Analysis of increased annoyance reactions after the introduction of new tramways, based on psychoacoustic parameters

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ABSTRACT

The introduction of new tramway types in the city of Graz (Austria) resulted in strong complaints from residents in certain areas. To better understand the underlying reasons for these complaints, a systematic measurement campaign was designed for 6 locations in Graz and 2 locations in a comparable European city. This procedure combined measurements for vibrations and sound, which were conducted from 8pm to 8am at each location. Measured vibration levels (Wm-weighting) remained below the limits of the applicable standard. A systematic difference between "old" and "new" tramways was not detectable with standard vibration or acoustic indicators. However, a strong underestimation of the acoustic feature by the A-weighting (C-A > 20 dB) was observed. The signal-to-noise-ratio based on C-weighted levels clearly distinguished "old" from "new" trams. Analysis of the psychoacoustic parameters revealed a high variability in loudness and roughness at different locations and tram types. Roughness and loudness was associated with higher values for "new" trams at some locations. However, the "new" trams exhibited higher values for sharpness, but mainly at higher speeds. The high variance of vibration and sound indicators at the various locations makes it difficult to identify a single main determinant. Rather the integrated consideration of the various indicators enables a proper assessment to implement appropriate technical solutions.

Keywords: tramway noise, sound pressure level, psychoacoustics parameters
I-INCE Classification of Subjects Number(s): 52.4

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 are rarely discussed, while effects of air pollution and related climate issues are discussed (4).

Moreover, publications covering both noise and vibration measurements in homes are rare and only few consider health aspects (5,6). The current scientific knowledge regarding tramway immissions is poor, compared with the knowledge base regarding conventional rail.

While the body of evidence for railway induced vibration (7) and associated health impacts (8–13) increased substantially during the last decade, the research of tram noise, vibrations and secondary sounds has never received that level of attention. This is particularly surprising, 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 older trams. However, the track systems were often not properly adapted to the new demands. Moreover, the tram services were extended into the night and morning hours. These hours are very sensitive and elicit annoyance and sleep disturbance, as the signal to noise ratio increases. This is mainly because the overall traffic noise decreases and silence is interrupted by passing trams, which is the case especially in quieter suburban areas. These so-called shoulder hours (10 to 12 pm and 5 to 7 am) are known as sensitive times for disturbing the sleep and restoration process (14,15). Eventually,

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

After 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 operator conducted vibration measurements; however, the concerned citizens did not have much trust in the provided data. Acoustic and health experts from two Universities were commissioned to conduct a new measurement series covering both noise and vibration in a more integrated fashion including psychoacoustics to gain insight into the key disturbing moments of the new trams.

The main aims of the current study are: firstly, the application of psychoacoustic analyses shall help to uncover the main triggers responsible for the expressed 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.

At Internoise 2014 we presented preliminary descriptive results (REF). The current study included a further measurement site and an extended psychoacoustic analysis involving more external variables (23).

2. METHODOLOGY

2.1 Investigation areas and noise (psychoacoustic) measurements

In this study 6 different measuring points in single homes and flats (Figure 1 to 4) 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 (old 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). We asked inhabitants not to be at home during recording time or to sleep in another part of the house or flat to get a true representation of the existing background noise. All recordings were done from 8 pm in the evening until 8 am the next morning to analyze especially the time periods corresponding to "going to bed", "sleep" and "getting up at morning". During about 1 am and 4 am there is no tramway traffic in Graz. In addition, velocity and number of each tramway was logged for assigning to the noise and vibration measurements, in order to get information about differences of vehicles at the same location and between other measuring points.

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

Figure 2a - Measuring Point 2, flat, 2nd floor, backyard, dummy head (left); Figure 2b - Measuring Point 3, single house, 2nd floor, dummy head (right)

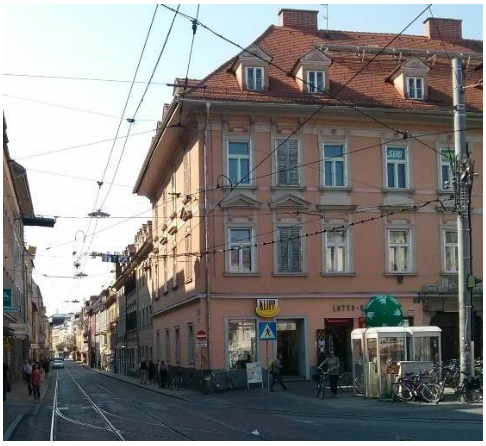

Figure 3a - Measuring Point 4, single house, ground floor, dummy head; Figure 3b - Measuring Point 5, flat, 2nd floor, dummy head

Figure 4 - Measuring Point 6, flat, 2nd floor, dummy head

2.2 Vibration measurements

Vibration measurements were done with a triaxial acceleration sensor (Model Isotron65H, 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 5).

Figure 5 - 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 6 points of investigation 433 single tramway pass-by's were extracted from the recorded database. Basic sound pressure parameters (Maximum, A-weighted and C-weighted energy-equivalent sound level) were calculated for every single tramway pass-by. In addition to standard sound parameters (SPL), psychoacoustic parameters (loudness, roughness, sharpness, tonality and fluctuation strength) were analyzed for all single passing tramways by means of the Psychoacoustics Module of the ArtemiS Analysis System (HEAD acoustics).

Finally, measured vibrations were analyzed based on Wm-weighted acceleration (ÖNORM S 9012) with time weighting slow, but also with fast time weighting to compare with German standards.

3. RESULTS

The mean of Wm-weighted acceleration measurements shows slightly different levels for the 6 measuring points. This is mainly due to different housing conditions/characteristics and differences in velocity levels of trams per each measuring point. Overall, the results show, that mean peak acceleration levels of "New Trams" are a bit higher than those from "Old Trams" at most measuring points. However, all mean peak values are slightly above the noticing level outlined by the Austrian standard (ÖNORM S 9012). The fast time weighting (as used in the German standard) indicates that a slight underestimation of (potentially noticeable) peak exposure can occur with the slow time weighting.

Among the classical acoustic parameters, the large difference between A- and C-weighted levels is striking and indicates that a dBA-assessment may not be an appropriate estimation of the actual perceived exposure (Table 1).

Table 1 - Noise exposure (Maximum-SPL A- and C-weighted) of analyzed tramways

Measuring points	$L_{AF,max}$ (dB) Mean	$L_{CF,max}$ (dB) Mean	$L_{CF,max}$ (dB) - $L_{AF,max}$ (dB) Mean
MP 1	48,4	63,8	15,4
MP 2	31,5	53,8	22,3
MP 3	42,3	54,1	11,8
MP 4	32,6	58,2	25,6
MP 5	37,1	56,9	19,8
MP 6	41,6	57,9	16,3

This hypothesis is supported by a further analysis, which includes the signal to noise ratio to compare "old" with "new" trams: while a difference between the trams is not significant with the A-weighting, a highly significant and clearly noticeable difference (~ 6 dBC) shows up with the C-weighted levels (Figure 6).

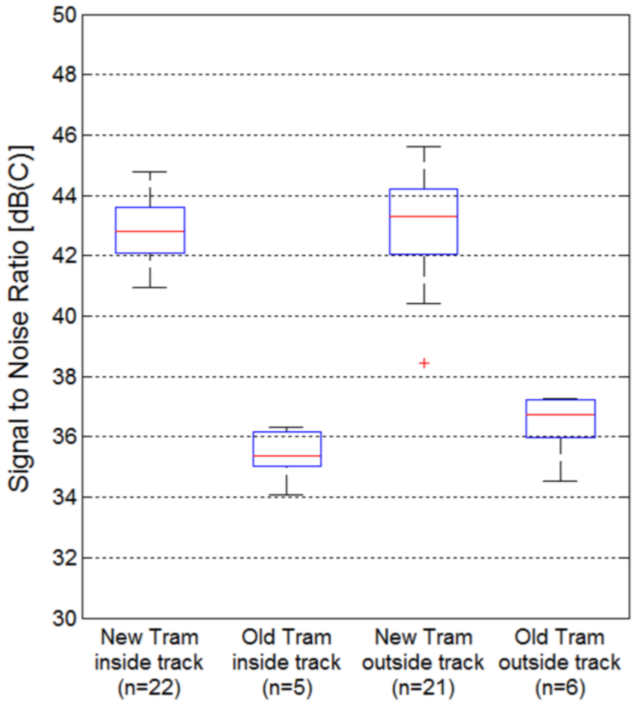

Figure 6 - Signal to Noise Ratio C-weighted (example from measuring point 1)

Figure 7 shows a comparison of a passing A- and C-weighted sound pressure level of the same "new tram (type Variobahn)" calculated by Fast Fourier transform algorithm over a time of 1 minute. Especially at lower frequencies a significant difference in the sound pressure levels is noticeable and indicates the focus in frequency spectra of tramways.

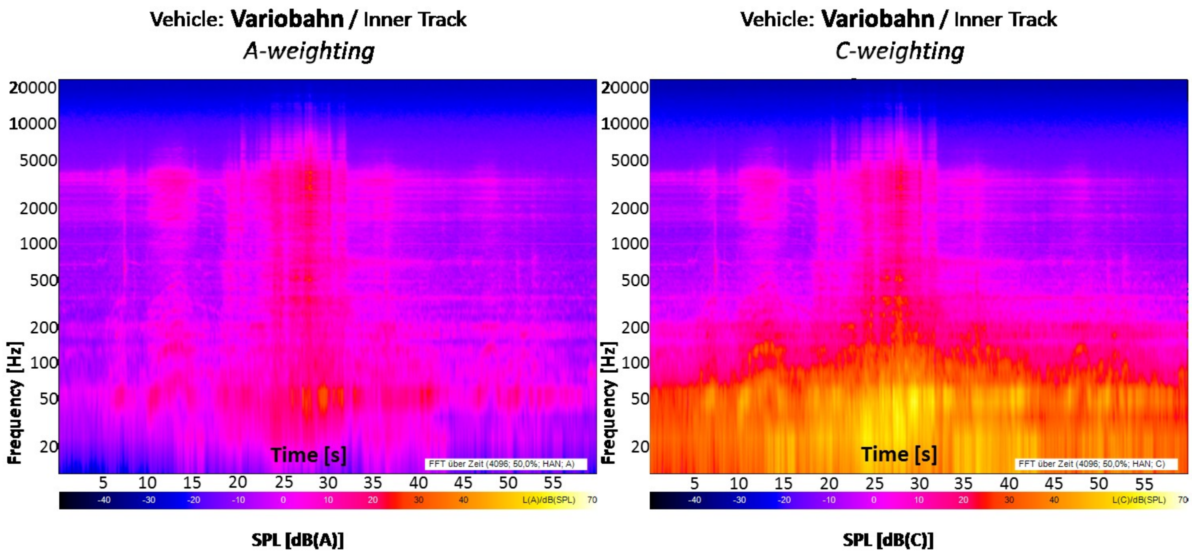

Figure 7 - Passing A- and C-weighted sound pressure level of the same "new tram (type Variobahn)" calculated by Fast Fourier transform algorithm

Additionally to the classical acoustic analysis psychoacoustic parameters were used for detailed investigation. Results revealed a high variability in loudness and roughness at different locations and tram types. Parameters like tonality and fluctuation indicated no relevance.
Figure 8 shows the maximum loudness level for each passing "new tram (Variobahn)" and "old tram (Serie 500/600 and CityRunner)" at measuring point 5. Especially the difference between inner and outer track is a significant factor at this measuring point and also the high variability for each tram type. The "new tram (Variobahn)" results show higher values in loudness over all measurements.

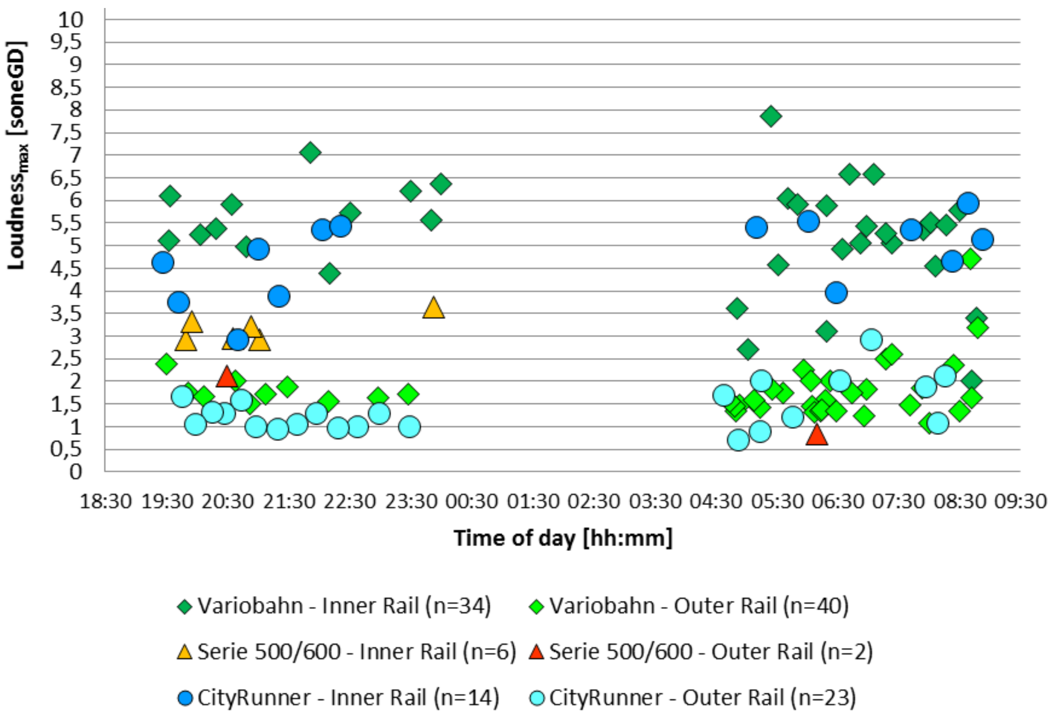

Figure 8 - Maximum loudness in [soneGD] at measuring point 5 for each passed tramway

Figures 9 and 10 show this high variability for the psychoacoustic parameter loudness over the whole measuring campaign and especially in Figure 12 the significant difference between the "new tram (Variobahn)" and "old tram (CityRunner)" is visible.

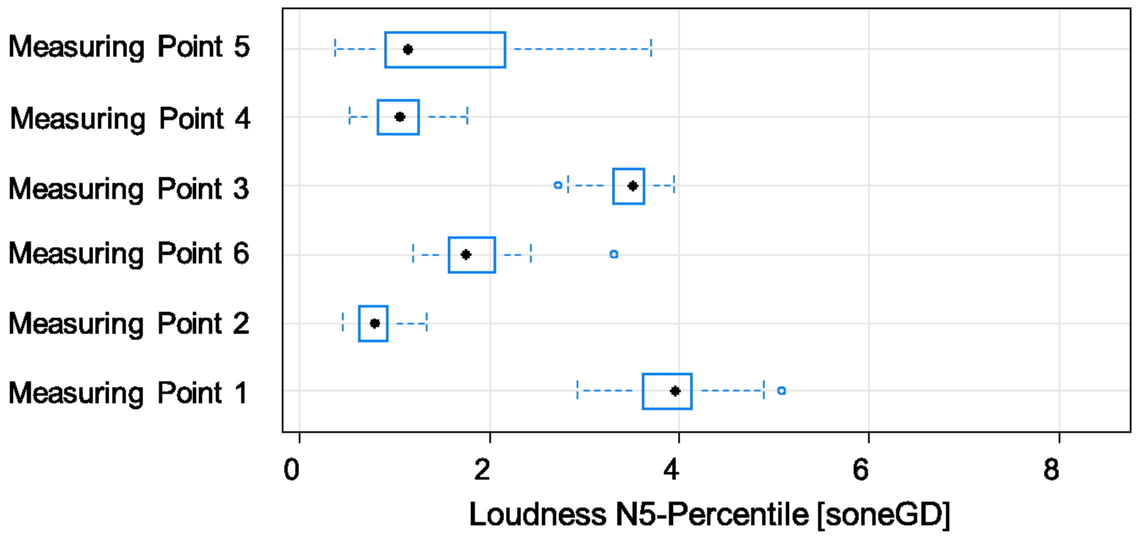

Figure 9 - Loudness N5-Percentile in [soneGD] at each measuring point for all passed tramways

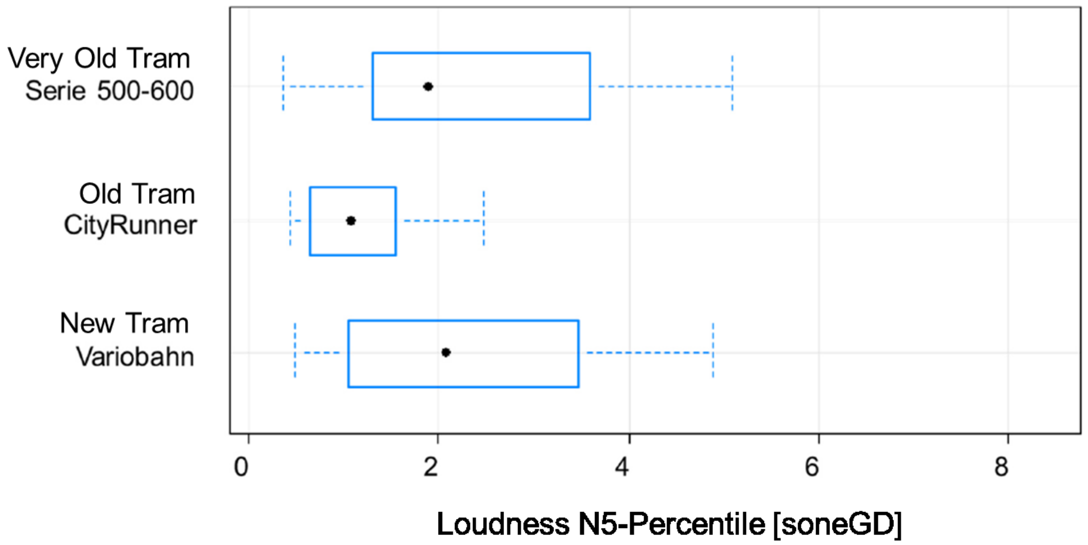

Figure 10 - Loudness N5-Percentile in [soneGD] over all measuring points subdivided into “New Tram (Variobahn)”, “Old Tram (CityRunner)” and “Very Old Tram (Serie 500/600)”

Figures 11 and 12 show this high variability and for the psychoacoustic parameter roughness over the whole measuring campaign and especially in Figure 14 for the “new tram (Variobahn)”.

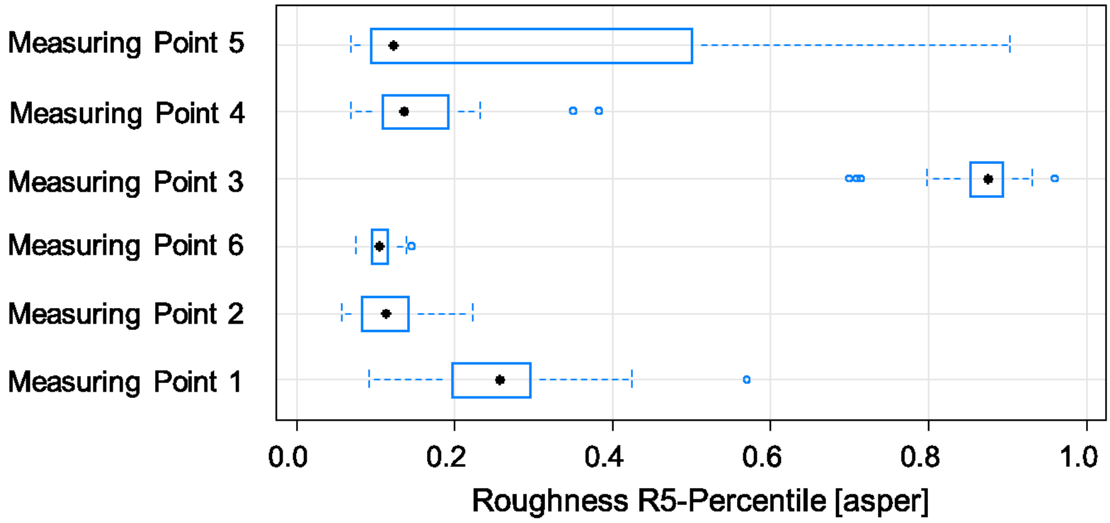

Figure 11 - Roughness R5-Percentile in [asper] at each measuring point for all passed tramways

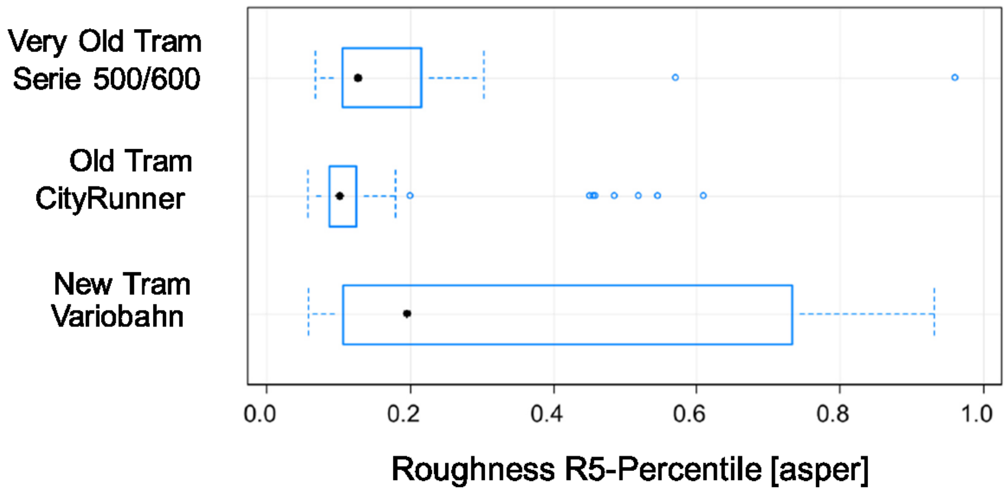

Figure 12 - Roughness R5-Percentile in [asper] over all measuring points subdivided into "New Tram (Variobahn)", "Old Tram (CityRunner)" and "Very Old Tram (Serie 500/600)"

Figure 13 shows the maximum sharpness level for each passing "new tram (Variobahn)" and "old tram (Series 500/600 and CityRunner)" at measuring point 4. Especially the high values and high variability for each tram type shows the complexity of an acoustical interpretation of the noise situation.

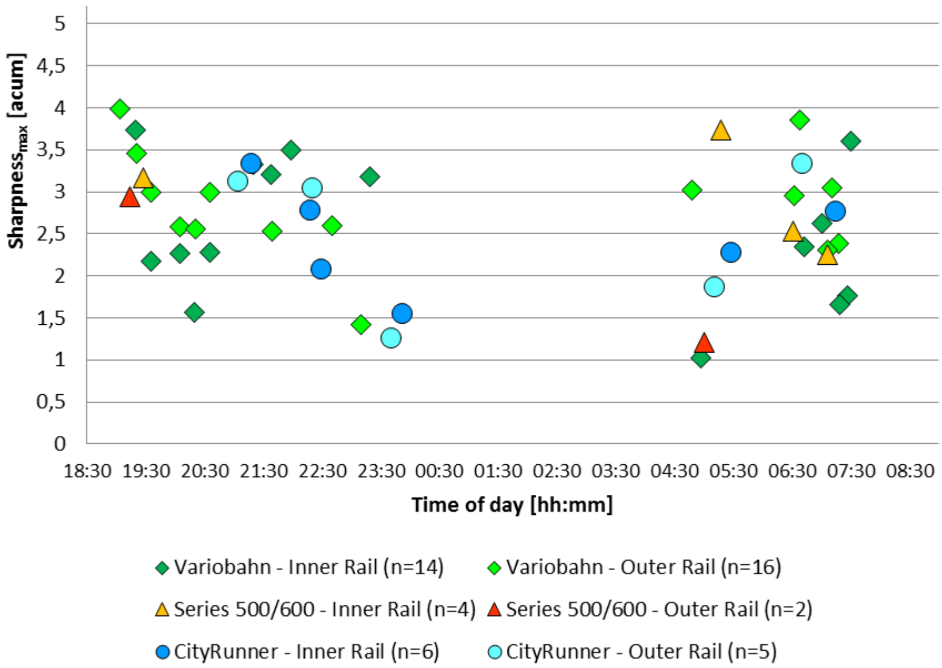

Figure 13 - Maximum sharpness in [acum] at measuring point 4 for each passed tramway

However, relevant differences and high values were found in the sharpness analysis for the "new" trams – but only at higher speed levels (Figure 14) – compared to no increase in sharpness with speed in case of the previous tram version (the older "CityRunner").

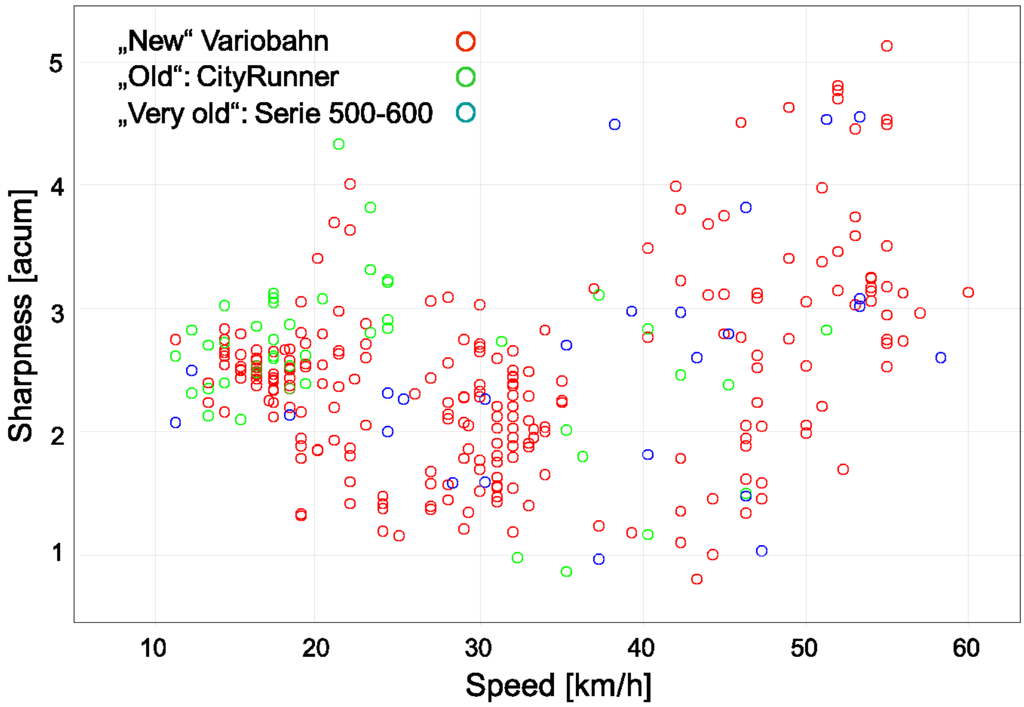

Figure 14 - Sharpness by speed over all measuring points subdivided into "New Tram (Variobahn)", "Old Tram (CityRunner)" and "Very Old Tram (Serie 500/600)"

The secondary airborne sound recordings were judged as not reliable and valid enough to be included in the overall analysis. The various mix of background and extraneous sounds at the 6 measuring points was too complex. However, secondary airborne sound was noticeable for both the inhabitants as well as for the investigators at some places and times.

4. SUMMARY and CONCLUSIONS

In a free field study ground-borne vibrations and sounds as well as secondary airborne sound recordings were carried out for various tramway types. To sufficiently account for this complexity an integrated psychoacoustic approach was applied.

Results in psychoacoustics revealed a high variability in loudness and roughness at different locations and tram types and especially the “new tram (Variobahn)” results show higher values in loudness over all measurements. Particular the high values and high variability for each tram type shows the complexity of an acoustical interpretation of the noise situation.

Additionally, in the presence of the very low background sound levels the C-weighted analysis of the signal to noise ratios showed a clear difference between “old” and “new” trams, which was not noticeable with the A-weighted approach. A noticeable difference was also uncovered regarding sharpness – especially at higher speed levels. A comparison with trams from another Austrian city revealed rather high sharpness values for the tramways in Graz.

Although the mean vibration levels stay below the typical guideline values for the average human, it is well known that the standards (e.g. ISO 2631-2:2003 or ÖNORM S 9012) may underestimate the potential effects on both more sensitive humans and during evening and night hours as suggested by recent exposure response curves (24). Furthermore, the observed presence of strong low frequency components can induce further vibration perceptions through cross-modality interactions (25,26). Such cross-over effects are not covered in typical “mono-sensory” guideline assessments, where primary and secondary airborne sound and ground vibration effects are separately assessed.

Immissions from trams are a multi-layered problem and need to be treated as such. Otherwise, the assessment runs the risk to underestimate the overall effect on humans in real life situations.

Therefore, the simple application of available exposure response information for vibration (27) may only be valid, when the ambient soundscape (28) and the other relevant environmental and social context mimics the conditions of the included surveys (10).

With the extended integrated approach in our case study in Graz we were able to pinpoint to a few critical issues which can help to explain the supposed “overreaction” of the concerned citizens – when only classical single guideline assessment is done.

It seems that the observed changes in psychoacoustic parameters in the presence of low background levels (higher than typical signal to noise ratio) and strong low frequency components (cross-modality effects) introduced a perceived step change in the annoyance response after the introduction of new tramway types (29).

Both, more noticeable noise and vibration exposure in combination (16,17,21,22) may have triggered such a step change in annoyance.

However, the observed high variance of vibration and sound indicators (see Figure 10) for the same tram types at different measurement sites makes it difficult to determine the main determining triggers for the observed subjective change in the perception of inhabitants.

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