Tram Squealing Noise and Its Impact on Human Health

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Abstract

Introduction: Tramway has become a serious urban noise source in densely populated areas. The disturbance from squealing noise is significant. Curve squeal is the very loud, tonal noise emitted by tram operation in tight radius curves. Studies had reported a relationship between noise levels and health effects, such as annoyance, sleep disturbance, and elevated systolic and diastolic blood pressure. Materials and Methods: This study aimed to analyze the wheel squeal noise along the tramway line in Košice, Slovakia, review the effects on human health, and discuss its inclusion in the design method. To observe the influence of a track curve on noise emission, several measurement points were selected, and the noise emission was measured both in the curve and in the straight lines employing the same type of permanent way. Results: The results in the sections with the radius below 50 m were greatly affected by the presence of a squeal noise, while the resulting noise level in the sections with the radius above 50 m depended on their radius. The difference between the average values of LAeq with and without the squeal in the measurement points with the radius below 50 m was 9 dB. The difference between the measurements in the curve sections with the radius below 50 m and those in the straight line was 2.7 dB. Conclusion: The resulting noise level in general was influenced by the car velocity and the technical shape of the permanent way. These results can be used in noise prognoses and in the health effect predictions.

Keywords: Health effects, noise levels measurement, squeal noise, tramway noise, transport

INTRODUCTION

Environmental noise, especially the traffic noise, represents a serious problem in densely populated urban areas, and it is generally present in some form in all areas of human activity. Its effects on humans could be emotional, physiological, and psychological. However, the adverse effects of noise pollution could include annoyance, sleep disturbance, anxiety, hearing damage, and stress-related cardiovascular health problems.[1-5]

Several studies had already reported significant noise levels and annoyance due to tramways.[6-12] Tramway has hence become an important urban noise source in populated areas.[11,13-17]

Many sources of noise coexist in urban environments, including not only road traffic and urban trains, but also tramways.[6-12] This work contributes to the study of annoyance caused as a result of tramway noise, especially an operating configuration in curve, when the tramway emits squeal noises leading to the inhabitants’ complaints. This investigation aims at determining an acoustical indicator of annoyance due to in-curve tramway noise by identifying and characterizing the acoustical factors that influence noise annoyance.

Goals of the study

This study is aimed at the problem of one of the specific and harmful noise sources – the tramway noise. The goal of the study was to identify this noise, specially curve squealing noise, and review the effects of squealing noise exposure on human health and discuss its inclusion in the design method.

BACKGROUND OF THE PROBLEM

Investigation

Tram transportation as a source of noise

Many studies and publications exist concerning the sources of railway noise. The Working Group Railway Noise of the European Commission published its Position Paper on the European strategies and priorities for railway noise abatement in 2003.[16] The International Union of

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Railways (UIC) published its “Environmental Noise Directive Development of Action Plans for Railways” in April 2008.\(^{[17]}\)

Both studies identified three dominant sources for railway noise:
- Rolling noise;
- Noise from traction and auxiliary systems;
- Aerodynamic noise.

Train speed is a major influence parameter for noise emission. The noise due to electrical traction and auxiliary systems tends to be predominant at low speeds, up to around 20 km/h. Wheel-rail rolling noise is dominant up to speeds around 200 km/h, after which aerodynamic noise takes over as the dominant factor.\(^{[17]}\) Tramways are a kind of urban railway transport, operating in densely populated areas. Trams run therefore speeds up to 50 km/h. At medium speed, the dominant source is rolling noise.\(^{[17]}\)

The transition speeds from traction noise to rolling noise and from rolling noise to aerodynamic noise depend entirely on the relative strength of these sources.

The rolling noise, for example, depends strongly on the surface condition (roughness) of wheels and rails, whereas aerodynamic noise depends on the streamlining of the vehicle. An example of a typical speed dependency for rail (including tram) transport is shown in Figure 1.

Accordingly, the noise source analysis\(^{[17-19]}\) indicated that most sources are located on the lower part of the vehicles. Predominant sources are the wheel areas that cause rolling noise, which is linked to the radiation of the wheels, the rails, and the platform. The area center was located either at a height of 0.5 or at 1 m from the ground [Figure 1].

Wheel-rail rolling noise from the tram is divided as the following:\(^{[18]}\)

**Rolling noise:** Rolling noises are produced by the rolling of the wheels on the tramway track and are caused by dynamical forces occurring at the contact between the track and the wheel as a result of surface roughness.

**Impact noise:** Impact noise occurs when a tramway wheel encounters discontinuities such as rail joints.

**Squeal noise:** Squeal noise is a high-pitched noise due to the friction between the wheel and rail while the tram rounds a curve with small radii.

The tram is often seen as environmental friendly, namely nonpolluting and silent. However, complaints from residents living along the lines prove that it may sometimes lead to annoyance. The most significant complaint is the disturbance from squealing noise. Curve squealing of tramway vehicle is a noise with high acoustic pressure and rather narrow frequency spectra. This noise turns out to be very annoying for the people living in the neighborhood of the locations wherein this phenomenon occurs.

**Generation of squealing noise**

Curve squeal noise is also caused by the interaction between the wheel and the rail but has a quite different character. It is strongly tonal, being associated with the vibration of the wheel in one of its resonances.\(^{[19-22]}\)

This quick movement of a tramway car that leads to a twitch, especially on the inner rail of the railway line, is one of the reasons for higher noise emission in curves in comparison with the straight line. A short-term noise of excessive acuteness that occurs during this movement results from impulse sliding – a wheel slide during its ride in track curves with small radius.

Squeal noise is the wheel-to-rail friction occurring in such rotational motion, while the wheel is moving on the outer side of the curve. It is forced to transverse motion by the moving wheel flange. Such forced wheel guidance does not arise in the wheel moving on the inner side of the curve [Figure 2].

Longitudinal stick-slip is caused by the different translation velocities between the inner and outer rails. When the stress in the wheel exceeds a certain specified magnitude, a sudden recoil movement and subsequent release occurs. This happens periodically and leads to the oscillation of the wheels.\(^{[23]}\) Depending on the existing frequency, the sound that is thus emitted into the environment is perceived as a short-term noise manifested by unpleasant creaking and wailing. This phenomenon is marked as a stick-slip effect. A similar phenomenon is the brakes squeal, in which tonal or multitonal noise is emitted during braking.

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**Figure 1:** Railway exterior sound sources and typical dependence on train speed. (Adapted from source: UIC 2008, p. 7.\(^{[17]}\))
MATERIALS AND METHODS

Measurement methods of noise level

To observe the influence of a track curve on noise emission, several measurement points were selected, wherein the syndrome of noise emission was measured both in the curve and in the straight line with the same type of permanent way. That made it possible to exclude the effects caused by different types of permanent ways and unequal types of tramway cars; nevertheless, different technical condition of rails could not be eliminated. All measurements were conducted in approximately equal meteorological conditions by means of which the influence of unfavorable weather conditions was avoided.[24,25]

The measurement points were selected in a way to make it possible for the analysis of the noise situation in the vicinity of the tramway line in points with a different permanent way and different route.

As there are three kinds of permanent ways in the territory of the city of Košice, the selection was as follows.

Measurement points were selected so that every representative type of permanent way was included:

1. Paneled permanent way;
2. Classical permanent way covered by bitumen or paving stones;
3. Classical open permanent way with wooden or concrete sleepers.

As a measurement device, a precise modular sound analyzer, Brüel & Kjær, Nærum, Denmark, was used. It directly recorded equivalent, maximum, minimum, and other complementary noise pressure levels in the external environment, and measured with the characteristic F and weight filter A. At least 25 measurements were conducted and the data recorded in each out of six selected measurement points.

According to van Ruiten,[21] the distinct short-term noise was best recognized during the ride of a car in the curves of the radius below 50 m.

Therefore, the measurement points were classified in the following two groups:

- Track curve sections with the radius lower than 50 m;
- Track sections in the straight line.

The selection specified above allowed for a comparison of single measurement points in various situations. Table 1 lists the photos of measurement points and the number of measured data.

According to Möhler,[26] the basic criterion for the characterization of a wheel squeal noise was the difference $\Delta L$ between the maximum ($L_{A_{\text{max}}}$) and equivalent sound pressure level ($L_{A_{\text{eq}}}$) at a reference measurement point (the measurement point situated at a distance of 7.5 m from the tramway line axis at the height of 1.2 m above the top of the rail head).

\[ \Delta L = L_{A_{\text{max}}} - L_{A_{\text{eq}}} \text{(dB)} \]

At $\Delta L > 8$ dB – a wheel squeal noise occurs;
At $\Delta L = 5–8$ dB – a soft wheel squeal noise occurs;
At $\Delta L < 5$ dB – a wheel squeal noise does not occur.

The noise measurement results for six measurement points [Table 1] were evaluated and submitted for spectral and statistical analyses. As far as statistical methods were concerned, descriptive statistics, correlation, and regression analyses, as well as the chi-square test of good conformity, were implemented.

RESULTS

Measurements results

After a detailed analysis it can be stated that, in all measurement points in the track curve sections with the radius ($r$) not greater than 50 m, the occurrence of a louder noise was identified. It was specified in a tone variety spectrum in the range between 400 Hz and 2000 Hz, with number of peaks from 1 to 3, as a disturbing noise, and marked as a squeal noise.[19-21]

In the measurement points in the track curve sections with the radius ($r$) below 50 m, the occurrence of squeal noise was recorded in 84% of all measurements, and in straight line sections, it occurred only as an exception – 3% [Figure 3]. After expressing the average value, the difference between the measurements in the sections with the radius below 50 m and those in the straight line was 2.7 dB [Figure 4].
The percentage of squeal noise occurrences in the set of measurements had a provable impact on the resulting noise level. The difference between the average values of $L_{Aeq}$ with and without the squeal noise in the measurement points with the radius ($r$) below 50 m was 9.5 dB [Figure 5].

To evaluate the impact of noise on human health, it is appropriate to make a detailed spectral analysis. The measurement points B1 ($r = 23$ m) and B2 (straight line) with classical permanent way covered by bitumen or paving stones were selected for the analysis.

In Table 2, the third-octave spectra of selected equivalent sound pressure levels with and without squeal noise are illustrated.

Vibrations were not measured in the study, but it was a dynamic interaction, and so they occurred there.[27]

Results of the spectral analysis

In the spectrograms with identified squeal noise, the peak until 93 dB (point B1) was observed. For measurements with identified squeal noise, the dominant frequency of more than 10 dB above other values in spectrograms emerged.

At the measurement point B1, annoying screeching noise lasted for an average of 9 s.[28] At the measurement point B1 (with the radius $r = 23$ m), higher values $L_{Amax}$ (up to 103 dB) were recorded.

Table 1: The list of measurement points

| Type of permanent way | Paneled permanent way | Classical permanent way covered by bitumen or paving stones | Classical open permanent way with wooden or concrete sleepers |
|----------------------|-----------------------|-------------------------------------------------------------|---------------------------------------------------------------|
| Number of measurement point | A1 | r = 25 m | B1 | r = 23 m | C1 | r = 30 m |
| Track curve sections | Photo |
| Straight line | A2 | 40 | B2 | 44 | C2 | 42 |

Figure 3: The percentage of squeal noise occurrences in the measurement points of a track curve

Figure 4: Noise levels $L_{Aeq}$ and speed within the interval of 5–25 km/h specified for different route guidance
The resulting noise level in the sections with the radius up to 50 m was greatly affected by the presence of a squeal noise. The resulting noise level in the straight line sections was influenced by the car velocity and the technical shape of the permanent way.\cite{28}

The difference between the average values of \(L_{\text{Aeq}}\) with and without the squeal noise in the measurement points B1 was 11.3 dB [Table 2].

According to the basic criterion for the characterization of a wheel squeal noise (1), the difference was \(\Delta L = 10.9\) dB. In the measurement point B1, wheel squeal noise occurrence was confirmed.

In the measurement point B1, 25 measurements were conducted; in 92% of the measurements, the wheel squeal noise occurrence was confirmed, and in 2 of the 25 measurements, it did not occur. The example in Table 2 was assessed according the basic criterion for the characterization of a wheel squeal noise (1). The difference was \(\Delta L = 4.9\) dB. In this measurement, the wheel squeal noise had not been confirmed, though in the third-octave spectrum the peak (middle frequency 500 Hz) was observed. The explanation was that the third-octave spectrum was characteristic of a specific measurement location.

All measurements were positioned at a distance of 7.5 m from the tram track, and at a height of 1.2 m above the running surface of the rail. This made it possible to eliminate all external influences. All measurements were conducted in approximately equal meteorological conditions by means of which the influence of unfavorable weather conditions was avoided. As a measurement device, a precise modular sound level analyzer was used. The measurements performed were only of technical character. A part of the measurements were performed during the “night.” According to the World Health Organization (WHO), the night noise levels \(L_{\text{night}} > 55\) dB were considered increasingly dangerous for public health.\cite{4} After recalculation, night measurements at a distance of 2 m in front of the building façade reached the value from 8 dB to 65 dB and all measurements exceeded the night limits of 45 dB set by the Slovak legislation.\cite{31,32}

**DISCUSSION**

The noise emission due to curve squeal should normally be verified by site measurement. If necessary, the design method for the calculation of noise levels can be used. The Slovak design method for calculation of tramway transport noise levels has been used since 1991.\cite{33} On the basis of the knowledge acquired from foreign literature and comparisons with the design methodology applied in other countries, it is obvious that there is a need to re-evaluate some parts of this design method. In particular, a higher number of input parameters should be taken into account. The layout/location of the railway line is one of the parameters that significantly influence the level of noise. This parameter has not yet been involved in the calculations. It means, the design method has not considered the impact of a curve squeal.

The outcome of this study is the difference between the measurements in the sections with the radius below 50 m and those in the straight line about 2.7 dB and the difference between \(L_{\text{Aeq}}\) with and without the squeal noise in the radius below 50 m and about 9.5 dB. For comparison, the German prediction model for tramway noise indicators calculation “SCHALL 03” considers correction for track curve sections with radius \((r)\) below 50 m and about 8 dB, and CNOSSOS-EU proposes to use a simple correction for curve radius under 300 m and about 8 dB for all frequencies.\cite{34,35}

The difference between the average values of \(L_{\text{Aeq}}\) with and without the wheel squeal noise in the measurement points with the radius below 50 m was nearly 10 dB. An average continuous equivalent noise level for squealing noise \(L_{\text{Aeq}}\) of 87.2 dB was found at 7.5 m from the tram track. Noise limits of 55 dB for daytime (according to the Slovak legislation)\cite{32} exceed up to a distance of 200 m from the tram track when the calculation takes into account the squealing noise. If the calculation does not take the squealing noise into account, it is about 100 m less.

Therefore, to work with adapted correction factors for the squealing in the tramway, noise prediction is necessary.\cite{31}

Noise acts as an environmental stressor on the human body, and stressful situations mobilize all the vital systems of the body. The need to consider the curve squeal is evident because squeal noise is very often the most disturbing noise source of tramway systems in the city. This kind of noise is very annoying for people living or working near tram lines.\cite{31}

The human ear is sensitive to sound from 20 Hz to 20 kHz. However, the sensitivity is not equal in the whole spectrum. Despite this limit of 20 kHz, the frequency range of the vehicle dynamics and sound generation is limited to 5 kHz. The measurements presented above confirmed the existence of curve squealing as a short lasting noise (in point B1, screeching noise lasted for an average of 9 s) of high...
amplitude (in point B1, $L_{Aeq}$ was more than 90 dB). The frequency spectrum of curve squealing is dominated by very sharp peak numbers of 1–3. Typically, frequency of the peaks was founded between 400 and 1000 Hz. Experiments according to Périard[36] show that the tonal sound of the curve squealing seldom exceeded 3 kHz, and according to Heckl,[37] the frequency of the peaks is typically between 1500 and 5000 Hz. All limits at 5 kHz guarantee that the disturbing part of the noise spectrum is taken into account, for which the human ear is sensitive.

The effects of railway traffic on annoyance/sleep disturbances and psychosocial well-being were evaluated in the older studies.[6,7] In Sweden, the results of the postal questionnaire on adults show that railway (included tramway) noise is more annoying in areas wherein there is simultaneous exposure to vibration from railway traffic.[7] Disturbance of communication was the most frequently mentioned annoyance reaction outside and inside the dwelling. To ensure an acceptable environmental quality wherein less than 5% of the exposed population is rather or very annoyed by railway noise, these noise levels must be below 80 dB $L_{Amax}$ and below 55 dB $L_{Aeq}$ in areas without vibration. In areas with simultaneous exposure to strong vibration, action against vibration or a longer distance between the houses and the railway line is needed corresponding to a 10 dB lower noise level than in areas without vibration.[6,7]

According to Rylander et al.,[6] the dose–response relationships for traffic noise and tramway noise were different. With an increasing number of heavy vehicles, the annoyance due to traffic noise increased more than for a corresponding increase in the number of tramways for a certain type of area.

In the study of Miedema and van den Berg,[8] in 44% of the adult respondents in the three cities Amsterdam, Hague, and
Rotterdam (n = 798), who were at least “just annoyed” by environmental noise, trams were a more important source of noise annoyance than road traffic. Total annoyance decreased if tramway annoyance did as well (and road traffic annoyance was not changed).

The basic determinants of tramway noise annoyance were the curve/junction and straight track. In the study, all curves and junctions produced squeal and/or impact noise and all straight tracks did not. Another determinant was the nighttime level (11 pm–7 am); $L_{Aeq} = 10$ dB was considered the right penalty for the nighttime level. 25% of the people living around depots report being disturbed often by tramway noise when falling asleep. The next determinant was $L_{Aeq}$ (24 h).[8]

According to the results of the recent study by Gidlöf-Gunnarson et al.,[9] on 1695 respondents in Sweden, both the number of trains and the presence of ground-borne vibrations induced by railway traffic, and not just the noise level per se, are of relevance for how annoying railway noise is perceived. Furthermore, orientation of bedroom window had a significant impact on railway noise annoyance. The other building situational factors (type of house, the year the house was built, or window type) as well as the demographic variables were not associated with noise annoyance.

Nowadays, in Austria since the introduction of new types of tramways in the city of Graz, strong complaints were conveyed by the local residents in certain areas. In addition to standard sound parameters (SPL), psychoacoustic parameters were analyzed. Initial results indicated differences between the different tramway types in both classical and psychoacoustic indicators. Preliminary analyses show slightly higher levels of loudness and roughness for the new tram pass-byes while mean vibration levels stay below the typical threshold values for the average human subject.[10] The introduction of a new tramway and a perceived step change in both noise and vibration exposure or in combination can result in higher annoyance responses.

In the noise annoyance study in Bratislava, Slovakia in terms of odds ratio, the tramway noise annoyance has increased during the years 1989–2013 ($OR_{MH} = 2.08$ (95% CI = 1.53–2.82 in 2013) versus $OR = 0.56$ (95% CI = 0.31–0.98 in 1989) and $OR_{MH} = 1.41$ (95% CI = 1.04–1.92 in 2009)).[11]

In Switzerland, researchers investigated the effects of railway traffic noise exposure on blood pressure and addressed potentially susceptible subpopulations.[12] They found evidence of an adverse effect of railway noise on blood pressure in the cohort of 6450 men and women, who were 28–72 years of age. Adjusted regression models yielded significant effect estimates for a 10-dB increase in railway noise for diastolic and systolic blood pressure during the night and for systolic blood pressure during the day. The study results imply more severe health effects by transportation noise in vulnerable populations, such as adults with hypertension, diabetes, or cardiovascular diseases.[12]

In experimental studies, the authors consider awakenings as the strongest reaction to nocturnal noise. Cardiac responses did not habituate to traffic noise within the night and may therefore play a key role in promoting traffic noise induced cardiovascular disease. Sleep disturbance means a decrease in sleep quality, waking up in the night/or too early in the morning, prolongation of the sleep inception period, difficulty in getting sleep, sleep fragmentation, reduced sleeping time, etc.[38] The study presented in the book “Environmental Noise Pollution” by Murphy and King,[35] found a strong correlation between the number of times disturbed and sleep stage change with the peak noise level and number of noise events. Sleep disturbance reduces sleep quality and is associated with an array of secondary impact—“after-effect,” which is generally felt the day after the disturbance occurred. The after-effect may be evident in low work capacity, reduced cognitive performance, changes in daytime behavior, as well as mood changes and associated negative emotions.[35]

According to the WHO, the night noise levels $L_{night} > 55$ dB are considered increasingly dangerous for public health. Adverse health effects occur frequently, and a sizeable proportion of the population is highly annoyed and sleep disturbed. There is evidence that the risk of cardiovascular disease increases.[39] The outside noise levels ($L_{Aeq}$) should be less than 55/45 dB (daytime/nighttime) to avoid serious annoyance or sleep disturbances.[40]

More recently, WHO–Europe[41] has reported on the burden of disease in terms of disability-adjusted life-years (DALYs) lost because of environmental noise. The findings suggest that sleep disturbance, mainly as a result of road traffic noise, constitutes the heaviest burden followed by annoyance, which accounts for 903,000 and 587,000 DALYs, respectively. The other factors associated with environmental noise are ischemic heart disease (61,000 DALYs), cognitive impairment in children (45,000 DALYs), and tinnitus (22,000 DALYs). The study concludes with the estimate that at least one million healthy life-years are lost every year from traffic-related noise in Western Europe.[40]

Railway noise is the second most dominant source of environmental noise in Europe, with approximately 9 million people exposed to levels A above 50 dB during the nighttime.[41] Contrary to road traffic, for which permissible noise limits at the source have existed in the EU since the 1970s, noise standards for trains only came into force at the beginning of the 21st century.[35]

**Conclusions**

In this study, the existence of curve squealing as noise of high amplitude occurring when the tramway turns in tight curves is presented. Tram lines in towns are often constructed with a small radius, and therefore curve squealing occurring at high level disturbs people living or working near tram lines. Curve squeal is characterized by extreme high-pitched noise levels,
resulting in major discomfort while sleeping, increased risk of cardiovascular disease, and other health problems.

The measured values presented in this study exceeded the limit values in most cases. Therefore, it is appropriate to consider how to prevent such situation. It is very difficult to omit small diameters from track sections—it is not possible in residential areas or at crossroads. It is necessary to maintain the permanent way in a good condition. In case of the wheel squeal noise occurrence, applying technical measures such as lubricating and damping elements for rails or wheels is recommended.

The human body is sensitive to the increased noise levels during the nighttime. Running speed is the parameter that most affects the resulting noise. It is therefore appropriate to consider reducing the running speed in the exposed sections. Transport area must be designed so that the tramway is far away from buildings with increased protection against noise. Street space is appropriate to supplement with the green belt, which helps to reduce noise.

In architectural designing of buildings, it is important to place a bedroom facing away from the street and to use materials for absorbing unwanted noise elements for facades.

The importance of this study is that these results can be used in noise prognoses, in the health effect predictions, and for pointing out the most important issues that need to be addressed in the future. Future studies should explore the relationship between short-term effects of squealing noise exposure and sleep disturbances in the night.

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Conflicts of interest
There are no conflicts of interest.

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