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5aNS8. Squealing noise in light rail transport systems: Implications in noise mapping

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Squealing noise is generated by railway vehicles riding through curves having closed radius. It is a result of wheels sliding on the rail when they negotiate a curve. This kind of noise is very annoying for people living in the surrounding areas where this phenomenon occurs because it has a characteristic spectrum that is dominated by discrete frequency components. Usually, squeal noise is not correctly accounted in urban areas noise maps. This paper presents the results of field measurements of squealing noise in Porto (Portugal) where a new light-rail system is operating. The goal was to characterize the acoustic effect of this type of noise in making noise maps. With the results obtained from in situ measurements, the squealing noise was simulated using Cadna/A software. This paper compares three variants of squeal noise use and simulation with the software CADNA/A. Comparing the noise map generated using the field measurements, with maps taking no account for squealing noise, a large difference in noise levels can be found (up to 17 dBA) leading to errors up to 100 m in noise exposed areas. A correction method was found to be easily incorporated in this model to improve the noise map estimation procedure.

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1. Introduction – The squealing noise generation

Squealing noise is generated by railways vehicles riding through curves having closed radius. It is a result of wheels sliding on the rail when they negotiate a curve. Sliding can occur because of three phenomenon possibilities [1]:

- Lateral sliding - At common two-axle vehicles the axle holds parallel and the curve negotiation forces make the tram wheels to slide perpendicular to the direction of rolling. The wheels than creep across the top of the rail. Due to finite length of the two-axle truck and the curvature radius of the rail, both axles cannot lie upon the curve radius. Under actual conditions, the leading axle of the truck rides toward the outside of the curve, while the trailing axle travels between the two rails. It means a reduction of the wheel creeping across the top of the rail at the trailing axle, but an increase of the wheel creeping across the top of the rail at the leading axle.
- Longitudinal sliding - On a curve the outside wheel have to negotiate a longer distance than the inside wheel, but the wheels roll the same distance because they are attached on the same axle. The difference in path length must be made up by the wheel sliding in a direction parallel to the rolling motion.
- Installation of restraining rail - Sometimes a restraining rail is installed next to the inside rail on curves, which safely helps negotiate the curve, therefore rubbing and squeal noise ensues.

2. Measurements

2.1 The study area

The chosen field measuring area was on the Yellow Line (or D Line) of the Metro system in Porto (Portugal) between the metro stations "*IPO*" and "*Pólo Universitário*". This part of the tramway track was selected due to the presence of closed curves, good accessibility for measurement and low traffic frequence. Measurements were done in the curve (March/May 2009) in measuring points I and II and also on a straight segment of the track (point III) which as used for comparisons with the noise levels measured in curve (Fig. 1).

2.2 The metro vehicle

The metros run with two vehicles coupled and their total length is 70 m. Each vehicle has four bogies (Fig. 2) and the average speed is 19 km/h in this segment of the track.

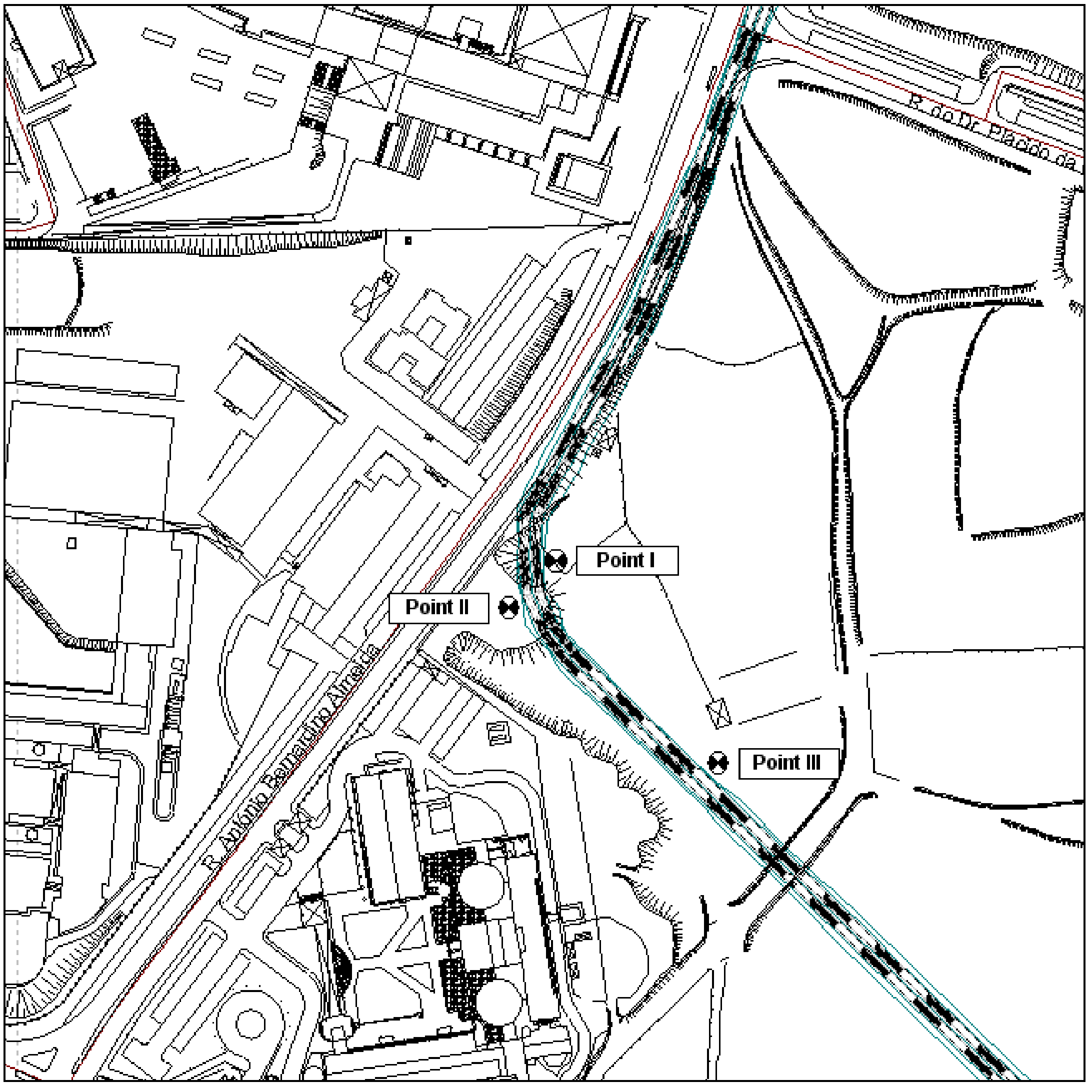


Fig. 1. Metro line with the three measuring points in the study area (I, II and III).

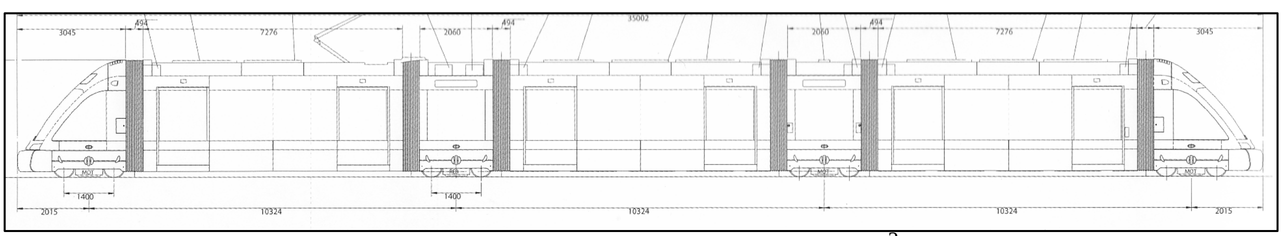


Fig. 2. Metro scheme of vehicle in Porto [2].

2.3 The track

The track is build with sleepers in concrete and it is finished with granite curbstones (Fig. 3). Grooved rails are used and the rails are welded. The track gauge is the standard 1435 mm. The track is without significant slope in the measurement segment. The outside curve has a radius of 54 m and the inside curve has a radius of 50 m (Fig. 4).

Fig. 3. Track in the measuring segment.

2.4 Measurement conditions

The measurements were done using a *Brüel & Kjaer* type 2260 sound level meter that was mounted 1.5 m above the metro track. All measurements were carried out under good meteorological conditions at air temperatures of 15°C to 25°C and with very low wind conditions.

Each measurement interval started when the squealing noise appeared and finished when it disappeared. Measuring point I is located on the inside of the curve, 7.5 m from the centre of the inside line (10.6 m from the outside line center) (Fig. 4). Measuring point II is located on the outside of the curve, 7.5 m from the center of the outside line (10.6 m from the inside line center) (Fig. 4).

During the field measurements the time interval for finding the pass-by speed of vehicles was measured, using a stopwatch and knowing the length of vehicle (70 m). The pass-by speed of the metro was calculated dividing the overall length of the train by the time interval.

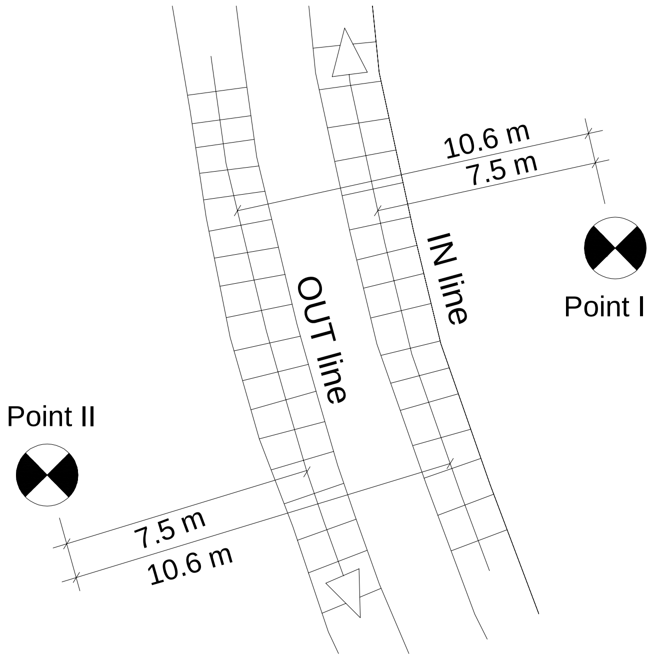


Fig. 4. Situation of field measurement area and measuring points (I and II) in the selected curve.

2.5 Measurement results

Data from the measurements in the curve were processed and comparisons were done with data from the measurements in the straight line segment. An average noise level for squealing noise $L_{Aeq\ (global)}$ of 85 dB was found. It is 16 dB(A) higher than the average noise level of the running metro in the straight line segment which was 69 dB(A). The comparative picture of the measured values is shown on figure 5. The squealing noise appears in some 1/3 octave frequency bands - 630 Hz, 800 Hz, 1.6 kHz, 2 kHz and 4 kHz. The largest difference between noise levels in outside line and straight line is 25 dB at the frequency band of 1.6 kHz (Fig. 6). The sound pressure levels 1/3 octave spectra of the inside line (I), outside line (II) and straight line (III) are presented on figure 7. The 2 kHz frequency band has the highest noise levels (around 82 dBA in the outside and inside lines). It was not possible to compare the squealing noise controlling for the metro speed because it was almost constant and the squeal noise did not change with small speed variations.

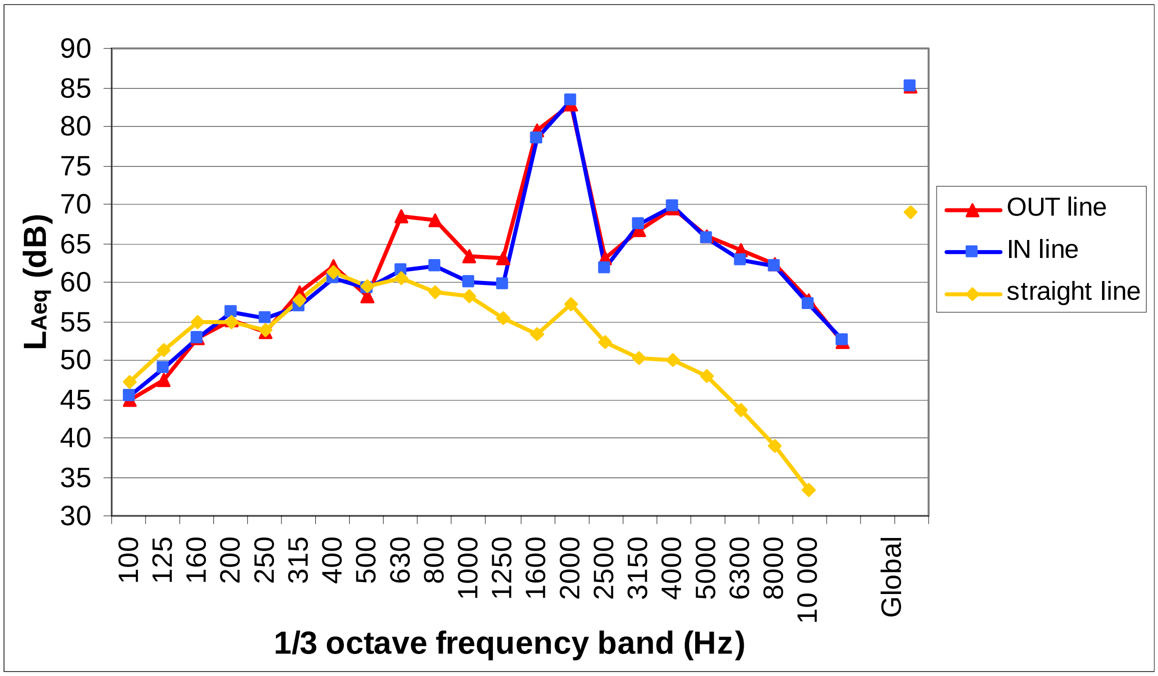


Fig. 5. Comparison of sound levels in the curve (inside I and outside II) and straight line (III) measurements.

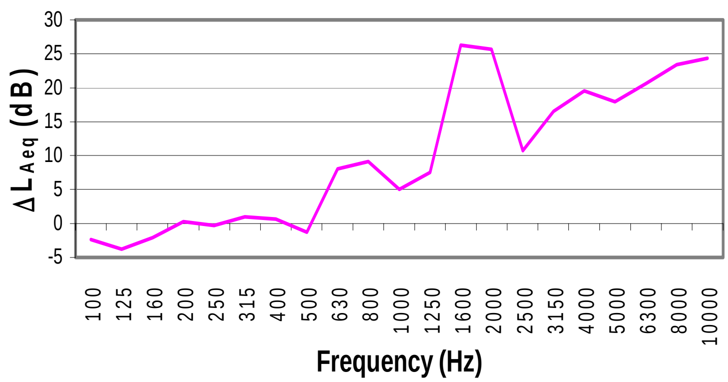


Fig. 6. Comparison of the sound levels differences ΔL_{Aeq} *(dB)* between outside and straight line measurements (= L_A *Out curve* - L_A *Straight*).

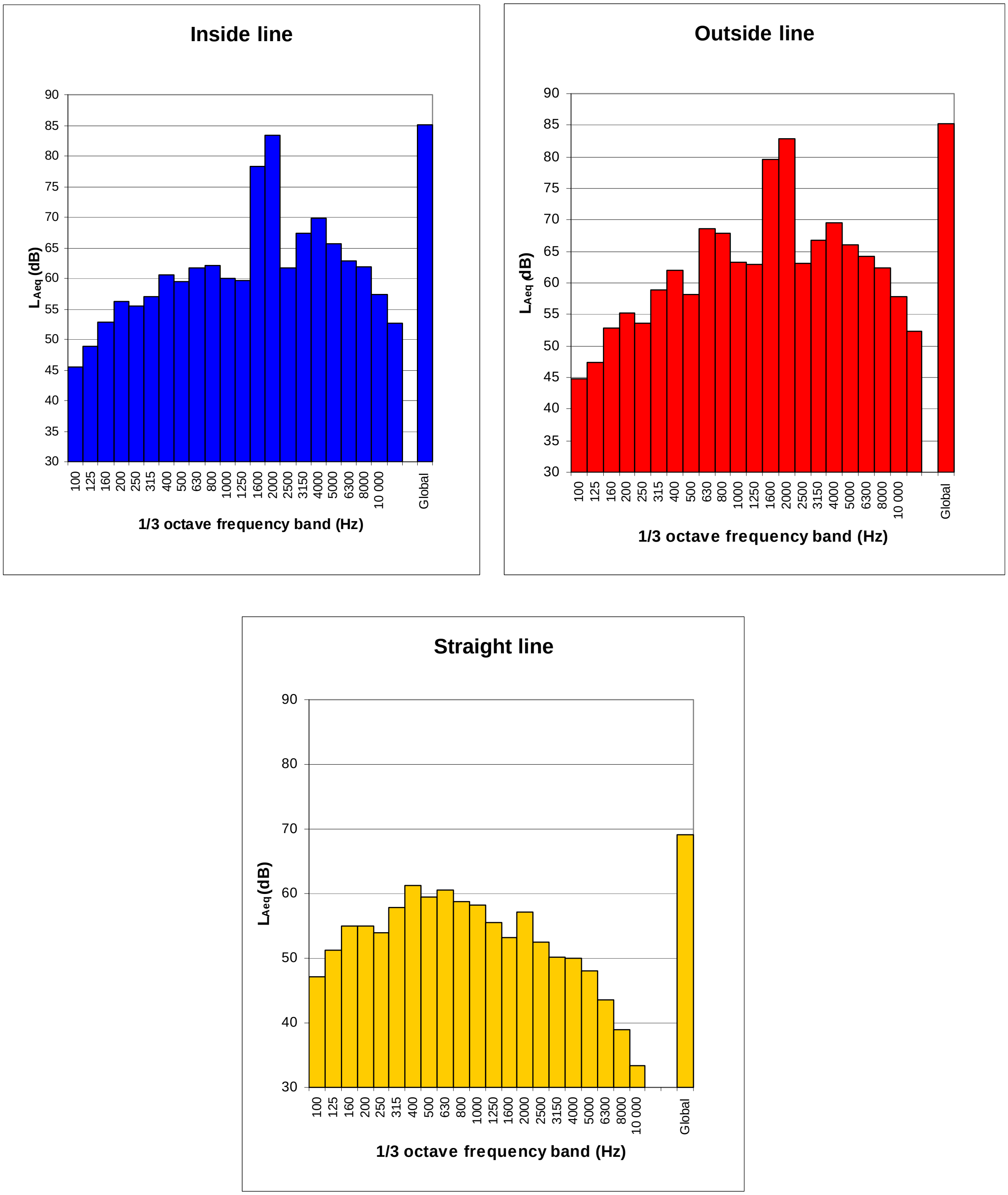


Fig. 7. L_{Aeq} - 1/3 octave frequency band spectra for the inside line (I), outside line (II) in curve and straight line (III) measurements.

3. Comparison with other measurements

Other measurements data about squealing noise were found in the literature. For instance, one was done in Bilbao, Spain, 2004[3] to compare the tram squealing noise on track with and without the application of lubrication on rails (Fig. 8). It was found that squealing frequency bands (800 Hz, 2 kHz and 4 kHz) were related to the curvature radius. The 800 Hz frequency band was the main squealing frequency but the tighter the curve the higher the sound pressure levels at the 2 kHz frequency band. The behavior of squeal noise at 4 kHz was related to the 2 kHz frequency and follows the same tendency. The squealing noise appears in the same three frequency bands as in the measurements in this article (800 Hz, 2 kHz and 4 kHz).

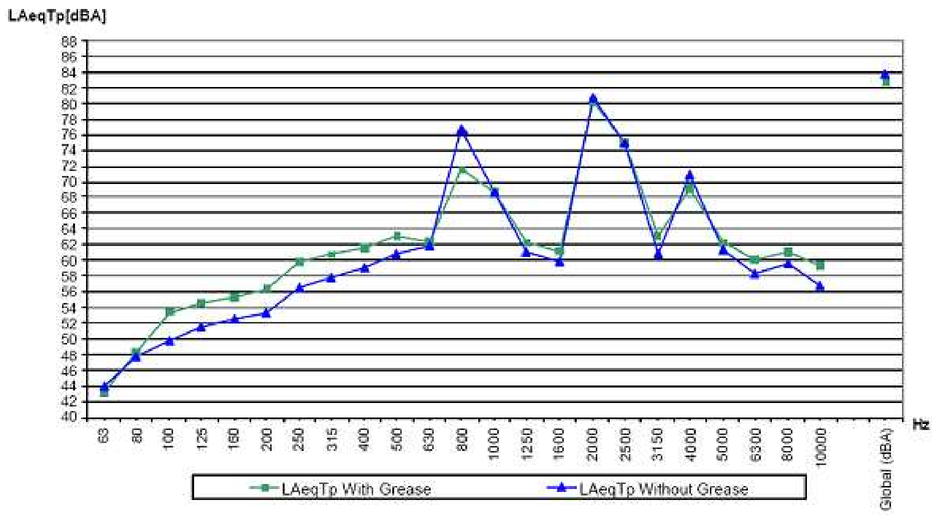


Fig. 8. Average noise levels measured at a distance of 5.5 m from the centre of the track in the inner side of the curve (curve of Pio Baroja, Bilbao, Spain) [3].

A second example is taken from the *Handbook of Acoustical Measurements and Noise Control* [1] (Fig. 9). It shows the spectrum of squealing noise from an urban rail-transit car where also some dominant frequencies appear (630 Hz, 2.5 kHz and 6.3 kHz). There is one same frequency band (630 Hz) as in the measurements in this article.

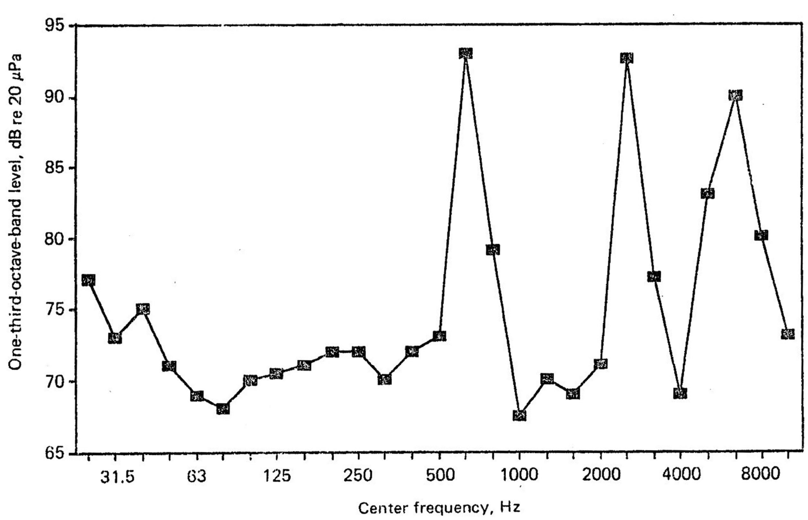


Fig. 9. Squealing noise spectrum from an urban rail-transit car [1].

4. Acoustic simulation in *Cadna/A*

4.1 Software Cadna/A

Usually, squeal noise is not included in the official noise calculation models and it is not integrated in noise mapping standard procedures (with the exception of the German document *Schall0*3 [4]). The measured data of squealing noise from this work were used for a simulation of squealing noise with software *Cadna/A* v. 3.6119.

Cadna/A (registered trademark of Datakustik GmbH, Munich, Germany[4]) is a software for calculation, assessment, prediction and presentation of noise exposure and it includes many noise types (industry, road, railway, etc.).

Calculation with the squealing noise in itself is not included in this software. It is possible however, to put a penalization for the radius of curvature according to the national standard. For acoustic simulation of this area the document *Schall03* [6] was used which offers to chose from three possibilities of curvature radius (< 300, 300-500 and ≥ 500 m) (Fig. 10). The penalization is +8 dB(A) for emission level *Lm,E* for a radius of less than 300 m according to *Schall03* [6] (*Lm,E* is the time-averaged sound level determined in the free field at a distance of 25 m from the centre-line of the track and at a height of 3.5 m above the top edge of the rail).

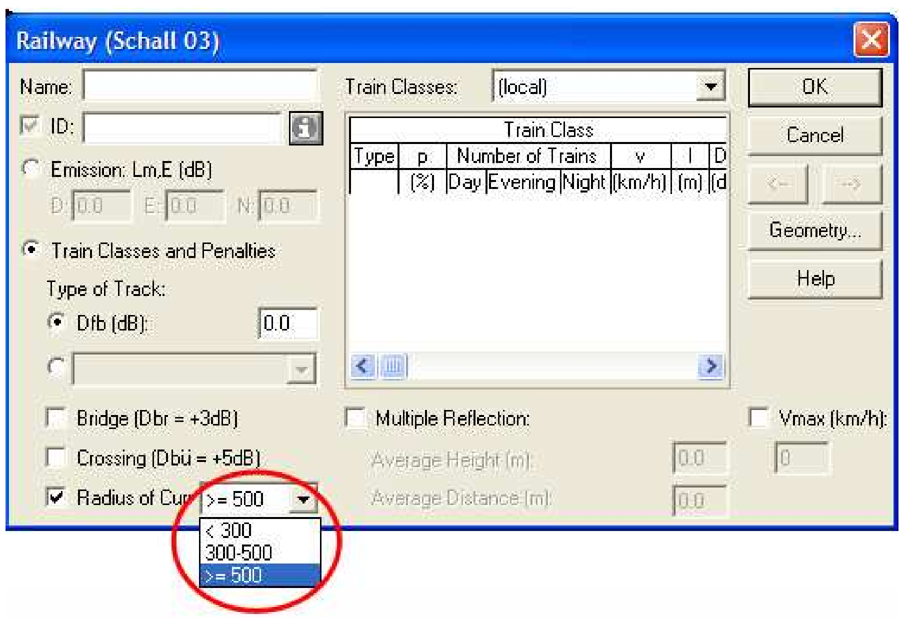


Fig. 10. Extract from software *Cadna/A* screen showing the possibilities of setting a penalization for the radius of curvature.

4.2 Calibration of sound source - urban rail squeal noise

To simulate the noise emitted by the metro running on the selected curve (including the squealing noise) a line source was modeled. This line source replaced the rail track on the curve segment of the metro line. The sound power level of the line source was characterized using the immission spectrum (L_{Aeq} in octave band spectrum) measured in the field, to specify the noise emission for the line source in *Cadna/A* as frequency dependent (Fig. 11).

The straight segments of the metro line were modeled as dedicated railway line sources, with noise emission according to the *Schall03* [6] using the traffic flow data for metro and selecting the train class *"Metro"*. The emission of this source was then compared to the field measured values. Since the values simulated in *Cadna*/*A* for the points of measurement were different, a correction factor was chosen and added to the standard sound power level of *Schall03* for the train type *"Metro"*. The value for this correction was found comparing data measured in the field and data calculated in *Cadna/A* in point III (straight line) to obtain similar values of measured and simulated sound levels. The correction for train type factor (*Dfz – FahrZeugart* as in "type of train") was set to +5 dB(A). The correction for type of track (*Dfb – FahrBahn* as in "type of rails") was set for solid track with no absorption: +5 dB(A).

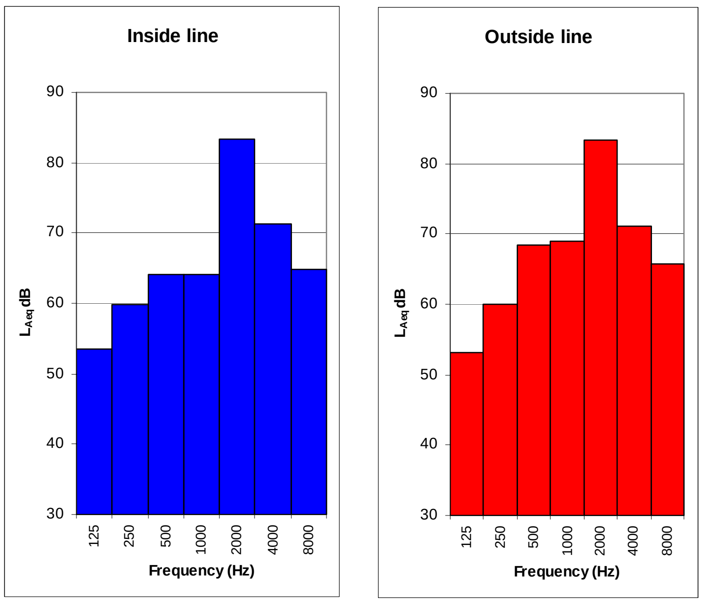


Fig. 11. Calculated octave band spectra (L_{Aeq}) used for acoustic simulation in *Cadna/A.*

4.3 Results of the calculation

4.3.1 Immission noise maps

After setting the input conditions for software *Cadna/A* the calculation was done with three possibilities of simulation (variants):

- Variant A - simulation of the rail track noise without consideration of the squealing noise (Fig. 12). This simulation was made using *Schall03* [6] for railway tracks.
- Variant B - simulation with consideration of the squealing noise measured in this selected area (Fig. 13). In this variant the calculated line source replaced the rail track on the curve segment. The sound power level of the line source was characterized using the immission spectrum measured in the field.
- Variant C - noise immission map with simulation using the correction for radius of curvature integrated in *Cadna/A* software (Fig. 14). The emission value was penalized according to *Schall03* [6].

Comparing the three noise maps generated using the software for these variants can be noticed the bigger area affected by the noise immissions in the map with the consideration of the measured squealing noise than at the other two noise maps.

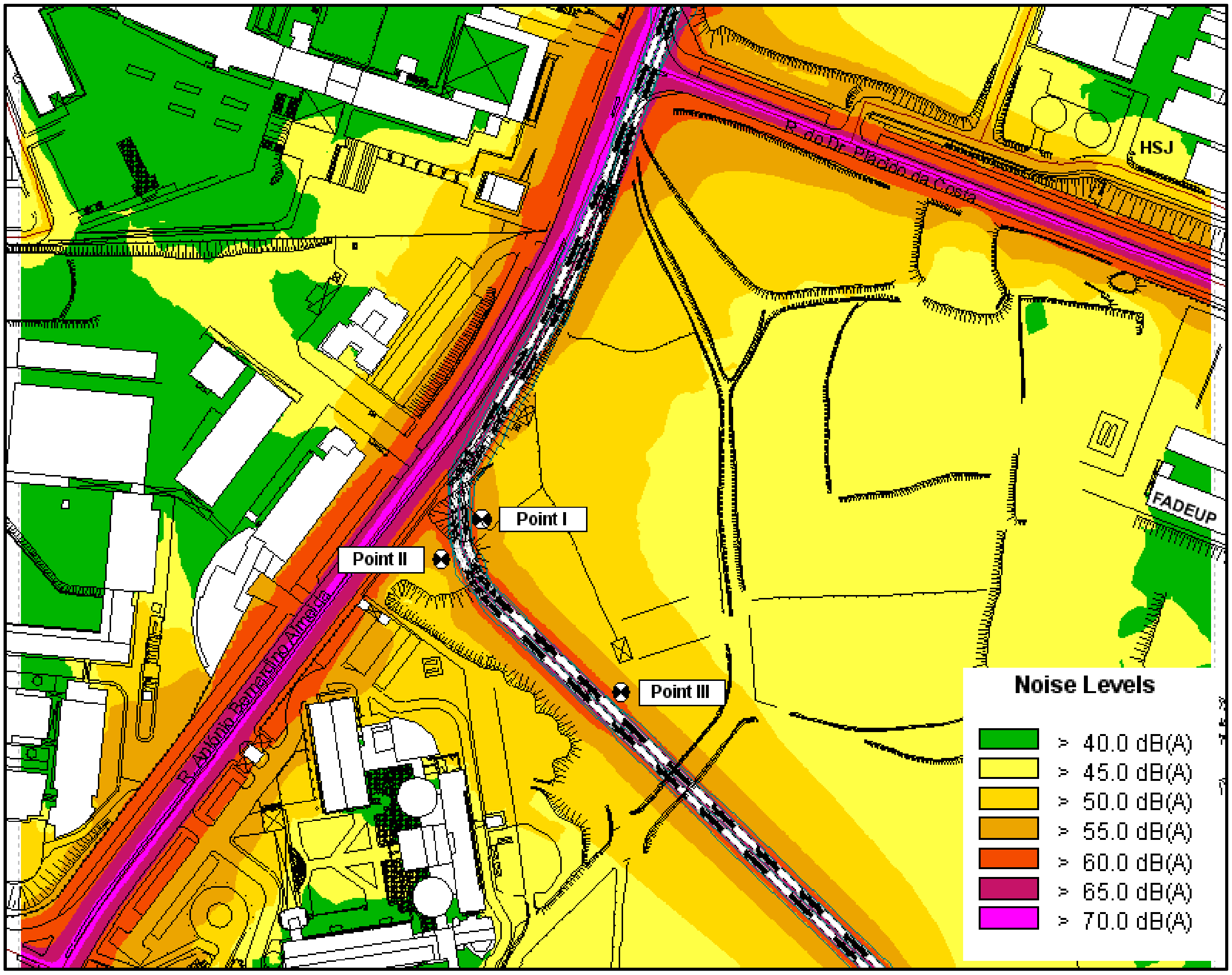


Fig. 12. Variant A - simulation of the rail track noise without consideration of the squealing noise

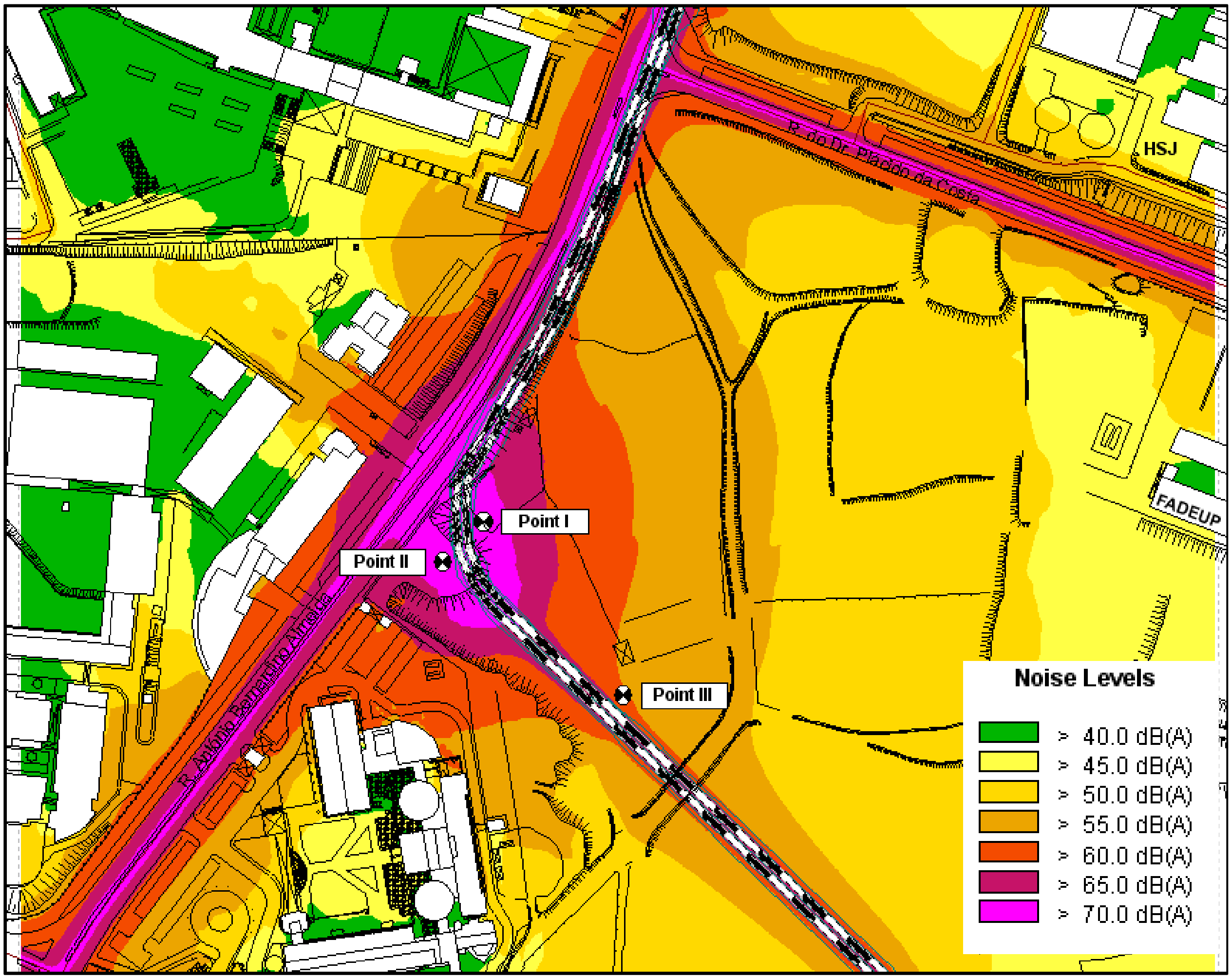


Fig. 13. Variant B - simulation with the consideration of the field measured squealing noise

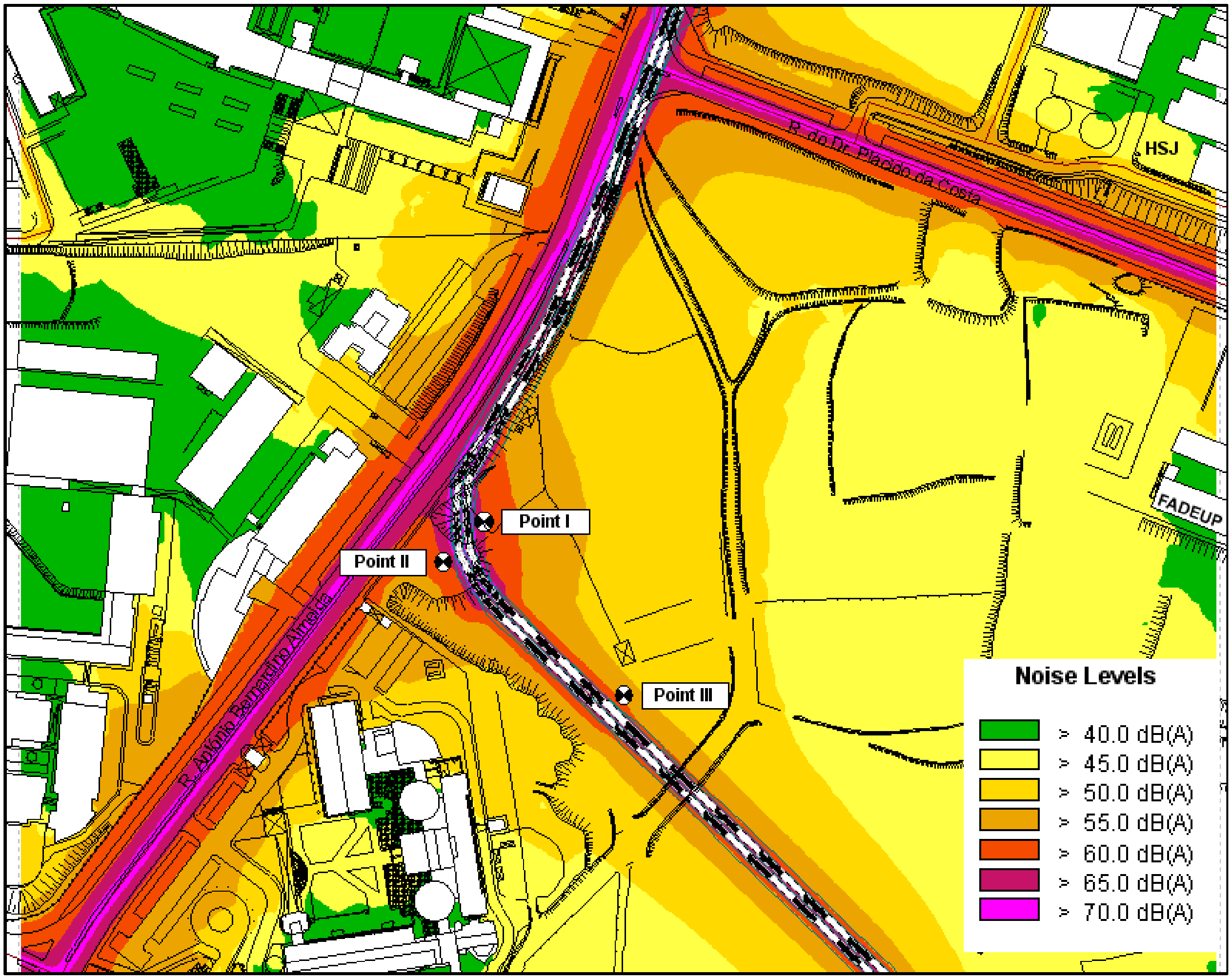


Fig. 14. Variant C - noise immission map with simulation using the correction for radius of curvature integrated in *Cadna/A* software

4.3.2 Noise indicator Ld

Calculations were made regarding the noise indicator L_d (*Lday*: Daytime A-weighted average sound level as defined in ISO 1996-2; from 7 to 20 h, in Portugal)) in Point I and the results are presented in table 1. The value of noise indicator L_d calculated in software *Cadna/A* in Variant B (with consideration of squealing noise measured in the field) is about 17 dB(A) higher than in Variant A (calculation without consideration of squealing noise). And about 10 dB(A) higher than in Variant C (using the software available correction for curvature radius). The difference ΔL_d between Variants B and A, and Variants C and A are shown in table 1 (17 and 7 dBA).

Table 1. Noise indicator L_d and difference ΔL_d calculated in Point I dB(A).

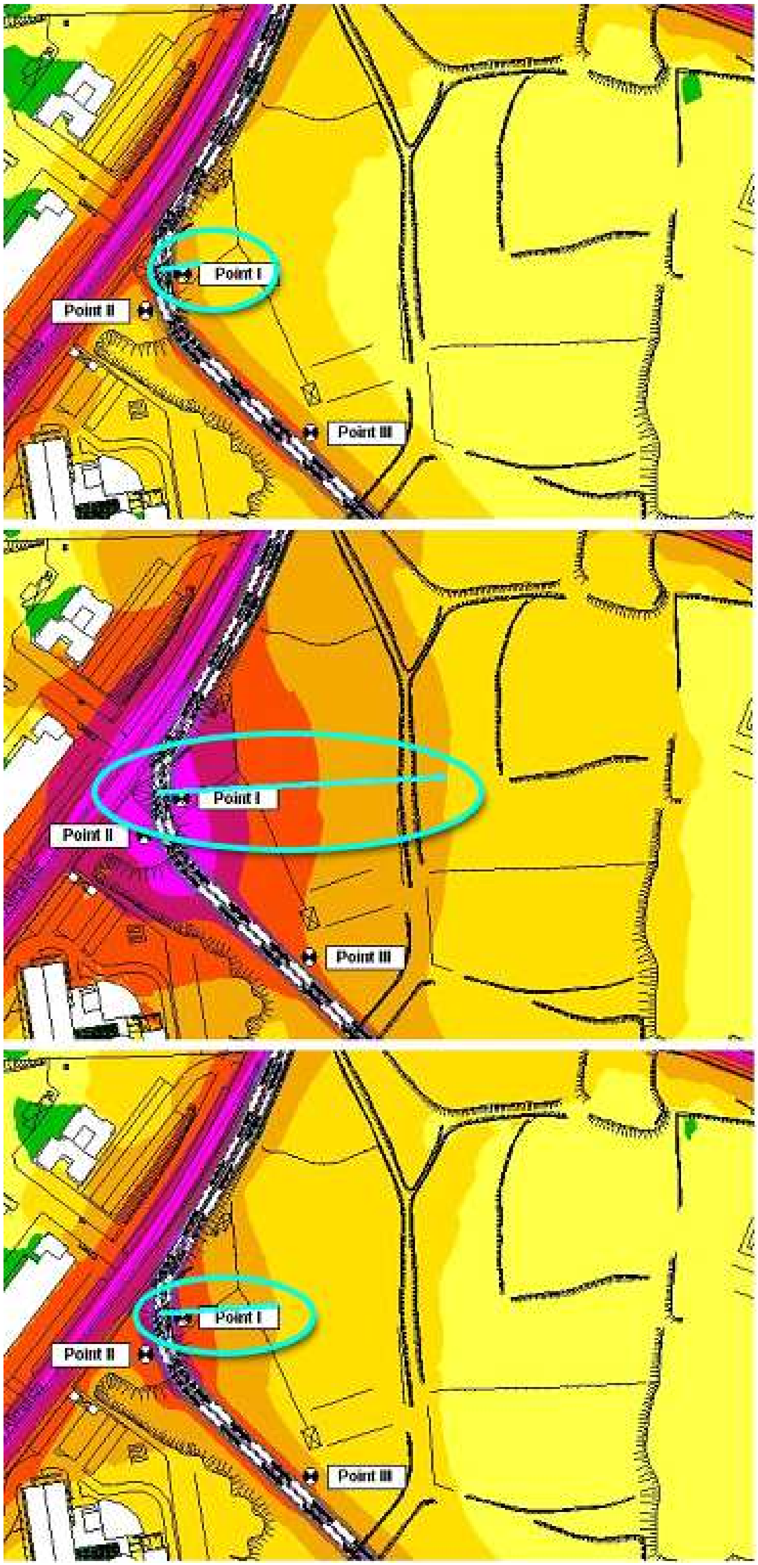
Point I	**Noise indicator L_d dB(A)**	**ΔL_d dB(A)**
Variant A – without consideration of squeal noise (reference value)	58.8	0
Variant B – with consideration of squeal noise measured in the field	75.7	16.9
Variant C – with *Cadna/A* radius of curvature correction	65.3	6.5

4.3.3 Confrontation with Czech legislation

One of the main juridical document in this subject in the Czech Republic is the law 148/2006 Sb. "*Health protection from negative impacts of noise and vibration*" [5]. It presents limits for the equivalent continuous A-weighted sound pressure level in protected outdoor space of buildings. The limit according to this law is 50 dB(A) plus a correction that takes into account the type of protected area and day or night time. A correction of +5 dB(A) is used for protected outdoor areas of buildings and other protected areas and for noise from urban infrastructures (roads, tramways, etc.) except of tertiary roads and railways tracks where other corrections are used. The correction for night time is -10 dB(A). The resulting limits are 55 dB(A) for daytime and 45 dB(A) for nighttime. Maximum distances for exceeding the noise limit (55 dBA), for each variant calculated (A, B and C) are listed in table 2. The area plans in which the distance was measured are shown on figure 15.

Table 2. Maximum distances from rail track where the noise limit of 55 dB(A) (according to 148/2006 Sb.[5]) were exceeded.

Variant	Distance for Daytime Limit (L_{Aeq}= 55 dB)
A	18 m
B	125 m
C	50 m



VARIANT A distance 18 m

Variant B distance 125 m

Variant C distance 50 m

Fig. 15. Visualization of maximum distance from rail track where the noise limit (55 dBA) is exceeded.

5. Conclusion

The goal of this work was to characterize the acoustic effect of squealing noise in noise map development.

Measurements were made on one metro track line (in Porto, Portugal). An average continuous equivalent noise level for squealing noise L_{Aeq} of 85 dB was found (at 7. 5 m) which is 16 dB(A) higher than the average noise level of the running metro in straight line (about 69 dBA).

Dominant frequency bands for squealing noise caused by the metro vehicle in this study were found (630 Hz, 800 Hz, 1.6 kHz, 2 kHz and 4 kHz). The results were compared with others in the literature and some common dominant frequencies were found.

Data from measurement was used for simulation in the software *Cadna/A* where three variants of noise simulation were compared in the same location (one using the data for squealing noise measured in the field and others using the *Schall03* standard).

Comparing the calculated immission noise maps from this area, a large difference in noise levels (about 17 dBA) was found between the Variant A (calculation without consideration of squealing noise) and Variant B (with consideration of squealing noise measured in the field).

For a more exact simulation of the sound power level of this type of vehicle, correction factors were chosen to be added to the standard sound power level of *Schall03* for this train type (*Dfz* = +5 dBA) and for this type of track (*Dfb* = +5 dBA).

Noise limits of 55 dB(A) for daytime (according to the Czech legislation [5]) are exceeded up to distance of 125 m from the rail track when the calculation takes into account the squealing noise. It is about 107 meters more than if the calculation does not take into account the squealing noise.

Therefore, this study shows that it is necessary to account for the squealing noise from urban rail transport in the noise mapping development, for instance, with new adapted correction factors. Otherwise, L_d values and the exposed areas (and population annoyed) can be wrongly calculated and misinterpreted.

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