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# Ground-borne vibrations, sounds and secondary airborne sounds from tramways: a psychoacoustic evaluation including health aspects

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## ABSTRACT

For decades, urban noise and vibration studies were mostly concerned with road traffic and trains. Tramway noise was rarely studied. Since the introduction of new types of tramways in the city of Graz strong complaints were brought up by local residents in certain areas. Typically, the annoyance by tramways results from a complex combination of sounds and vibration exposure depending on ground structure and building conditions. To sufficiently account for this complexity an integrated psychoacoustic approach was applied.

In a free field study ground-borne vibrations and sounds as well as secondary airborne sound recordings were carried out for various tramway types. For this purpose a binaural dummy head measurement system for noise and a triaxial accelerometer for vibrations were used to operate in synchrony.

In addition to standard sound parameters (SPL), psychoacoustic parameters were analyzed to learn more about the complex psychological and physiological responses associated with the introduction of the new tramway types in Graz. First results indicate 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-bys while mean vibration levels stay below the typical threshold values for the average human subject.

Keywords: tramway, sound, vibration, disturbance, standard, I-INCE Classification of Subjects Number(s): 13.4.3, 49.1, 63.2, 66.1, 72.2, 79, 82

## 1. INTRODUCTION

The demand for public transport is increasing continuously not only for large, but also for medium and smaller sized cities in order to mitigate congestion and to provide flexible mobility. There is still an ongoing cross-disciplinary discussion about costs, flexibility and environmental impacts of tram (Light Rail Transport) versus Bus (Bus Rapid Transport) solutions (1–3). Interestingly, potential adverse effects of noise and especially vibrations were rarely discussed, while effects of air pollution and related climate issues were often at the center of the debates (4).

Moreover, publications covering noise and vibration measurements of modern tramways in residential homes are scarce and only few considered health aspects (5,6). There is a serious gap in the available current scientific knowledge for tramways compared with conventional rail.

While the body of evidence for railway vibration (7) and associated health impacts (8–13) increased substantially during the last decade, the study of tram noise, vibrations and secondary sounds has never received the attention it would deserve. This is surprising, in particular, because the tramway systems and its use have undergone a profound change in the past two decades.

The typical weight of modern trams in use is now around 40 tons compared with 25 to 30 tons of the older trams. However, due to the monetary limits of medium and smaller cities the track systems were often not properly adapted to the new requirements. Moreover, the trams run more frequently and extended the service into the night and morning hours. These hours are very sensitive to elicit

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annoyance and sleep disturbance, as the signal to noise ration increases when the other traffic noise decreases, especially in quieter suburban areas. These so-called shoulder hours (22 to 24 pm and 5 to 7am) are considered as sensitive times for disturbing the sleep and restoration process (14,15).

Eventually, noise and vibrations show potential mutual interactive effects on annoyance and sleep disturbance (16–22).

In the course of the introduction of a new tram system in the city of Graz several citizen initiatives issued complaints about the new trams regarding both higher noise and vibrations exposure. The company conducted vibration measurements; however, the concerned citizens did not give much trust in the provided data. Acoustic and health experts from two Universities were commissioned to plan and conduct a new measurement series covering both noise and vibration in an integrated fashion with binaural equipment to gain more insight into the key disturbing moments of the overall exposure by these new trams.

The main aims of the current study are: firstly, the rigorous application of psychoacoustic analyses shall provide the main culprits responsible for the existing annoyance in order to respond appropriately to the citizen's concern and secondly to examine the appropriateness of the current standards for vibrations from trams.

## 2. METHODOLOGY

In this free field study ground-borne vibrations and sounds as well as secondary airborne sound recordings were carried out for various tramway types in 5 different investigation areas in the city of Graz. For this purpose a binaural dummy head measurement system for noise and a triaxial accelerometer for vibrations were used to operate in synchrony.

This measurement method was used to find an explanation for the complex combination of sounds and vibration exposure based on different tramway types. Especially the complex interaction of ground-borne vibrations and sounds, secondary airborne sounds and direct airborne sounds requires in future a multivariate analysis method.

### 2.1 Investigation areas and noise measurements

In this study 5 different measuring points in single homes and flats in the city of Graz were analyzed. The different areas were chosen based on experience of local residents and their perception related to subjective annoyance against tramways.

The pass-by noise of different tramway types (older and new trams) was binaurally recorded with a dummy head measurement system HSU III.2 in combination with a SQuadriga II mobile recording system (HEAD acoustics GmbH) in 5 different single houses and flats (Figure 1 to 5).

The usage of the dummy head system is prerequisite for the following analysis of psychoacoustic parameters.

The background noise was very low at all recording point's because we asked inhabitants not to be at home during recording time or to sleep in another part of the house or flat.

All measurements (recordings) were done from 8 p.m. in the evening until 8 a.m. the next morning to analyze especially the time period “going to bed”, “sleep” and “getting up at morning”. During about 1 a.m. and 4 a.m. there is no tramway traffic in Graz.

In addition, velocity and number of each tramway was logged for assignment with noise and vibration measurements for further statistical analysis. Especially velocity is relevant to get information about different values at the same recording point. We observed that driven velocities were nearly the same for all tramways per measuring point.

Figure 1 – Measuring Point 1, single house, 1st floor, dummy head

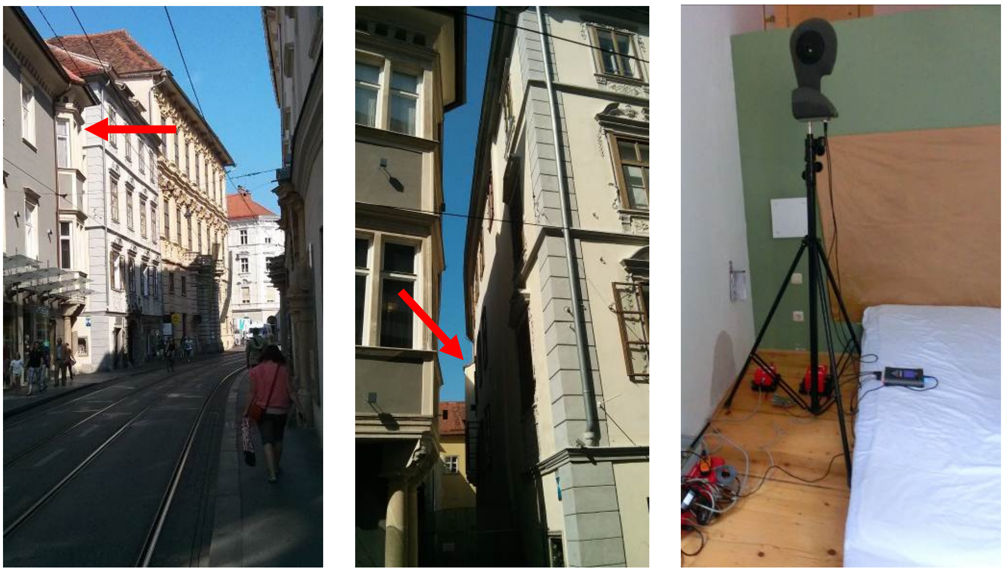

Figure 2 – Measuring Point 2, flat, 2nd floor, backyard, dummy head

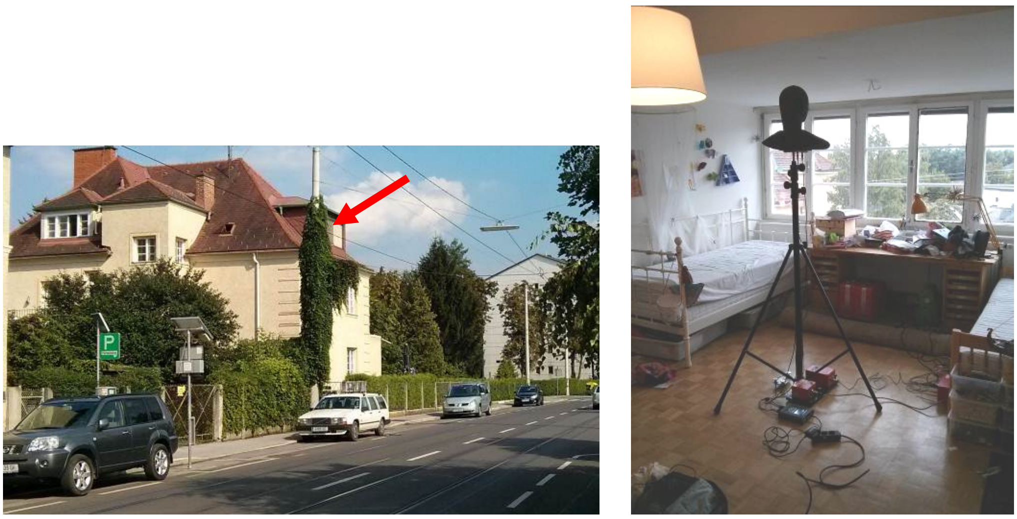

Figure 3 – Measuring Point 3, single house, 2nd floor, dummy head

Figure 4 – Measuring Point 4, single house, ground floor, dummy head

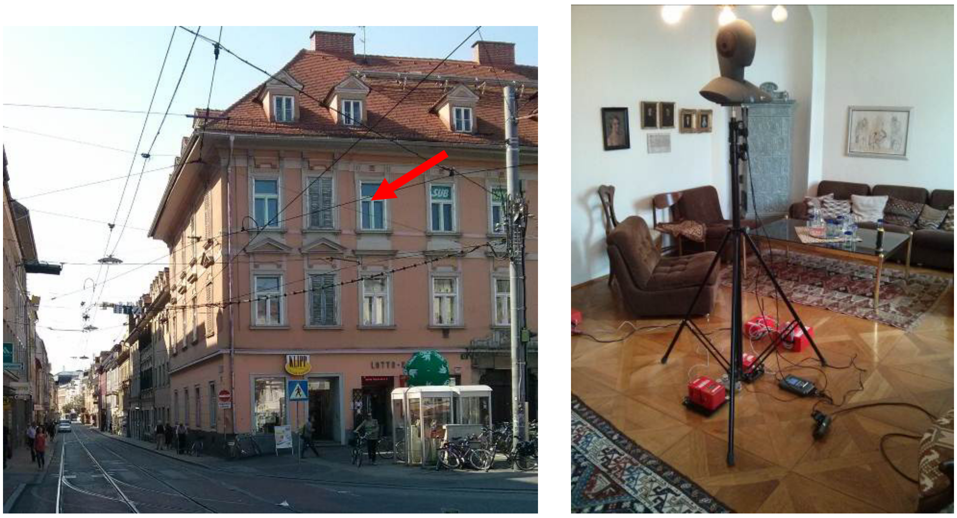

Figure 5 – Measuring Point 5, flat, 2nd floor, dummy head

## 2.2 Vibration measurements

Vibrations caused by tramways are a complex phenomenon and often show quite different characteristics (Figure 6). Especially ground-borne vibrations caused by trams in streets within old cities like Graz with narrow streets (Figure 5) are a special problem. The vibrations propagating to the buildings close to the track and within these buildings may be directly perceived by the inhabitants and may also be noticed via structure-borne sound radiated to the rooms.

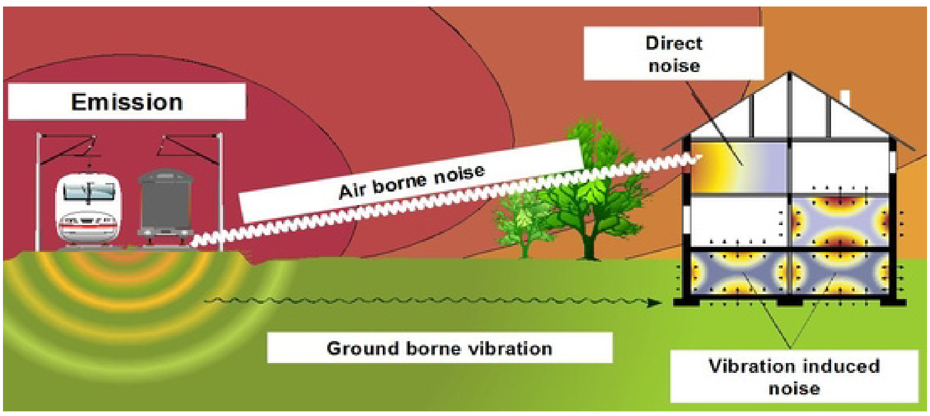


Figure 6 – Generation of vibration by rail (tramway) traffic (Source of figure: EU-project RIVAS)

Vibration measurements were done with a triaxial acceleration sensor (Model Isotron 65H, from Endevco). Recordings of vibrations were also done with the SQuadriga II mobile recording system (HEAD acoustics GmbH) to operate in synchrony with sound recordings (Figure 7).

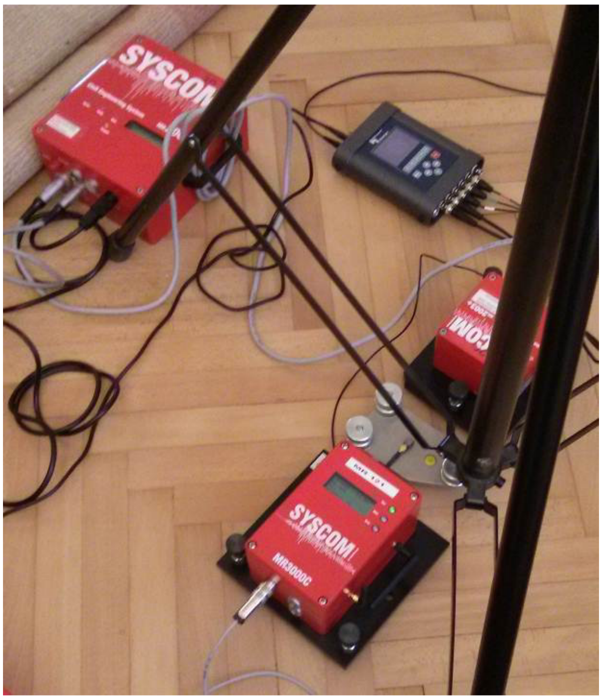


Figure 7 – Vibration measuring system with triaxial acceleration sensor based in the center of the room below dummy head measurement system

### 2.3 Calculation of objective parameters

Based on all recordings at the 5 points of investigation 372 single tramway passings of 1 min duration were extracted from the recorded database.

As basic information different sound pressure parameters (Maximum, A-weighted energy-equivalent sound level) were calculated for every single tramway pass-by.

In addition to standard sound parameters (SPL), psychoacoustic parameters were analyzed to learn more about the complex psychological and physiological responses associated with the introduction of the new tramway types in Graz. In this case all single passing tramways were processed with the Psychoacoustics Module of the ArtemiS Analyses System (HEAD acoustics). The psychoacoustic parameters loudness, roughness, sharpness, tonality and fluctuation strength were chosen for calculation.

Finally measured vibrations were calculated based on Wm-weighted acceleration (ÖNORM S 9012).

## 3. RESULTS

Afterwards the first results of measured and calculated parameters for vibration (Table 1) and noise (Table 2 and 3) exposure of 372 analyzed tramways.

In Table 1 the mean of weighted peak acceleration shows slightly different levels for the 5 measuring points. This is mainly due to different housing conditions, different housing characteristics and different velocity levels of tramways per measuring point. The important part was to analyze differences between “New Tram” and “Old Tram”. Overall, the results show that mean peak accelerations of “New Trams” are a bit higher than those from “Old Trams”. At measuring point 4 and

5 single peak acceleration of "New Trams" are nearly twice as high than the weighted mean peak acceleration of "Old Trams".

Table 1 – Vibration exposure of analyzed tramways

| Measuring area | Type of tramway | Number of measured tramways | $W_m$ Weighted peak acceleration (m/s²) Mean | $W_m$ Weighted peak acceleration (m/s²) Max | $W_m$ Weighted peak acceleration (m/s²) Min |
|---|---|---|---|---|---|
| Measuring point 1 | "New Tram" | 51 | 0,0046 | 0,0061 | 0,0040 |
| | "Old Tram" | 14 | 0,0041 | 0,0043 | 0,0039 |
| Measuring point 2 | "New Tram" | 41 | 0,0041 | 0,0050 | 0,0039 |
| | "Old Tram" | 19 | 0,0041 | 0,0046 | 0,0039 |
| Measuring point 3 | "New Tram" | 70 | 0,0061 | 0,0075 | 0,0040 |
| | "Old Tram" | 2 | 0,0053 | 0,0056 | 0,0050 |
| Measuring point 4 | "New Tram" | 36 | 0,0066 | 0,0144 | 0,0042 |
| | "Old Tram" | 19 | 0,0054 | 0,0082 | 0,0040 |
| Measuring point 5 | "New Tram" | 74 | 0,0069 | 0,0111 | 0,0045 |
| | "Old Tram" | 46 | 0,0063 | 0,0085 | 0,0039 |

In Table 2 measured maximal A-weighted sound pressure levels are displayed for the 5 investigation areas stratified by "New Tram" and "Old Tram". The mean of Maximum-SPL show no significant difference between the two types of tramways. Only in measuring point 5 the SPL levels of "new" tramways are in general higher than the levels recorded during pass-bys of "old" trams. A mean difference ($L_{AF,max}$) of nearly 3 dB is observable between tram types.

Table 2 – Noise exposure (Maximum-SPL) of analyzed tramways

| Measuring area | Type of tramway | Number of measured tramways | $L_{AF,max}$ (dB) Mean | $L_{AF,max}$ (dB) Max |
|---|---|---|---|---|
| Measuring point 1 | "New Tram" | 51 | 32,8 | 37,8 |
| | "Old Tram" | 14 | 32,7 | 35,8 |
| Measuring point 2 | "New Tram" | 41 | 30,1 | 34,3 |
| | "Old Tram" | 19 | 30,7 | 33,9 |
| Measuring point 3 | "New Tram" | 70 | 43,7 | 45,9 |
| | "Old Tram" | 2 | 43,9 | 44,3 |
| Measuring point 4 | "New Tram" | 36 | 34,5 | 37,9 |
| | "Old Tram" | 19 | 33,9 | 37,2 |
| Measuring point 5 | "New Tram" | 74 | 42,4 | 50,1 |
| | "Old Tram" | 46 | 39,7 | 46,3 |

In Table 3 the difference between "New Trams" and "Old Trams" of measured maximal loudness and maximal roughness is shown. Overall, recordings of "New Trams" revealed a higher mean Maximum-Loudness and mean Maximum-Roughness than "Old Trams".

Table 3 –sychoacoustic parameters of analyzed tramways: mean difference of Maximum-Loudness and Maximum-Roughness between "New Tram" minus "Old Tram"

| Measuring area | Difference "New Tram" minus "Old Tram" | Difference $N_{max}$ (sone) Mean | Difference $R_{,max}$ (asper) Mean |
|---|---|---|---|
| Measuring point 1 | "New Tram" – "Old Tram" | + 0,23 | + 0,03 |
| Measuring point 2 | "New Tram" – "Old Tram" | + 0,19 | + 0,023 |
| Measuring point 3 | "New Tram" – "Old Tram" | + 0,26 | + 0,028 |
| Measuring point 4 | "New Tram" – "Old Tram" | + 0,33 | + 0,032 |
| Measuring point 5 | "New Tram" – "Old Tram" | + 0,73 | + 0,067 |

## 4. SUMMARY

Since the introduction of new types of tramways in the city of Graz a lot of complaints were brought up by local residents of certain city areas. Typically, the annoyance by tramways results from a complex combination of sounds and vibration exposure depending on ground structure and building conditions. To sufficiently account for this complexity an integrated psychoacoustic approach was applied.

In a free field study ground-borne vibrations and sounds as well as secondary airborne sound recordings were carried out for various tramway types. For this purpose a binaural dummy head measurement system for noise and a triaxial accelerometer for vibrations were used to operate in synchrony.

In addition to standard sound parameters (SPL), psychoacoustic parameters were analyzed to learn more about the complex psychological and physiological responses associated with the introduction of the new tramway types in Graz.

First acoustic analyses suggest a slight overall difference between "New Trams" and "Old Trams" at the investigated homes – when psychoacoustic parameters are applied. Using standard Maximum-SPL-levels a relevant level difference showed up only at one measuring point. Whether the small mean overall differences in the psychoacoustic parameters may be responsible for the strong complaints of the inhabitants in some areas cannot be answered yet.

Although the mean vibration levels stay below the typical threshold values for the average human subject it is well known that the standards (eg. ISO 2631-2: 2003 or ÖNORM S 9012) may underestimate the potential effects on both more sensitive subjects, on evening and night hours (23) and for certain frequencies.

Therefore, further detailed frequency analyses and a higher level of integration are necessary to make a safe judgment from the viewpoint of public health. In a next step an extended analysis between all sound pressure levels, all psychoacoustic parameters and results of acceleration will be done to analyze the potential effect of combinations between all parameters.

Eventually, we have to consider that with 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 (24)

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