Do current guidelines on vibration sufficient health protection at the community level independent of the accompanying soundscape?

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Summary
The introduction of new types of tramways in the city of Graz (Austria) resulted in strong complaints from local residents in certain areas of the city. Pilot vibration measurement observed some increase in one area where the geological conditions favoured propagation. However, no consistent patterns were found which could explain also the raise in complaints from other locations. To better understand the underlying reasons for the complaints a systematic measurement exercise was designed for 5 locations and combined measurements for vibrations and sound were conducted from 8pm to 8am by means of a dummy head measurement system HSU III.2 in combination with a SQuadriga II mobile recording system (HEAD acoustics GmbH). All measured vibration levels (Wm weighted) remained below the limits of the standard (ÖNORM S 9012). However, the required slow weighting (ÖNORM S 9012) showed significant underestimation of the actual perceived vibration exposure. On some locations nearly no relevant spread were observed - while larger spread was found on other locations. An overall systematic difference between "old" and "new" tramways was not detectable with standard acoustic indicators. However, a strong underestimation of the acoustic feature by the A-weighting (C-A > 20 dB) was observed. The most prominent difference between "old" and "new" trams exhibited the signal to noise ratio based on C-weighted levels. Analysis of the psychoacoustic parameters revealed only marginal differences in loudness, tonality and roughness with a slight trend towards higher values with the "new" trams. Relevant differences and high values were found in the sharpness analysis for the "new" trams – but only at higher speed levels. A high variance of both vibration and sound indicators levels makes it difficult to determine the single main responsible determinants. Rather a combination of slight changes seem responsible.

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 are discussed [4].
Moreover, publications covering both noise and vibration measurements in homes are rare and only few considered health aspects [5,6]. The current scientific knowledge regarding tramway immissions is poor compared with that of conventional rail.
While the body of evidence for railway vibration [7] and associated health impacts [8–13] increased

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substantially during the last decade, the study 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 the 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 to elicit annoyance and sleep disturbance, as the signal to noise ratio 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 known 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].
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 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 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 culprits 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.

2. Methodology

2.1. Investigation areas and noise measurements

In this study 5 different measuring points in single homes and flats (Figure 1 to 5) 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).
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 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 to get information about differences at the same and between recording points.

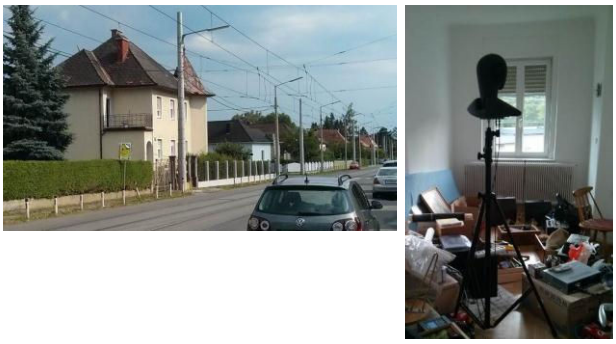

Figure 1. Measuring Point 1, single house, 1st floor, dummy head

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

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 6).

Figure 6. 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 pass-bys of 1 min duration 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 Analyses System (HEAD acoustics).

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

3. Results

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/characteristics and differences in velocity levels of tramways per measuring point. Overall, the results show that mean peak accelerations of "New Trams" are a bit higher than those from "Old Trams". However, all mean peak values are slightly above the noticing level outlined by the Austrian standard (ÖNORM S 9012).

The additional fast time weighting (as used in the German standard) indicates that a slight

Table 1. Vibration exposure of analyzed tramways

Measuring points	Type of tramway	Number of measured tramways	W_m Weighted peak acceleration (SLOW) (m/s²) Mean	W_m Weighted peak acceleration (SLOW) (m/s²) SD	W_m Weighted peak acceleration (FAST) (m/s²) Mean	W_m Weighted peak acceleration (FAST) (m/s²) SD
Measuring point 1	"New Tram"	51	0,0046	0,0005	0,0070	0,0009
	"Old Tram"	14	0,0041	0,0002	0,0062	0,0003
Measuring point 2	"New Tram"	41	0,0041	0,0002	0,0063	0,0003
	"Old Tram"	19	0,0041	0,0002	0,0063	0,0003
Measuring point 3	"New Tram"	70	0,0061	0,0006	0,0091	0,0014
	"Old Tram"	2	0,0053	0,0004	0,0077	0,0001
Measuring point 4	"New Tram"	31	0,0066	0,0023	0,0099	0,0031
	"Old Tram"	18	0,0055	0,0011	0,0086	0,0021
Measuring point 5	"New Tram"	74	0,0069	0,0020	0,0099	0,0029
	"Old Tram"	45	0,0060	0,0013	0,0089	0,0021

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 2).

Table 2. 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

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 7).

Among the psychoacoustic parameters we found only marginal differences in loudness, tonality and roughness in the distribution towards higher values with the "new" trams (Table 3).

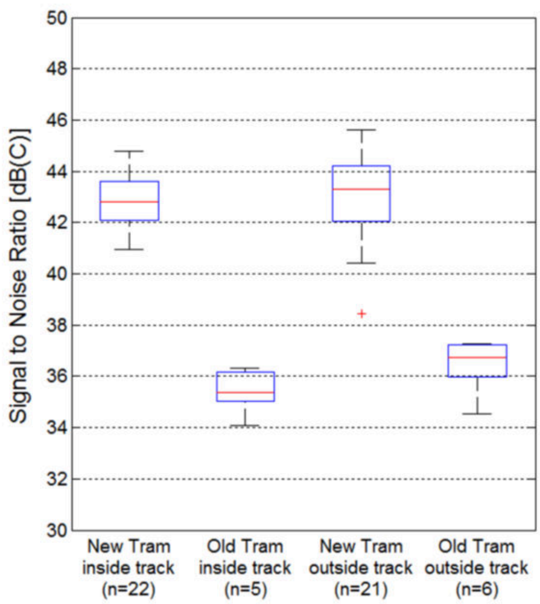

Figure 7. Signal to Noise Ratio C-weighted (example from measuring point 1)

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

Measuring points	Difference N_{max} (sone) Mean	Difference $R_{,max}$ (asper) Mean
MP 1	+ 0,23	+ 0,030
MP 2	+ 0,19	+ 0,023
MP 3	+ 0,26	+ 0,028
MP 4	+ 0,33	+ 0,032
MP 5	+ 0,73	+ 0,067

However, relevant differences and high values were found in the sharpness analysis for the "new" trams – but only at higher speed levels (Figure 8) – contrasting no increase in sharpness with speed for the previous tram version (the older "CityRunner").

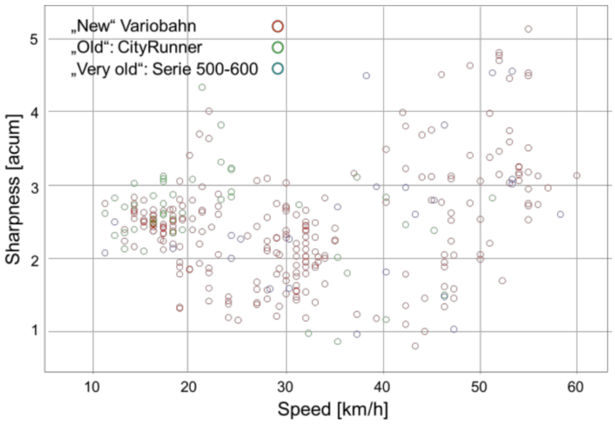

Figure 8. Sharpness by speed over all measuring points subdivided into "New Tram", "Old Tram" and "Very Old Tram"

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 5 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.

The analyses suggest a slight overall mean difference between "New" and "Old Trams" at all of the investigated homes – when psychoacoustic parameters are applied. Whether the small mean overall differences in the psychoacoustic parameters are solely responsible for the strong complaints of the inhabitants in some areas cannot be answered with certainty. However, 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 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 and on evening and night hours as suggested by recent exposure response curves [23]. Furthermore, the observed presence of strong low frequency components can induce further vibration perceptions through cross-modality interactions [24,25]. 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 [26] may only be valid, when the ambient soundscape [27] 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 slight changes in psychoacoustic parameters (especially sharpness) 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 [28].

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 8) for the same tram types at different measurement sites makes it difficult to determine the main determining culprits for the observed subjective change in the perception of the inhabitants.

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