kHz [6]. Bullen et al. proposes an algorithm for automatic detection and separation of flanging noise and curve squeal based on wayside measurements [8]. Curve squeal is identified based on its tonal character implemented as a requirement in level difference between a dominating 1/24-octave band frequency and its closest neighbors. Flanging noise is determined based on a comparison of the broad-band frequency content between 2–10 kHz and the total energy content in the entire recorded frequency range. In terms of perception, flanging noise is described to have a higher fundamental frequency, to be more intermittent and to have a more broad-band frequency content as compared to squeal from the inner wheel [9]. In [6], flange squeal is described as having a"hissing" character.

Findings from several comprehensive field studies of curve squeal on Australian rail infrastructure are summarised in [10]. Jiang et al. presented results from a long-term wayside measurement campaign in a 284 m radius curve of ballasted track located in Sydney, Australia, carrying mostly freight traffic. Noise, rail acceleration of both high and low rails and AoA were measured [1]. Tonal curve squeal and broadband flanging noise were separated using a method based on their different frequency characteristics (cf. [8]). The occurrence and level of curve squeal increased with increasing AoA. However, flanging noise showed no obvious relationship to AoA. Interestingly the majority of tonal curve squeal events were found to be generated by the outer wheel [1]. Results from a 200 m radius curve carrying passenger traffic showed 5 % and 0.5 % of passing wheelsets (corresponding to 40 % of passing vehicles) to generate curve squeal and flanging noise, respectively [11]. In this case squeal was identified as events when the sound pressure level of any of the 1/3-octave bands with centre frequencies 3.15 kHz, 4 kHz and 5 kHz measured with wayside microphones mounted close to the high and low rail exceeded 90 dB. No correlation was found between curve squeal occurrence and AoA. The long-term measurements conducted across various types of rail bound transport systems in Australia consistently revealed that leading wheelsets exhibit a higher tendency to generate curve squeal or flanging noise [10].

Jiang et al. investigated the importance of AoA, vehicle speed, rail lubrication and rail grinding using data collected by a wayside condition monitoring system during three years of mixed passenger and freight traffic through a 300 m radius curve in Sydney [12]. Only severe squeal events of levels that exceed 120 dBA measured 1.2 m from the rail were accounted for. Passenger trains did never generate squeal that fell into this category and were excluded. In total 2 000 000 wheelset passages and 2 490 squeal events were accounted for in the analysis. Squeal was related to poor steering of freight trains equipped with unbraced three-piece bogies and occurred almost exclusively for AOA over 10 mrad. A subsequent study that examined the steering performance of different types of bogies when passing through the same curve found that wheelsets of poor steering three-piece leading and trailing bogies tended to develop a flange contact with the high and low rail, respectively [13]. Rail grinding was performed twice during the studied period. At both occasions a significant increase in rate of curve squeal was observed (by comparison of squeal occurrence during the first months after and before the rail grinding) [12]. This observation is in agreement with results in [5] where a statistical significant increase in inner wheel squeal occurrence after rail grinding was found in an analysis that accounted for 26 curves on the Stockholm metro.

This work is part of a research project that aims to better understand the significance of design (i.e. track gauge, rail profiles, pad stiffness, etc.) and maintenance status of the track superstructure on curve squeal occurrence. The ultimate motive is to identify interventions in the track superstructure that can become part of a strategy to prevent or mitigate curve squeal. Previous work in the project has included statistical analysis of noise data collected over an entire metro line [5] as well as the development of a numerical model for simulation of curve squeal capable of simultaneously capturing the low-frequency steering dynamics and high-frequency excitation of unstable friction-induced vibrations [14]. The analysis reported herein is based on field data originally measured to validate the model introduced in [14]. To give attention to the deviant observations made on this dataset, the reporting of the validation exercise was divided into two separate parts; this case study and subsequent work that will focus on the model validation and root-causes for curve squeal at the Stockholm metro.

2. Test site

The track consists of continuously welded BV50 rails (50 kg/m and steel grade 350HT) with inclination 1:40 on ballast. Pandrol fastenings mount the rails on Pandrol pads to monobloc concrete sleepers separated by 60 cm. The designed track gauge is 1435 mm. Measured track gauge as well as rail profiles are presented in Section 4.

At the site there is a double track layout located in a tunnel consisting of a complex alignment with several curves linked together with a varying vertical gradient. Trains make a stop at a station located directly after the exit of the studied curve. The studied curve has a radius of 213 m and a superelevation of 100 mm. Passing trains arrive from a 583 m radius curve via a transition curve of 44 m length and vertical gradient −4.2 ‰ (downwards slope). The studied circular section has length 178 m and a vertical gradient that changes from −4.2 ‰ to 3.7 ‰. At the exit of the curve the vertical gradient reduces to 1.3 ‰. Transition curves have linearly varying curvature and ramp.

The traffic at the site consists exclusively of C20 trains manufactured by Bombardier Transportation. A C20 trainset is composed of 2–3 units of 47 m length. Each unit is a semi-trailer arrangement with one central car with two bogies, and two hinged end cars with one bogie each. The axle load is estimated to be below approximately 12.5 tonnes. All wheelsets are coupled to traction motors which also work as electrodynamic brakes. From speeds of about 10 km/h to standstill, tread brakes contribute with additional braking force. The wheel profile is S1002 with a flange thickness of 31.5 mm. The steel material used for the wheelsets is B88, which is similar to material EN R8T specified in the standard EN 13 262. The vehicle speed at the studied curve is approximately 55 km/h and the accumulated traffic load amounts to 30 megagross-tonnes per track/travelling direction (corresponding to about

130 200 train passages).

3. Measurement setup

Rail roughness was measured using an APT-RSA trolley [15]. It is a hand operated device for measurement of longitudinal rail irregularities using three parallel displacement sensors that measure vertical displacement with respect to a 1 m reference beam mounted on the rail. The sampling distance was 1 mm. Measurements comply with ISO 3095:2005 [16]. Post-processing of the measured data in this paper are carried out in the software Matlab.

Wayside pass-by noise was measured in five simultaneous channels positioned 25 m apart in the circular curve. Measurements were performed with Brüel & Kjaer microphones of type 4189-A-021. Brüel & Kjaer LAN-XI 3050-A-060 was used for acquisition. The sampling frequency was 65.5 kHz. Due to the measurement location in a narrow tunnel the use of stands was restricted and instead microphones were attached to a cable ladder at the tunnel wall. Microphones were located at the approximate same height and at a lateral distance of 1.5 m from the low rail. Rail profiles were measured using a MiniProf [17].

The Stockholm metro performs condition monitoring of their subway railway infrastructure using the condition monitoring system “Quiet Track Monitoring System” (QTMS) originally developed as part of the European financed project “Quiet track” [18,19]. The system is provided by the consultancy firm Tyréns and contains microphones mounted behind the leading bogie of the leading car or in front of the trailing bogie of the trailing car of a C20 trainset (dependent of the traveling direction of the train). Two microphones are located at an approximate distance of 0.8 m from the wheel–rail contacts of both wheels of the instrumented wheelset and two microphones are positioned at the middle car at approximate distance 7 m from the instrumented bogie. The current study has only used noise measured by the microphones located close to the wheel–rail contacts. The microphone sensitivity is 50 mV/Pa and the sampling frequency 22 kHz. QTMS provides a continuous detection of curve squeal in time windows of 250 ms using the following criteria evaluated for the two microphones mounted close to the wheel–rail contacts:

- The vehicle is located in a curve.
- The sound pressure level exceeds 95 dB.
- The sound pressure level measured at the low rail exceeds that at the high rail by at least 3 dBA. This criterion is evaluated for sound pressure levels that are A-weighted and subsequently bandpass filtered in the frequency range between 1.6–6.3 kHz.

It should be noted that the criteria above means that only squeal emitted by the inner wheel in contact with the low rail will be registered. Hence, squeal noise radiated from the outer wheel is disregarded.

As part of the case study presented herein, it has not been possible to relate observations of squeal noise to specific locations of contact on the wheel and rail (i.e. to separate so-called “flanging noise” that originates from the wheel flange and tonal “curve squeal” generated by contact located on the rail crown). Therefore, the term “flanging/flange noise” is not adopted and hence “curve squeal” in this study may refer to squeal radiated from wheel–rail contacts located on the wheel tread or further out towards the wheel flange.

4. Measurements on track

Measurements in the studied 213 m radius curve were performed on two occasions; one day before and one day after the rails were ground. Profiles of the high and low rails and track gauge were measured at five locations separated by 25 m in the circular curve (the same approximate locations as where wayside noise measurements were performed). Fig. 1 presents measured rail profiles at the high and low rails together with a nominal BV50 rail profile inclined 1:40. The variation in rail profile shape between measurement locations is small and hence it is deemed sufficient to show results from one location in the circular curve. The track gauge varies between 1438–1443 mm.

Roughness at the high and low rails of the studied circular curve were measured for a stretch of 100 m. Fig. 2 shows 1/3 octave band roughness spectra of both rails obtained as the average of the roughness measured in three parallel lines. Roughness levels before and after rail grinding are compared against the limit according to ISO standard 3095 [16]. The low rail shows roughness levels before grinding that significantly exceed that measured for the high rail as well as the ISO 3095 limit, see Fig. 2. Magnified roughness levels are observed in the wavelength interval between 4–25 cm with peaks at approximate wavelengths 8 cm and 16 cm. With the trafficking speed of the current curve around 55 km/h, the 8 cm and 16 cm corrugation wavelengths correspond to excitation frequencies 191 Hz and 92 Hz, respectively. These agree with the resonance frequencies of the two wavelength-fixing mechanisms concluded to be responsible for the severe corrugation development observed at another curve with radius 120 m located on the same metro line [20]. For this curve, simulations of dynamic

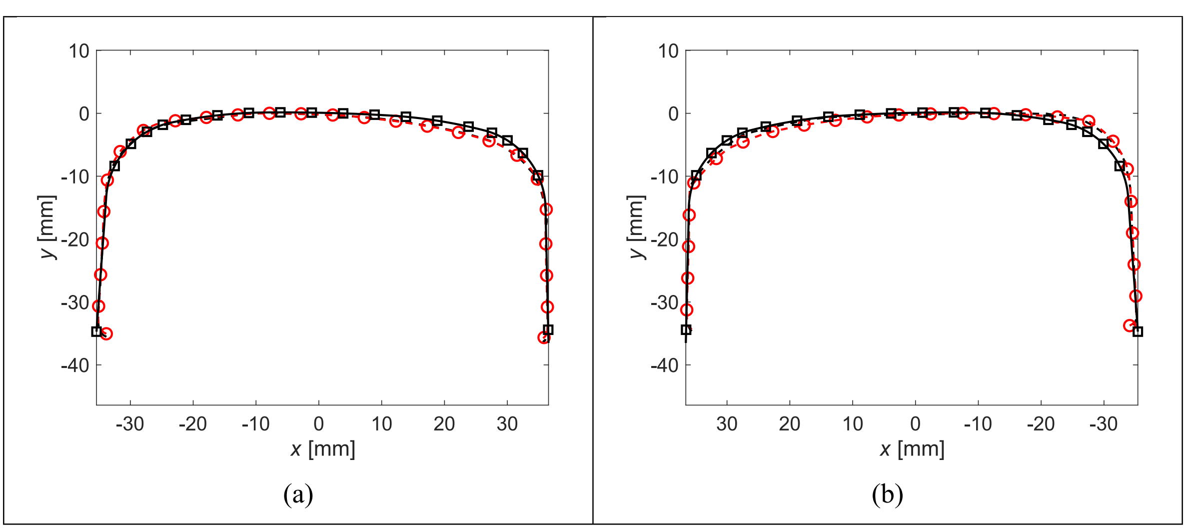

Fig. 1. Rail profiles measured at the high (a) and low (b) rail before (- - -) and after (-○-) rail grinding on the studied curve. —□—: Nominal BV50 rail profile with inclination 1:40.

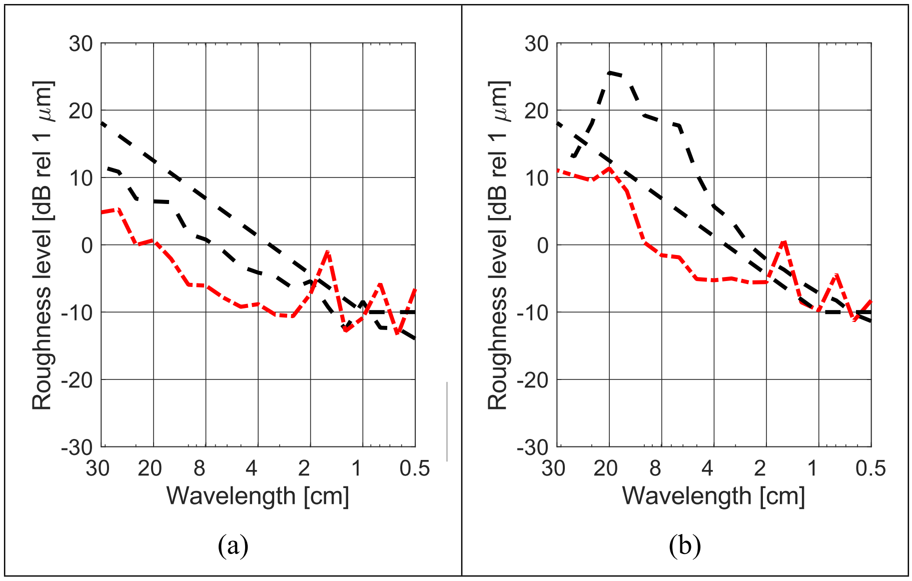

Fig. 2. Roughness level spectra in 1/3 octave bands based on measurements before and after rail grinding of the high (a) and low (b) rail on the studied curve. Roughness levels are averaged from measurements in three parallel lines over a distance of approximately 100 m. ▬ ▬: Before rail grinding, ▬·▬: After rail grinding, ▬▬: Limit according to ISO 3095.

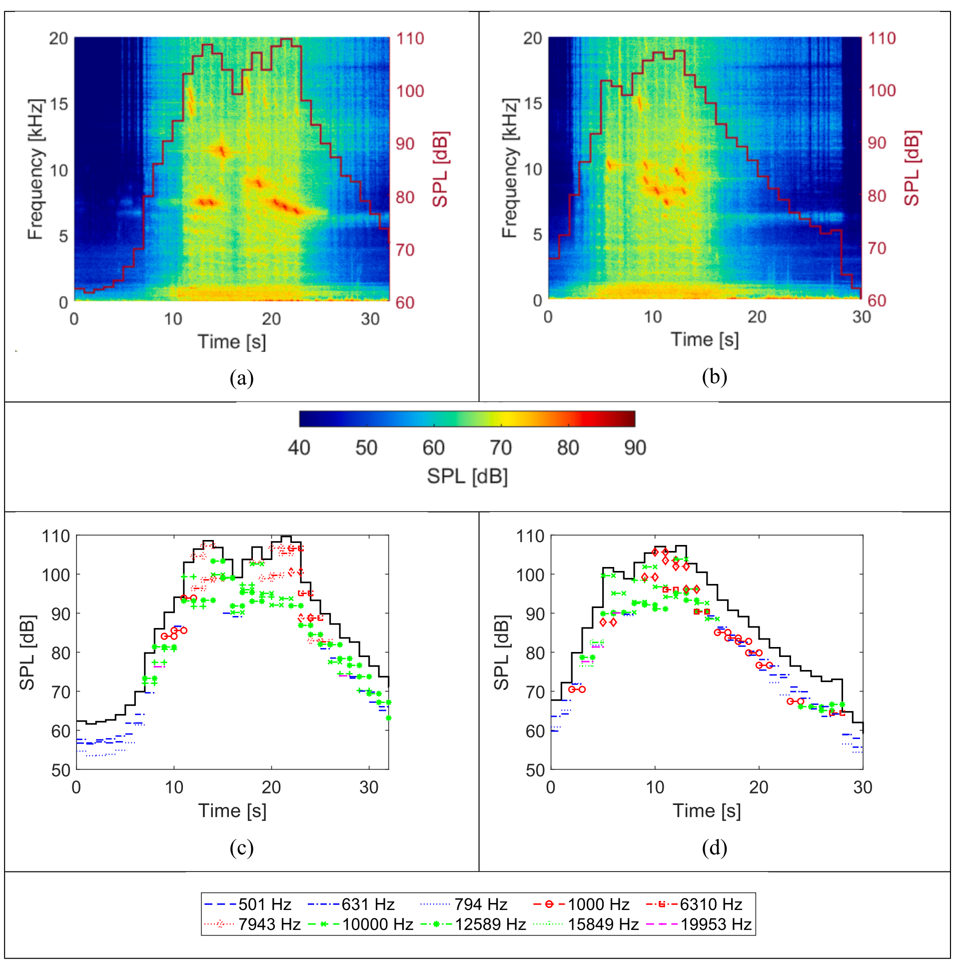

Fig. 3. (a) and (b): Examples of sound pressure level (SPL) spectrograms measured during pass-by of two vehicles. The solid line shows total SPL evaluated for window length 1 s and taking into account the frequency range above 400 Hz. (c) and (d): The three 1/3-octave bands with largest SPL together with the total SPL evaluated for windows of 1 s length. Results in sub-figures (c) and (d) corresponds to passages (a) and (b), respectively.

vehicle–track interaction showed the wavelength-fixing mechanisms to be primarily associated with the first anti-symmetric and symmetric bending eigenmodes of the leading wheelset of passing bogies [20]. The appearance of grinding marks is noticed in the measurement performed after rail grinding as distinct peaks at short wavelengths (below 2 cm), see Fig. 2. This is consistent with observations made in previous studies involving roughness measurements in conjunction with rail grinding [21].

5. Wayside noise measurements

Wayside noise was measured on 5 channels equally distributed along a stretch of 100 m in the studied curve. A total of 69 train passages were collected. Information on the measurement equipment and setup is found in Section 3. The sample frequency is 65.5 kHz. The measurements were performed before lunch five days before the first measurement of rail profiles and rail roughness presented in Section 4 (labelled “before rail grinding” in Figs. 1 and 2).

Squeal noise was generated from all measured vehicle passages. The emitted squeal was perceived as having an intermittent high-frequency character. This is confirmed by Fig. 3(a and b) that show spectrograms of two example vehicle passages together with the total sound pressure level (SPL) evaluated in the frequency range above 400 Hz. The high-pass filter at this cut-off frequency is used to suppress the rolling noise caused by the magnified roughness magnitudes observed in Fig. 2(b). Spectrograms are calculated for a Hamming window of length 8192 (corresponding to 125 ms) with an overlap of 50 %. The intermittent squeal noise character is noticed in the spectrograms as sudden peak spectral components distributed in an extended frequency range above approximately 5 kHz, see Fig. 3(a and b). Fig. 3(a) shows a peak SPL of 110 dB (note that the microphone could not be positioned in accordance with ISO 3095, see Section 3).

Fig. 3(c and d) show the centre frequencies of the three 1/3-octave bands with largest SPL evaluated for windows of 1 s lengths. Fig. 3(a and c), and Fig. 3(b and d) represent the same vehicle passages, respectively. On several occasions during the passages of both vehicles 1/3 octave bands with centre frequencies above 10 kHz make the largest contribution to the total SPL. For both passages, the 1/3 octave band with centre frequency 7 943 Hz makes important contributions at instances when the total SPL reaches local maxima. Fig. 3(c and d) illustrate the intermittent character of the squeal noise radiated from the studied curve though the significant and continuous variation in dominating 1/3 octave bands with centre frequencies in the range between 6.3–15.8 kHz.

Fig. 4 shows histograms of the number of squealing events. SPL spectra in 1/24 octave bands are recurrently evaluated for window lengths of 1 s for all vehicle passages. A squealing event is defined as an instant when the SPL of any 1/24 octave band exceeds 90 dB. The level 90 dB is taken from [11] where it was used as limit to detect squeal noise. Here the criterion is rather used to give an overall representation of the frequency characteristics of the curve squeal emitted at the current curve. The results obtained at two locations of the circular curve separated by 50 m are compared. Trains pass the microphones used for Fig. 4(a and b) in consecutive order. The microphone of Fig. 4(b) is located closest to the station at an approximate distance of 50 m. It is noticed that the number of squealing events at location A (1 964) far exceeds them at location B (711), see Fig. 4. At both locations squeal events are primarily registered in the frequency range between approximately 3–17 kHz. Moreover, for both locations, the largest number of squeal events are associated with the 1/24 octave band with centre frequency 8 294 Hz. Differences in squeal events collected at the two locations are also noticeable. For example, location B shows a peak

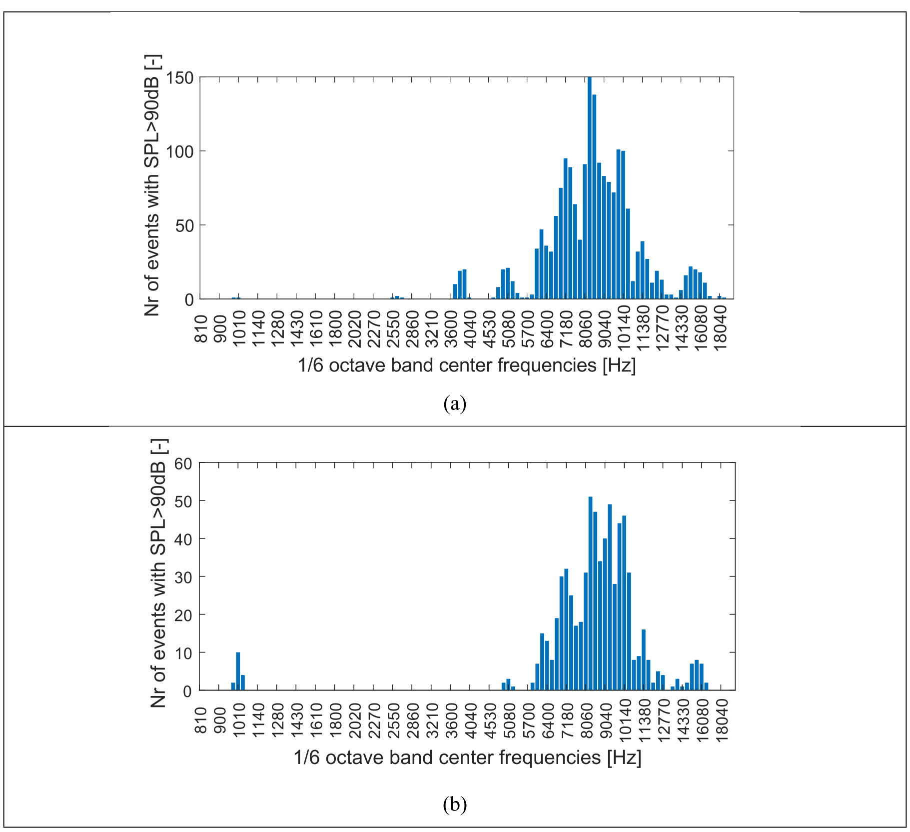

Fig. 4. Histogram of squeal events identified as spectral components with sound pressure level exceeding 90 dB. The analysis is based on 1/24 octave band spectrum evaluated for windows of 1 s length. The results of (a) and (b) are obtained from wayside noise measurements of 69 vehicle passages performed at locations separated by 50 m in the studied circular curve of 213 m radius.

in number of events at 9 306 Hz that is not noticed at location A. And oppositely, location A shows a unique peak at approximately 3 924 Hz.

6. On-board noise measurements

The study has obtained data recorded by the QTMS-system mounted on two different vehicles that have trafficked the green line at the Stockholm metro between 211216–221110 (vehicle A) and 211209–230114 (vehicle B). The data have been examined and all vehicle passages with vehicle speed below 20 km/h removed. The later to exclude passages where the vehicle has braked to stand still (e.g. due to queuing to the station) alternatively has been operated at a deviating low speed. The total number of curve passages included in the analysis is 733 and 1190 for vehicles A and B, respectively. The average speed for all passages of both vehicles through the studied curve is 38 km/h. In the current work, the QTMS-system needs to detect at least 0.5 s of sustained inner wheel squeal in order for the passage to be considered as a squealing passage. This criterium is inherited from [1].

The train end running in front alternated during the period when noise data were collected. This means that the position of the instrumented wheelset alternated between running as leading or trailing in passing bogies. On average, based on results obtained for both vehicles, the occurrence of inner wheel squeal is observed to be 50 % higher when the instrumented wheelset is running in leading as compared to trailing bogie position, see Table 1. Additionally, the squeal propensity for vehicle A and vehicle B is observed to be 56 % and 72 %, respectively. Hence vehicle B is significantly more inclined to generate inner wheel squeal than vehicle A. This observation is consistent with the results from the statistical analysis in [5]. It should be noted that part of this difference is explained by relatively larger proportion of curve passages with the instrumented wheelset in leading bogie position for vehicle B as compared to vehicle A, see Table 1.

Fig. 5 shows the squeal propensity evaluated for vehicle passages made a period of 2 months before and after rail grinding performed on 2022–09-08, separately. Before this occasion, the most recent rail grinding of the current curve was performed on 2022–04-29. In total, for both vehicles, the number of passages accounted for before and after rail grinding are 299 and 474, respectively. On average, for both vehicles, the propensity of inner wheel squeal is found to increase from 64 % to 74 % after rail grinding. The difference in squeal propensity before and after rail grinding for leading wheelsets of both vehicles is observed to be insignificant.

Noise recorded by microphones positioned close to the inner and outer wheel–rail contacts of the instrumented wheelsets are first A-weighted and thereafter passband filtered in the frequency range between 1.6–6.3 kHz. This is in accordance with the QTMS curve squeal detection algorithm described in Section 3 [2]. Bandpass filtering is performed with a finite impulse response filter based on a Kaiser window with stop band attenuation 60 dB and transition band steepness 0.85 (using the Matlab function 'bandpass'). The A-weighted and bandpass filtered sound pressure level, $L_{A1.6\text{-}6.3kHz}$, is then calculated for window lengths 250 ms (corresponding to 5 500 samples for the sampling frequency of the on-board measurements being 22 000 Hz, see Section 3). This corresponds to the procedure for automatic curve squeal detection by the QTMS-system.

Table 1
Occurrence of inner wheel squeal in the studied 213 m radius curve based on noise measured with an instrumented wheelset mounted on two different vehicles. Results obtained with the instrumented wheelset running in leading and trailing positions of passing bogies are shown separately. The number in the parenthesis shows the total number of recorded vehicle passages.

	Leading position	Trailing position
Vehicle A	71 % (311)	45 % (422)
Vehicle B	82 % (713)	58 % (477)

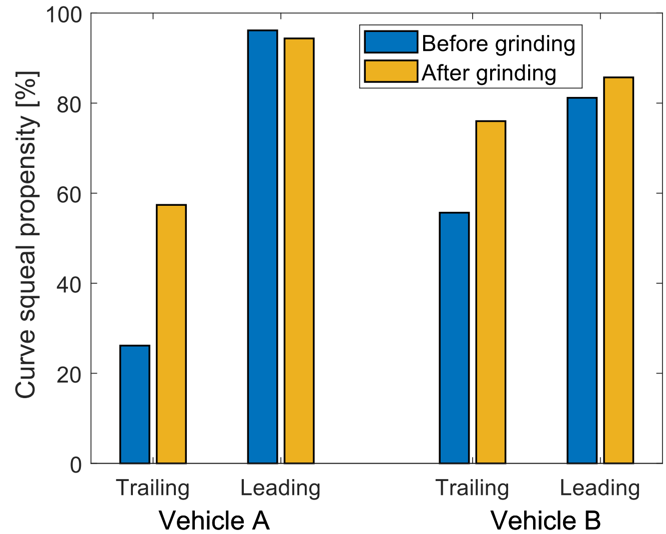

Fig. 5. Comparison of inner wheel squeal propensity for both vehicles evaluated for vehicle passages performed before and after rail grinding, separately.

Fig. 6(a and b) show histograms of maximum $L_{A1.6\text{-}6.3kHz}$ for all curve passages during the entire studied period for vehicle A and B, respectively. The maximum is taken of $L_{A1.6\text{-}6.3kHz}$ evaluated for window lengths of 250 ms. The portion of passages when inner wheel squeal is detected is outlined in yellow colour. The occurrence of inner wheel squeal is evaluated using an implementation of the QTMS-algorithm (see Section 3). The maximum $L_{A1.6\text{-}6.3kHz}$ recorded for vehicle B is noticed to exceed that for vehicle A by approximately 5 dBA, see Fig. 6. Further, a general shift in the distribution towards higher noise levels recorded for vehicle B compared to vehicle A is noticed. This observation is consistent with the results in Fig. 5 indicating vehicle B to be more inclined to generate inner wheel squeal than vehicle B. In accordance with the QTMS-algorithm, inner wheel squeal is only detected for passages when the maximum $L_{A1.6\text{-}6.3kHz}$ exceeds 95 dB, see Fig. 6.

The large magnitude high-frequency (>5 kHz) spectral components of pass-by noise shown in Fig. 4 indicate the outer wheel as the noise source [6]. To the authors knowledge, no on-board noise monitoring algorithm for squeal radiated from the outer wheel is yet presented in literature. To anyhow follow up on this remark, the QTMS-algorithm is applied in inverse, i.e. squeal during a 250 ms time instant is identified if $L_{A1.6\text{-}6.3kHz}$ at the outer wheel exceeds 95 dB and simultaneously that evaluated for the inner wheel by 3 dB. It should be noted that the QTMS-algorithm has been developed to capture squeal from the inner wheel and cannot be expected to feature successful detection of outer wheel squeal. The purpose of the analysis herein is explorative and motivated by the limited literature on outer wheel/flange squeal.

In correspondence with the results for squeal generated by the inner wheel, the maximum $L_{A1.6\text{-}6.3kHz}$ evaluated at the outer wheel of vehicle B exceeds that from vehicle A, see Fig. 7. The propensity for squeal generation at the outer wheel is found to be 11 % and 6 % for vehicle A and B, respectively. However, 52 % of the passages that contain squeal events radiated from the outer wheel also feature squeal from the inner wheel (however, occurring at different 250 ms time instants). Interestingly, Fig. 7 shows squeal radiation from the outer wheel for only a small portion of the passages with maximum $L_{A1.6\text{-}6.3kHz}$ exceeding 95 dB. Possibly this is related to crosstalk of noise from the low to the high wheel–rail contact.

Fig. 8 illustrates examples of passages with squeal radiated from the outer wheel, inner wheel and simultaneously from both wheels, based on noise data collected by the instrumented wheelsets. Cases of squeal generated by the outer wheel has been identified using the inverse QTMS-algorithm as described in the previous paragraph. 250 ms time instances where squeal from the outer and inner wheels are detected are

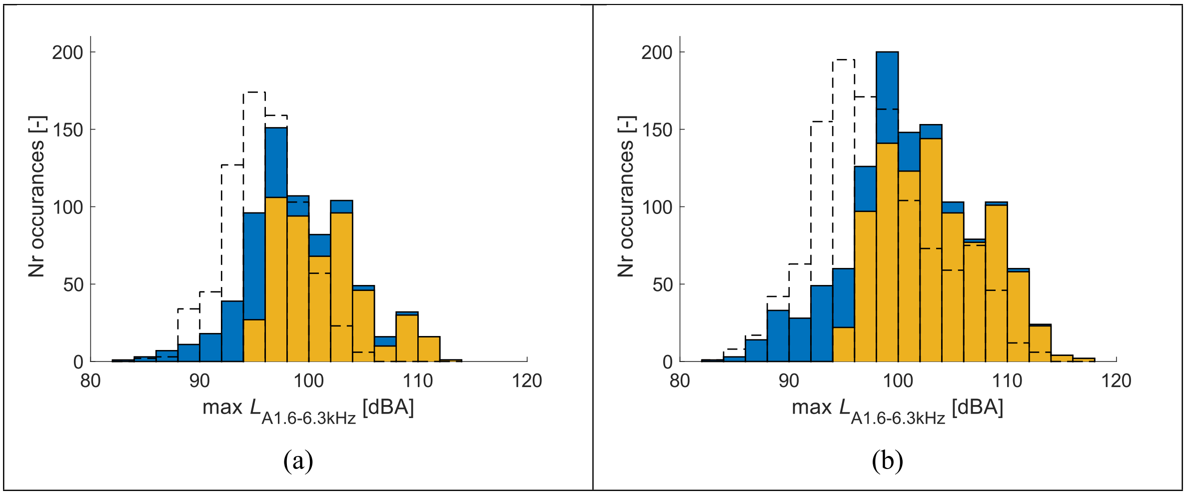

Fig. 6. Histogram of maximum A-weighted and passband filtered (between 1.6–6.3 kHz) sound pressure levels recorded in the studied 213 m radius curve by the QTMS-system mounted on vehicle A (a) and B (b) during one year of regular traffic. ▬: Inner wheel and no detected squeal, ▬: Inner wheel and detected squeal, [ ]: Outer wheel.

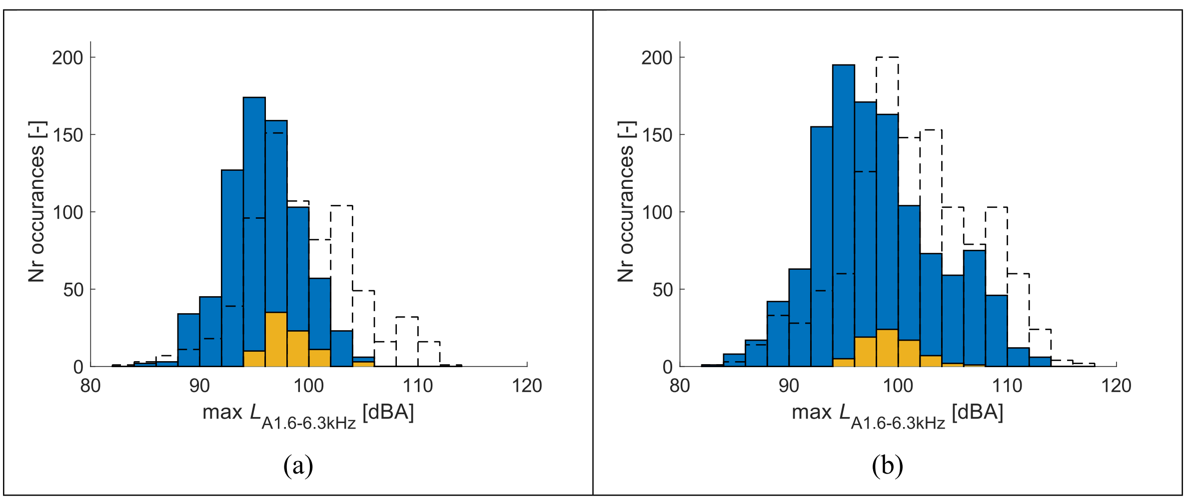

Fig. 7. Histogram of maximum A-weighted and passband filtered (between 1.6–6.3 kHz) sound pressure levels recorded in the studied 213 m radius curve by the QTMS-system mounted on vehicle A (a) and B (b) during one year of regular traffic. ▬: Outer wheel and no detected squeal, ▬: Outer wheel and detected squeal, [ ]: Inner wheel.

outlined in turquoise and purple color, respectively. Crosstalk is noticed as the noise measured at both wheels show consistent frequency content and temporal characteristics (only moderated by sound pressure level). The squeal radiated from the outer wheel shows similar spectral characteristics as the case of squeal generated from the inner wheel (compare the first and second row of Fig. 8). For the vehicle passage that features squeal from both the inner and outer wheel (bottom row of Fig. 8), the contribution from the outer wheel is noticed as short bursts at approximately 5.5 kHz.

7. Discussion

Compared to field measurements of curve squeal reported in literature the current case study shows increased levels of acoustics energy in the high frequency range above 10 kHz. For example, the wayside noise measurements presented in Fig. 3 show time instances when the total noise level is dominated by 1/3-octave bands with centre frequencies up to 15.8 kHz. As reference, the review of field studies on curve squeal covering metro, tram and freight traffic report squeal to occur in the frequency range below 5 kHz [7]. The only exception corresponds to a tram with resilient wheels negotiating a curve of 60 m radius constructed with grooved rails. For this case squealing frequencies of up to 8.1 kHz were measured [21]. Several field studies in literature do not report noise data for the entire audible frequency range below 20 kHz. Although this may be interpreted as frequency components above e.g. 10 kHz are insignificant, it would have been clarifying if the extended frequency range was covered.

The wayside noise measurements of Fig. 3 contain recurrent discrete jumps between 1/3 octave band centre frequencies in the range between 6.3–15.8 kHz. Probably this is related to the passage of individual wheelsets that radiate squeal of different characteristics. As commented in Section 5, squeal noise was emitted for all vehicle passages collected by the wayside noise measurements. However, the on-board noise measurements presented in Section 6, showed generation of curve squeal (from the inner wheel) for approximately 65 % of the passages. This can be compared against [11] where curve squeal was measured for 5 % passing wheelsets but 40 % of vehicle passages. A C20 trainset is composed by 3 units corresponding to a total of 24 wheelsets. Naturally, fewer squeal events are registered for a single wheelset (as for the on-board measurements) as compared to what is perceived by a trackside

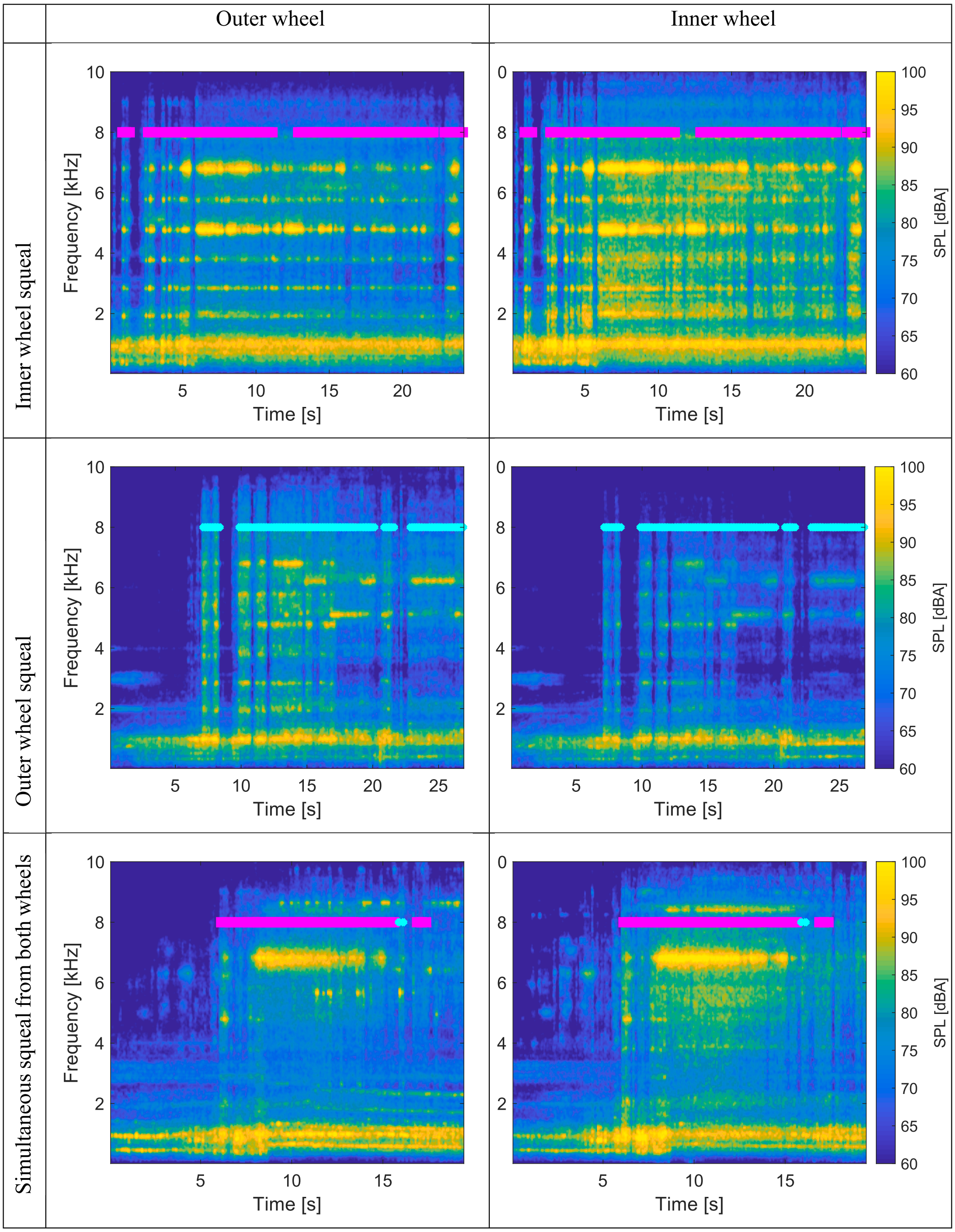

Fig. 8. A-weighted sound pressure level spectrograms obtained from the microphones belonging to the QTMS-system mounted close to the inner (right column) and outer (left column) wheel–rail contacts, respectively. Examples of passages that are characterized by squeal emitted from the inner wheel (top row), outer wheel (middle row) and simultaneous generation from both wheels (bottom row). ◻: Inner wheel squeal detection, ✖: Outer wheel squeal detection.

observer (as for the wayside measurements). Here it can also be noted that the on-board noise measurements risk missing out of squeal events due to the limited sampling frequency of 22 kHz and the analysed frequency range between 1.6–6.3 kHz.

Due to the large AoA and associated magnified lateral creep forces developed at its wheel–rail contacts, squeal noise is typically radiated by wheelsets mounted in the leading position of passing bogies. This is confirmed by [7] as well as the long-term monitoring of curve squeal performed at different Australian railway lines [10]. With respect to this, the results of Table 1 indicating squeal noise generation for 52 % of passages when the instrumented wheelset was mounted in the trailing position may seem contradictory. However, a portion of these passages are believed to be caused by crosstalk from the leading wheelset. In this regard, notice the elevated maximum noise levels of magnitude up to 118 dB measured at the inner wheel in Fig. 6. Noise levels at these magnitudes may, through crosstalk from the leading to the trailing wheelset, be able to exceed the noise limit for detection of squeal events set to 95 dB. Further investigation of this matter is suggested for future work.

The current case study follows up on results with respect to rail grinding and vehicle individual presented in the statistical analysis in [5]. The results herein confirm a significant difference in propensity to generate curve squeal between the vehicles of 15 %. Unlike [5], the current study draws this conclusions also accounting for the running position of the instrumented wheelset (leading or trailing), see Table 1. This indicates the difference to be related to individual vehicle characteristics such as for example the maintenance status with regard to wheel profile wear and wheel dampers (the Bombardier C20 vehicles are manufactured with wheel plate absorbers). As for rail grinding, the results in [5] showed a significant increase in curve squeal occurrence after rail grinding. The results obtained for the 213 m radius curve investigated here align with this result by an indicated increase in curve squeal occurrence of 10 % for vehicle passages performed after rail grinding. Measurements of rail roughness performed before rail grinding show severe corrugation in the wavelength interval between 4–25 cm, see Fig. 2. Possible impact of rail corrugation on the generation of curve squeal remains to be investigated in future work.

Fig. 4 shows the largest number of time instances exceeding 90 dB in the frequency range between 6–13 kHz. Additional peaks are noticed at around 4 kHz and 5 kHz which is within the frequency range between 1.6–6.3 kHz used by the bandpass filtering performed as part of the QTMS squeal noise detection system. Cases of squeal noise radiation from the outer wheel with tonal components in this frequency range are shown in Fig. 7 and Fig. 8. The sampling frequency of the on-board noise monitoring system at 22 kHz does not allow to study the entire extended frequency range with magnified spectral components found by the wayside noise measurements. Fig. 8 shows two cases of squeal noise radiation from the inner wheel recorded by the instrumented wheelset. Both feature sustained tonal components which contrasts the intermittent squeal observed in the wayside measurements. Interestingly, the squeal noise radiated from the outer wheel presented in Fig. 8 shows similar spectral characteristics as for the cases with inner wheel squeal.

8. Insights

Based on this case study, the following insights with implications for future modelling and monitoring of curve squeal at the Stockholm metro are reached:

- The Stockholm metro exhibits curve squeal at an exceptionally high frequency range as compared to field studies reported in literature. To capture the dynamic behavior of wheels and rails in this frequency range requires high-resolution and detailed modelling of their structural flexibility. Furthermore, a computationally efficient method for the time integration of the corresponding large (in terms of degrees-of-freedom) and nonlinear system of equations of motion will be required. The simulation tool introduced as part of previous work in the current research project meets these requirements by pre-calculated impulse response functions (Green's functions) [14].
- The curve squeal emitted from the studied curve is very intermittent. An example measurement of pass-by noise shows the dominant 1/3 octave band to vary continuously between five different 1/3 octave bands with centre frequencies in the range between 6.3–15.9 kHz. To explain the governing mechanisms (e.g. location of contact on the wheel, local friction conditions, individual differences in maintenance status and wheel diameter between wheelsets, etc.) to this variation in noise characteristics is an interesting and important task for future research. Note that the current study cannot attribute squeal noise to wheel–rail contact locations on the rail crown or rail gauge face (i.e. flanging noise). For noise emissions in the frequency range below approximately 6 kHz, the study shows the inner wheel to be the dominant source.
- This study shows tonal squeal noise of similar frequency characteristics radiated from the outer and inner wheels. In addition, the study presents a case when the inner and outer wheel on the same axle generates squeal simultaneously during curve passage. These are challenging conditions with respect to algorithms for automatic squeal noise detection. To address this, the authors propose the QTMS-system to be further developed to assess the level difference between the two wheels of the instrumented wheelset for individual frequency components rather than for a wide frequency range (in its current implementation the level difference is evaluated for a passband filter between 1.6–6.3 kHz). Further, the measured frequency range needs to be expanded significantly. The current study shows important squealing frequency components up to 16 kHz.

9. Conclusions

A comprehensive case study of curve squeal in a 213 m radius curve on the Stockholm metro is presented. It includes measurements of track characteristics (rail profile, rail roughness and gauge width) and noise measured at the trackside and by two vehicles equipped with an on-board mounted noise monitoring system. The current work follows up on an earlier extensive statistical analysis of curve squeal occurrence on the entire metro line [5], and will be followed by a subsequent paper where modelling of dynamic vehicle–track interaction in an extended frequency range will be used to investigate governing mechanisms of the curve squeal observed in the current curve.

Wayside noise measurements show squeal noise emission for all vehicle passages with an intermittent character that contains discrete jumps between dominating 1/3 octave bands with centre frequencies in the range between 6.3–15.8 kHz. The sound pressure level (SPL) for all vehicle passages was evaluated in 1/24 octave bands for window length of 1 s and compared against a limit of 90 dB. Exceeding events were particularly concentrated to the frequency range between 6–13 kHz. This means that the squeal observed in the studied curve has spectral components at a frequency range that is significantly higher as compared to the main body of field measurements presented in literature.

The project received noise data measured during approximately one year of regular traffic of two metro vehicles on the current metro line. Noise was recorded close to the wheel–rail contacts of both wheels of one instrumented wheelset. In total, for both vehicles, the dataset contained 1923 passages through the studied curve. The data indicate curve squeal radiation form the inner wheel for about 65 % of the vehicle passages. The curve squeal occurrence is found to increase by 10 % after rail grinding. Moreover, a difference of 15 % in curve squeal occurrence attributed to differences in individual vehicle characteristics is found.

The criterion for detection of curve squeal currently applied by the noise monitoring system in operation at the Stockholm metro was implemented to search for events with squeal noise emitted by the outer wheel. The algorithm prescribes the noise measured close to the wheel–rail contacts to be A-weighted and bandpass filtered in the frequency range between 1.6–6.3 kHz. Squeal is detected if this filtered signal exceeds 95 dB and simultaneously causes a level difference of 3 dB between the wheels of the instrumented wheelset. Based on this criterion, squeal noise generation from the outer wheel is identified for 8 % of the vehicle passages. This includes vehicle passages that contain squeal radiated from both the inner and outer wheels at different time instances. Further, the current work demonstrates a case of squeal radiated from the outer wheel with similar characteristics as that typically associated with squeal generated by the inner wheel (e.g. sustained tonal squeal).

CRediT authorship contribution statement

P.T. Torstensson: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **A. Pieringer:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **M. Höjer:** Resources, Investigation, Data curation. **R. Nilsson:** Resources, Investigation, Data curation. **V. Simonsson:** Visualization, Methodology, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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