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Analysis of Psychoacoustic and Vibration-Related Parameters to Track the Reasons for Health Complaints after the Introduction of New Tramways

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Abstract: Background: A change to new tramways in Graz (Austria) led to severe complaints in residential areas. To understand the underlying reasons for these complaints, a systematic measurement campaign was designed. Methods: Six locations in Graz and two locations in a comparably sized city were selected. Parallel indoor recordings of sound and vibrations were conducted from 8:00 p.m. to 8:00 a.m. (due to sleep problems) at all locations. Results: Vibration levels remained below the limits of the Austrian standard (Wm-weighting) although variability was observed among sites, tram types and pass-bys. A complex characteristic of the acoustic feature space was found with A-weighting (differences between A- and C-weighting of more than 15 dB were observed). C-weighted background to peak noise ratios clearly distinguished "old" from "new" trams. Psychoacoustic indices indicated a high variability between locations and tram types. Roughness and loudness was higher in "new" versus "old" trams at most locations. "New" trams exhibited high sharpness values and variability, especially at higher speeds—when compared with trams from a control city. Conclusions: Standard indicators of sound and vibration were not sensitive enough to uncover the reasons for the complaints. Only the integrated analysis of the ambient soundscape (high signal-to-noise-ratio), the more noticeable sound (in psychoacoustic terms) and the observed high variance of the immissions provided guidance to implement appropriate technical solutions.

Keywords: tramway; vibration; noise; psychoacoustics; annoyance; sleep; health risk assessment

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 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 health effects of noise and especially vibrations are rarely discussed, while effects of air pollution and related climate issues are the central themes [4].

There are a decent number of (older) studies related to tram sound emissions [5,6], determining factors [6,7] and about special issues such as squeal noise [8–10]. However, the current scientific data base regarding tramway immissions is small, most (except [11–13]) reported sound levels only in dBA, neglecting potential low frequency components and other specific characteristics of tramway sounds, which are produced by the various noise sources of this complex vehicle [7].

Only few studied annoyance responses at the community level [14,15] and no exposure response data from field studies are available. The majority of publications report results from experimental studies [12,13,16]. Often, articles concentrate only on vibration generation and propagation [17,18], simulation/model validation [19] or strategies for abatement of emissions [20,21]. Often, the knowledge base stems from railway vehicles or metros [22,23].

Publications covering both tram noise and vibration measurements in homes are rare [17]. The consideration of potential effects of trams in combination with other sound sources or effects of combined sound and vibration exposure was studied only in the laboratory [12,24] and is not yet considered in national standards.

In contrast, the body of evidence for railway induced vibration [25,26] and associated health impacts [27–33] increased substantially during the last decade and changes in policy are addressed [34]. The research on potential adverse health effects of tram noise, vibrations and structure born sounds has never received that level of attention—although the tram pass-by happens closer to residential buildings and national approval procedures for trams apply the same sound criteria as for mainline railways.

This is particularly surprising, because the tramway systems and its public use have undergone a profound change in the past two decades in European countries [7]. The typical weight of modern trams in use is now around 40 tons compared with 25 to 30 tons of older trams, as illustrated by the example of Graz, visualized in Figure 1 [35–37]. However, the track systems were often not properly adapted to the new demands. Moreover, the night and morning hours of operation of the tram services were extended (from 11:00 p.m. to 12:00 p.m. and 5:30 a.m. to 04:30 a.m.). These hours are acoustically highly sensitive in terms of the potential for sleep interference, as the background to peak noise ratio increases. Typically, the overall traffic noise decreases and silence is interrupted by passing trams, especially in quieter suburban areas. In addition, sleep research has found these so-called shoulder hours (10:00 p.m. to 12:00 p.m. and 5:00 a.m. to 7:00 a.m.) to be sensitive times for noise exposure and subsequent interference with the sleep and restoration process [38–40]. Eventually, noise and vibrations show potential for mutual interactive effects on annoyance and sleep disturbance [24,41–46].

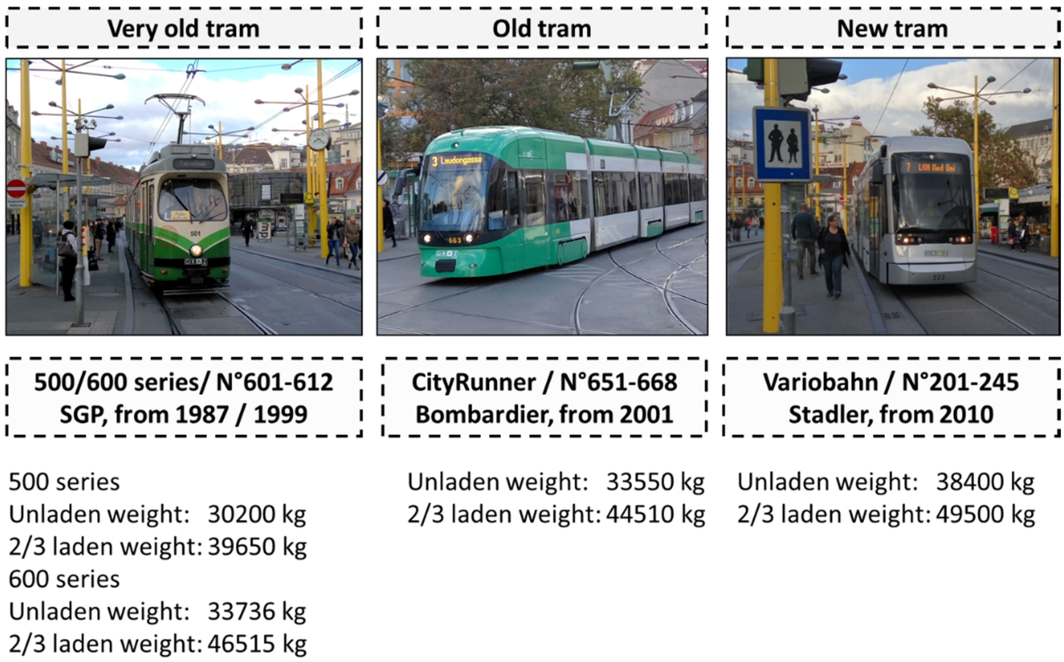

Figure 1. Tramway fleet in Graz with technical information.

After the introduction of a new tram system in the city of Graz (2011) several citizen initiatives issued complaints about the new trams regarding both higher noise and vibrations exposure.

The operator commissioned acoustic and vibration measurements. A few measures resulted in improvements at vibration hotspots after two years. However, complaints remained at a high level.

Acoustic and health experts from two Universities were commissioned in 2014 to conduct a new independent measurement series covering both noise and vibration in a more integrated fashion including psychoacoustic methods to gain insight into the key disturbing moments of the new trams in the context of the soundscape of Graz [47].

In order to respond appropriately to the citizen's concern, the main aims of the current study were: Firstly, the application of psychoacoustic analyses to uncover the main triggers responsible for the expressed annoyance and sleep interference. Secondly, to examine whether the current regulations and standards for vibration and noise sufficiently protect against potential health effects from trams (health risk assessment). Thirdly, whether the existing approval procedure for trams is appropriate to support the prevention of adverse health effects in the general population.

2. Materials and Methods

2.1. Areas of Investigation, Tramway Types and Sound (Psychoacoustic) Recordings

In this study six different sampling points in single homes and flats (Figures 2–4) in the city of Graz were analyzed. The areas were selected primarily on the perception and complaints of local residents and balanced against an expert judgment related to critical and representative sections of the tram network. Three tram types were in use: very old (500/600 series), old (City Runner) and new (Variobahn) (Figure 1). The pass-by noise of the tramway types (old and new trams, Figure 1) was binaurally recorded with a dummy head measurement system HSU III.2 in combination with a SQuadriga II mobile recording system (HEAD acoustics GmbH, Herzogenrath, Germany).

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 8:00 p.m. in the evening until 8:00 a.m. the next morning to analyze especially the time periods corresponding to "going to bed", "sleep" and "getting up at morning". During about 1:00 a.m. to 4:00 a.m., there is no tramway traffic in Graz. In addition, speed was measured and the vehicle number of each tramway was logged for assignment to the noise and vibration measurements, in order to get information about differences of vehicles at the same location and between other measuring points. The amount of vehicles varied at each measuring point due to the operational plan; especially the very old tram (Series 500/600) was recorded only a few times. However, the main issue in that regard is the more frequent constellation Variobahn/CityRunner.

(a) (b)

Figure 2. Measuring Point 3, single house, 2nd floor: (**a**) outside view facing tramway rails; and (**b**) measurement setup in the children's room.

(a) **(b)**

Figure 3. Measuring Point 5, flat, 2nd floor: (**a**) outside view facing tramway rails; and (**b**) measurement setup in the living room.

(a) **(b)** **(c)**

Figure 4. Measuring Point 6, flat, 2nd floor: (**a**) outside view facing tramway rails; (**b**) measurement setup in the bedroom; and (**c**) vibration measuring system with triaxial acceleration sensor based in the center of the room below dummy head measurement system.

Although structure born sound was sometimes noticeable at a few of the measuring points, it was not a constant perceptual phenomenon, therefore we did not include it in the overall analysis.

2.2. Vibration Recordings

Vibration measurements were done with a triaxial acceleration sensor (Model Isotron65H, from Endevco, Irvine, CA, USA). Recordings of vibrations were also done with the SQuadriga II mobile recording system (HEAD acoustics GmbH, Herzogenrath, Germany) to operate in synchrony with sound recordings (Figure 4c).

2.3. Calculation and Analysis of Objective Parameters

Based on all recordings at the six points of investigation, 422 single tramway pass-bys were extracted from the recorded database. Every recorded pass-by has been carefully (1–5 times) listened to and was afterwards rated for the observed audio quality. This step ensured the exclusion of pass-bys during which other unrelated sounds were also recorded and thus providing a database of recorded pass-bys without the influence of third party noise sources. 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, Herzogenrath, Germany).

Finally, measured vibrations were analyzed based on Wm-weighted acceleration with time weighting slow (according to [48]), but also with fast time weighting to compare with the German standard.

3. Results

Figure 5 shows the boxplots of Wm-weighted acceleration measurements at the six measuring points. The observed differences are mainly due to different housing conditions/characteristics and differences in velocity levels of trams per each measuring point. However, all peak values (except measuring Point 2) are slightly above the noticing level outlined by the Austrian standard ([48]). The variability at each point is also noticeable in terms of human perception.

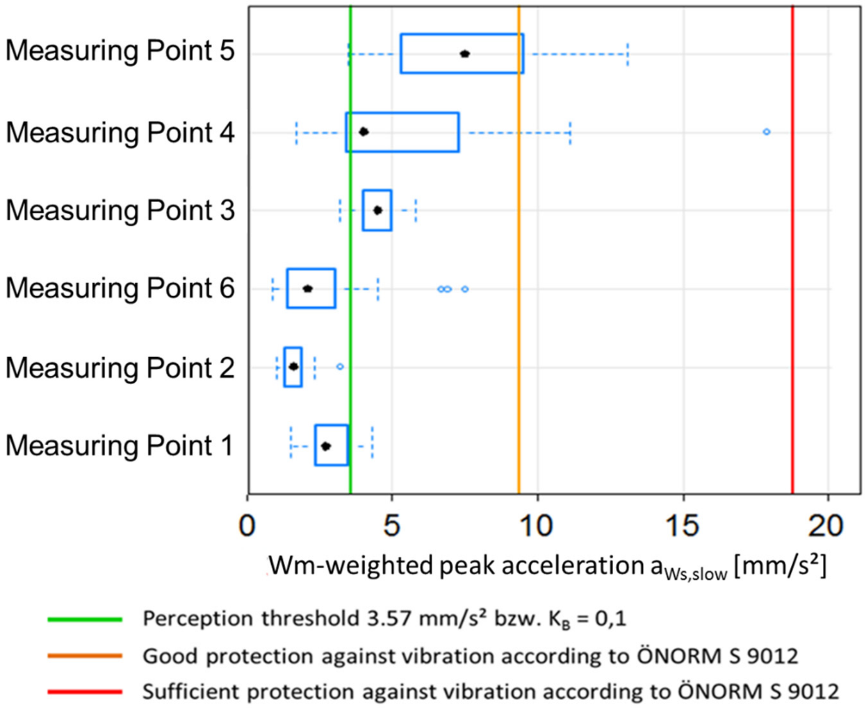

Figure 5. Vibration measurement results for each measurement point—compared with the Austrian Standard.

Overall, mean peak acceleration levels of "New Trams" are a bit higher than those from "Old Trams" at most measuring points (see Table A1 in the Appendix A). The "fast" time weighting (as used in the German standard) indicates that a slight underestimation of (potentially noticeable) peak exposure can occur with the time weighting "slow" (see Table A1 in the Appendix A).

As the sound analysis revealed strong low frequency components and the classical A-weighting curve is known to underestimate this acoustic feature and may lead to incorrect assessment of the true disturbance of the exposed people [49], we analyzed the difference between the A-weighting and the C-weighting as recommended by DIN 45680 in such cases [50].

The observed large difference between A- and C-weighted levels (Table 1) indicates that a dBA-assessment may indeed not be an appropriate estimation of the actual perceived exposure.

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

Measuring Points	Number of Measurements	$L_{AF,max}$ (dB) Mean	$L_{CF,max}$ (dB) Mean	$L_{CF,max}$ (dB) – $L_{AF,max}$ (dB) Mean
MP 1	54	48.4	63.8	15.4
MP 2	51	31.5	53.8	22.3
MP 3	67	42.3	54.1	11.8
MP 4	47	32.6	58.2	25.6
MP 5	119	37.1	56.9	19.8
MP 6	85	41.6	57.9	16.3

This hypothesis is supported by a further analysis, which includes the background to peak 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 (Figures 6 and 7).

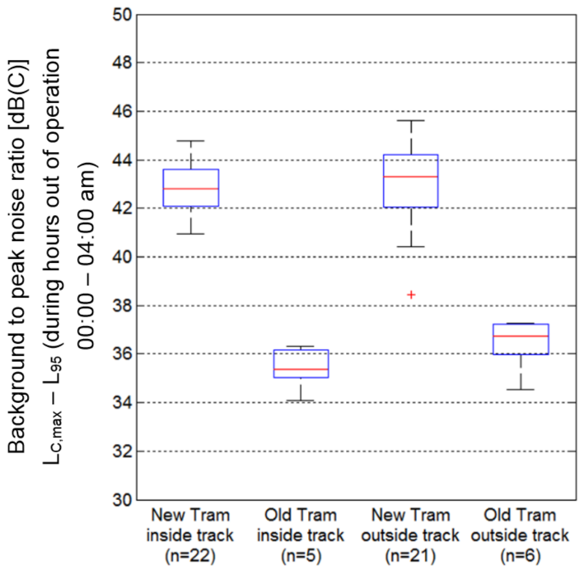

Figure 6. Background to peak noise ratio C-weighted: tram comparison at measuring point 1.

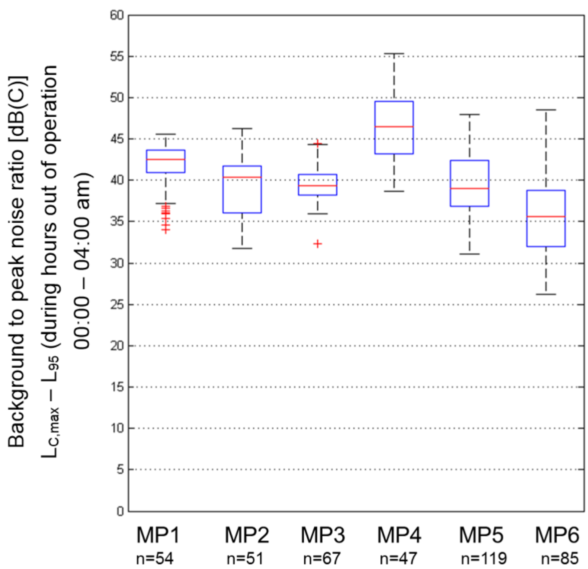

Figure 7. Background to peak noise ratio C-weighted: site comparison.

Figure 8 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 min. Especially at lower frequencies, a significant difference in the sound pressure levels is noticeable and points to the importance of these frequency spectra for assessing the annoyance and sleep interference potential of the studied tramways.

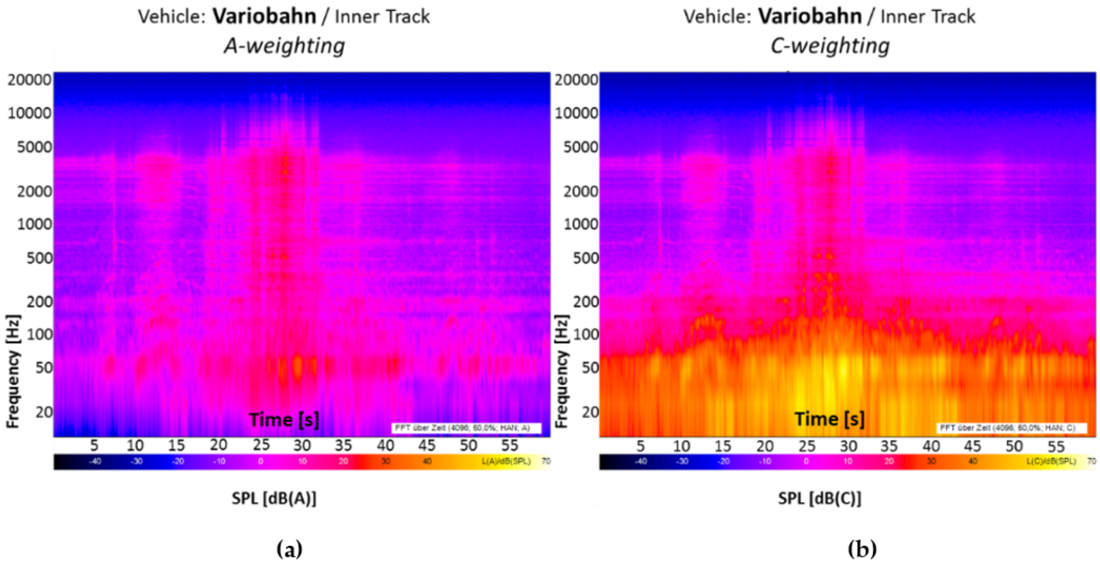

Figure 8. Pass-by sound pressure level of the same "new tram (type Variobahn)" calculated by Fast Fourier transform algorithm: (**a**) A-weighted signal; and (**b**) C-weighted signal.

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. No systematic difference was observed with parameters like tonality and fluctuation.

Figure 9 shows the N5 percentile loudness level for all passing tramways at each measuring point and Figure 10 for the three tram types in use. Both Figures 9 and 10 indicate a perceptually relevant variability for the psychoacoustic parameter loudness across the locations and tram types.

The data of Figure 10 show a significant difference in loudness values between the "new tram (Variobahn)" and the "old tram (CityRunner)" (Mann–Whitney U test—*p*-value: 2.574×10^{-15}). Loudness values were calculated based on ISO 532 B for a diffuse sound field. The latter shows also a smaller variability of the loudness distribution. Note: An increase in median sone from one to two means doubling of perceived loudness. As the spread goes from below one to five a substantial variation in the loudness of the Variobahn pass-by is therefore a perceptually relevant change.

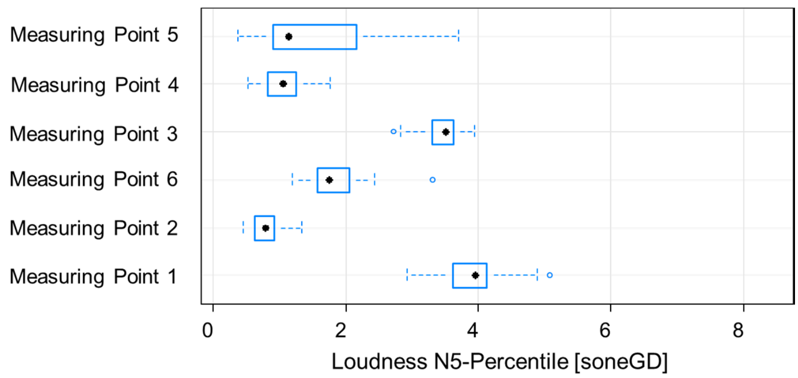

Figure 9. Loudness N5-Percentile in (soneGD) at each measuring point for all passing tramways.

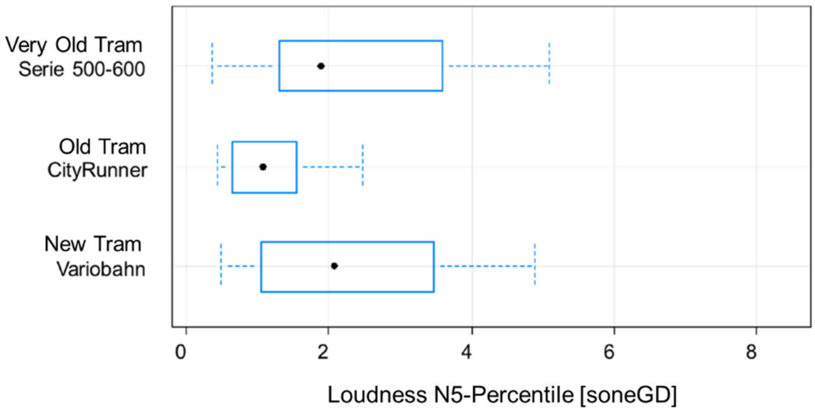

Figure 10. Loudness N5-Percentile in [soneGD] over all measuring points subdivided into "New Tram (Variobahn)", "Old Tram (CityRunner)" and "Very Old Tram (Series 500/600)".

Figures 11 and 12 show an even higher variability for the psychoacoustic parameter roughness for several locations—with very high values at Point 3. Figure 12 points to the substantially larger variability in roughness of the "new tram (Variobahn)", as well as significant higher values compared to the "old tram (CityRunner)" (Mann–Whitney U test—*p*-value: 1.239×10^{-11}). Loudness values were calculated based on Hearing Model after Sottek for a diffuse sound field [51]. Note: The perceptual threshold for roughness is slightly below 0.1 asper. Therefore, the large variability is not only well perceptible but in addition impairs the adaption of the exposed citizen.

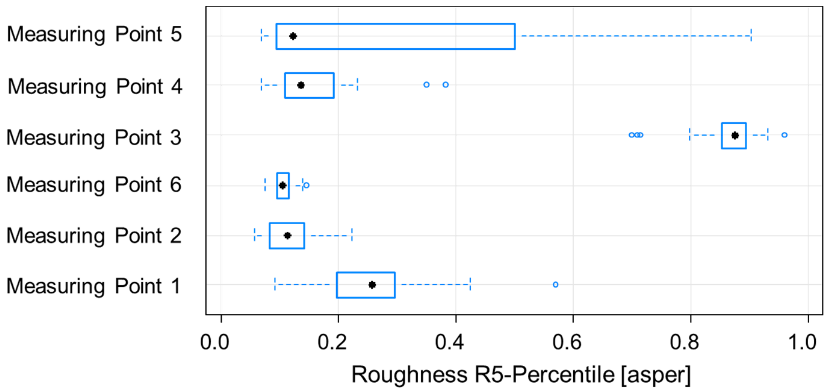

Figure 11. Roughness R5-Percentile in (asper) at each measuring point for all passing tramways.

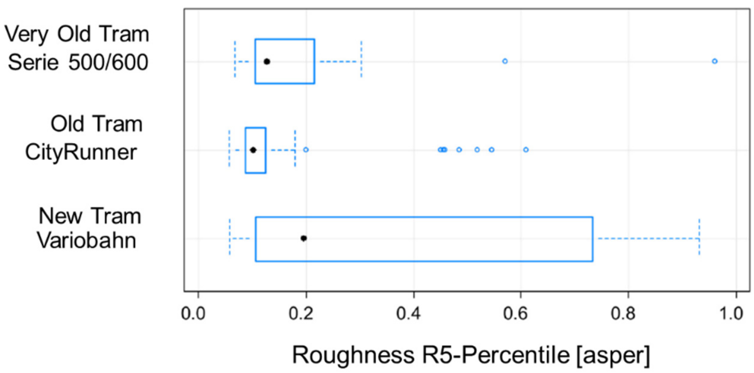

Figure 12. Roughness R5-Percentile in (asper) over all measuring points subdivided into "New Tram (Variobahn)", "Old Tram (CityRunner)" and "Very Old Tram (Series 500/600)".

Figure 13 shows the maximum of sharpness levels for each passing tramway at each measuring point. Sharpness values were calculated based on Aures' method in combination with ISO 532 B for a diffuse sound field. The very high values and the high variability provide a strong support for a perceptually critical acoustic situation.

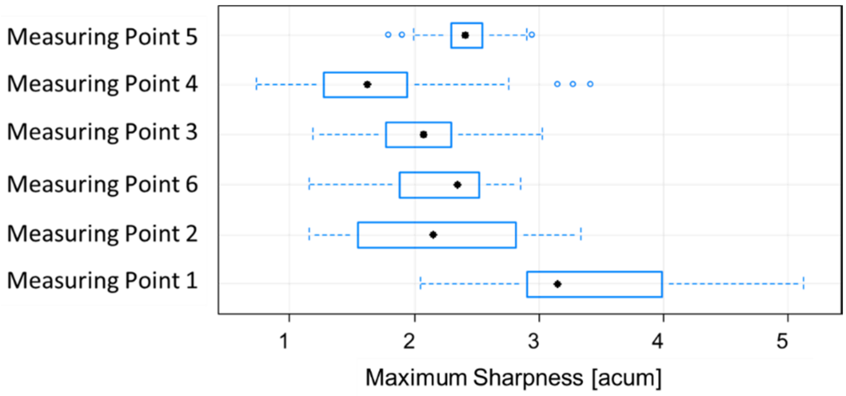

Figure 13. Maximum Sharpness in (acum) at each measuring point for all passing tramways.

Furthermore, higher values and variability 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"). Note: The trams in a comparably sized city also show a slight increase with speed—but the peak values do not exceed three acum at higher speed and the variability of the observed value range is much smaller.

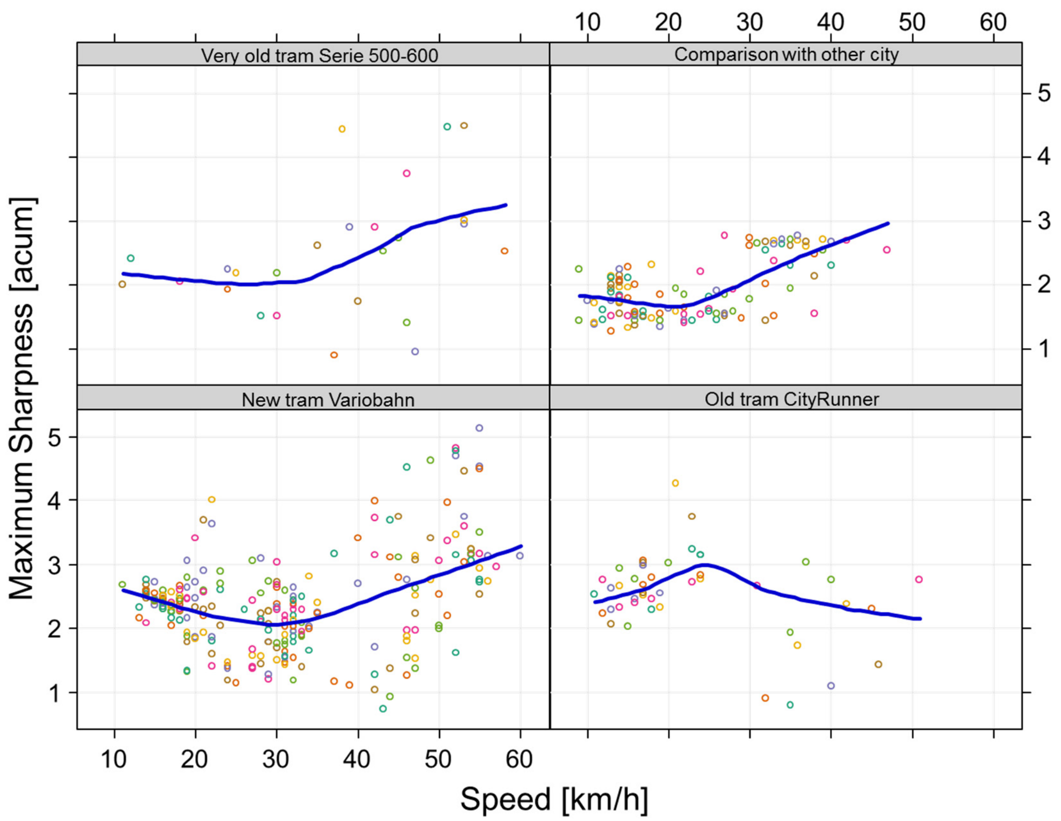

Figure 14. Maximum of Sharpness in (acum) by speed over all measuring points subdivided by tram type with a comparison of trams in a different city (upper right corner).

4. Discussion

In a field study of homes, parallel indoor recordings of ground-borne vibrations and sounds were carried out for three tramway types in current use. To sufficiently account for the variety of the involved sound characteristics, an integrated psychoacoustic approach was applied. We found compelling support for the accuracy of the issued complaints (especially sleep interference) of the citizens and a poorer acoustical performance of the "new" introduced tram (Variobahn) when compared with the "old" tram (CityRunner) mainly in use before 2011. In addition, the "very old" trams showed lower median values of roughness. However, their number of pass-bys was small compared to the "new" trams and did not dominate the soundscape.

To assess the potential risk of sleep disturbance the measured maximum indoor sound levels were used to estimate awakening probabilities. Based on the 42 dBA threshold value of the WHO-night noise guidelines [52], we computed the percentage of exceedances (see Table A2 in the Appendix A). The "new" trams showed significantly higher threshold exceedances (47%) compared with the "old" (20%) and even with the "very old" tramways (32%). The exceedances varied from location to location. At one location the threshold was even exceeded in 100 percent of the recorded events during nighttime. As with a large number of exceedances the awakening probability increases, these data support both the issued complaints about sleep disturbance and the citizen's perception of a deterioration after the introduction of the "new" trams.

Furthermore, dBC-dBA-analysis (Table 1) revealed strong low frequency components: all sites showed differences larger than 15 dB, which is the recommended criterion when the prediction of annoyance is the main aim [53]. Three sites even met the stricter DIN 45680 criteria of 20 dB, which would clearly indicate the inappropriateness of the use of the dBA-weighting in such a case [54]. Leventhall judged the use of the A-weighting in situations with strong low frequency components as inadequate and leading to incorrect decisions by regulatory authorities [49]. Schomer has proposed a 10 dB penalty in the case of relevant low frequency components—depending on the level of the ambient soundscape [55]. Due to the very low background sound levels at most locations we conducted an additional C-weighted analysis of the background to peak noise ratios. The observed ratios at all locations were very high for an urban area (Figure 7) and can result in relevant autonomous cardiovascular reactions during sleep [38,52,56]. The analysis indicated also a clear difference between "old" and "new" trams (Figure 6), which was not distinguishable with the A-weighted approach and further supports not to use A-weighting for this environmental health risk assessment.

The citizen's simultaneous exposure to low frequency noise, which also features high sharpness values, raises another question, since those characteristics can be understood as opposed noise phenomena. This question has to be answered by looking at the various noise sources of the complex system tramway. Whereas most of the low frequency noise stems from the rotating wheels on the rail track, the sharp sounds responsible for the high sharpness values are produced by both the pantograph and the corresponding transformer within the vehicle.

Overall the psychoacoustic analyses revealed a substantial variability in loudness, roughness and sharpness values across locations and the three tram types. In our view this high variability is one of the main determinant of the citizen complaints. The large variation in time makes the emissions not only well perceptible and intrusive but inhibits also habituation and impairs the adaption of the exposed persons. This view is supported by the older noticeability research, which demonstrated that annoyance was observed to be directly proportional to the detectability of the sounds [57–59]. Other research on traffic flow found rapidly alternating patterns of pass-by noise responsible for anomalies in annoyance [60]. Furthermore, changes in temporal and spectral signal features are other factors for an enhanced annoyance response found in laboratory and field studies [61–63]. These results are in compliance with neuro-biological and hearing research on the spectrotemporal filter mechanism of auditory attention [64–67]. If permanent changes of the temporal and frequency features occur the auditory system has difficulties to habituate and adapt—especially during nighttime.

In her multicomponent approach Preis [68] has summarized the main determinants of annoyance: the time-averaged difference between the loudness of the noise and that of the background noise (annoying loudness), the time-averaged difference between the sharpness of the noise and that of the background noise (called intrusiveness) and the distortion of the informational content. All those features were present in this case study.

A notable annoying feature in this context was the large differences observed with the indicator sharpness—especially at higher speed levels.

The control-study with trams from a comparable sized city revealed both: higher sharpness values and a wider spread in intensity for the "new" tramways in Graz (Figure 14).

Particularly the high variability observed with the new tram type in most psychoacoustic indices underlines the difficulty of a straight interpretation of the acoustic situation based on a single indicator. Nevertheless, this observed variability in the emissions of the new tram (Variobahn) is the key for improvements by strict quality control. In Figure 14 the Variobahn shows a reasonable number of trips with sharpness values below two—even with speed up to 50 km/h. This means: when all new trams can be "reprofiled" to these levels, the noticeability would be significantly reduced. Currently, a small quality control study is conducted to shed more light on the possible general implementation of this feature.

One has further to consider that due to atmospheric absorption effects the parameters sharpness and roughness behave differently with increased distance to a sound source compared to sound levels measured in dBA [69,70]. Therefore, another substantial underestimation is to expect by using the A-weighting in cases like in Graz: you will notice the tram over longer distances and the affected population will be larger than estimated by classical indicators.

A recent review [71] concluded, that commonly used weighting curves (e.g., Wm in Austria) do not correctly reflect annoyance caused by vibrations with multiple frequency components. Furthermore, recent evidence from exposure response curves [72,73] suggest that the standards (e.g., [74] or [48]) may underestimate the potential effects on sleep during evening and night hours". Unfortunately, the exposure response information in these studies used different vibration dose estimation parameters. To make this exposure-response information utilizable a mathematical conversion of the observed vibration values based on [48] into the one used in those studies (Wk-weighted RMS (m/s^2) or $VDV_{b,24hr}$ ($m/s^{1.75}$) and fast weighted, 0.125 s) was necessary. This concerned conversion from Wm-weighting to Wk-weighting, from slow to fast integration time and the calculation of the final overall dose (RMS or VDV). A full explanation of this procedure is provided in [75] and the resulting exposure response assessment is added as supplementary Figure A1 (annoyance) and Figure A2 (sleep disturbance). Based on these recalculations and considering upper 95% confidence intervals for the investigated effects, we could expect to have up to 15% highly annoyed and up to 25% sleep disturbed by the observed vibration values in Graz. These calculated effects are also comparable to those reported from the Cargovibe meta-analysis project [73]. Nevertheless, as these estimated prevalences are derived from main rail vibration exposure a cautious interpretation is necessary.

However, taking into account the extraordinary high background to peak noise ratio at all investigated sites (Figure 7) this means that all perceptible exposures (sound and vibration) will be easier noticeable. Such an interpretation is supported by studies which had lower background levels of noise and showed a stronger mutual effect of noise and vibration on reported annoyance [24,45,76].

Therefore, although the mean observed vibration level at all locations remained below the national guideline values, a sufficient protection against potential health impacts may not be guaranteed in a situation of combined exposures under critical environmental conditions (multiple frequency vibration, low background noise, complex sound exposure). A recent pilot study investigating lower vibration values at low background noise (LAEq = 25 dB) suggested that alterations of sleep depth and cortical arousals may begin already at 0.3 mm/s [77].

Furthermore, the observed presence of strong low frequency components can induce further vibration perceptions through cross-modality interactions [78,79]. Such cross-over effects are not covered in typical "mono-sensory" guideline assessments, where primary and secondary airborne sound and ground vibration effects are assessed separately.

This study extends previous tram noise studies by using a broad based technical and integrated health approach to investigate the possible reasons for strong citizen complaints after the introduction of a new tram generation. There are also some constraints.

Due to the already emotionally heated community situation (no significant improvements over two years) we had to abstain from carrying out an accompanying field survey to get our own data on annoyance and sleep disturbance. Instead we used external annoyance and sleep disturbance reference data and referred our obtained exposure data to this established general information. As no tram field exposure response information was available for potential health effects we had to resort to an approximation by using main rail response data.

Eventually, due to budget limitations, we were unable conducting parallel indoor and outdoor measurements at each location. This could have given further insight into the tram noise transmission through wall and windows.

5. Conclusions

Emissions from trams are a multi-faceted 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 [75] may only be valid when the ambient soundscape [80] and the other relevant environmental and social context mimics the conditions of the included surveys [28].

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. In addition, the case study shows the limitations in health risk assessment when only separate, classical single sound and vibration guideline assessments are carried out.

It seems that the perceptible change of the tram emissions verified by psychoacoustic parameters and vibration measurements was accentuated in the presence of low background levels (higher than typical background to peak noise ratio) and strong low frequency components. Altogether, the interaction between these sensory changes (cross-modality effects) may have introduced a perceived step change in the annoyance response after the introduction of the new tramway types [41,42,45,46,81]. However, the observed high variance of vibration (Figure 5) and all psychoacoustic indicators (see Figures 9–14) for the same tram types at different measurement sites makes it difficult to determine the main trigger for the observed subjective change in the perception of inhabitants. Further quality control studies are needed with "reprofiled" tramways to implement systematic changes.

The results point also to the constraints of applying national standards in isolation, when the health risks of combined exposures need to be assessed. This study provides further support to the statement in the review by Trolle et al. 2015 [71] that typical vibration weighting used in standards (e.g., Wm) do not provide sufficient protection under certain circumstances. Furthermore, the required time weighting "slow" in the Austrian standard can lead to a slight underestimation of the exposure peaks at the perceptual level.

Eventually, the fact that tramways are not required to undergo vibration assessment during the approval process (in Austria) does neither fit with the need for more public transportation nor with the stricter requirement to protect the public against adverse health effects from transportation.

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Author Contributions: P.L. was commissioned to do this work; P.L. and M.C. conceived and planned the design of the study; M.C. and M.L. conducted the field work and made the post processing; M.C., P.L. and M.L. analyzed the data and agreed on its interpretation; P.L., M.C. and M.L. drafted the article; P.L., M.C. and M.L. critically revised the article; and all authors approved the final version.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

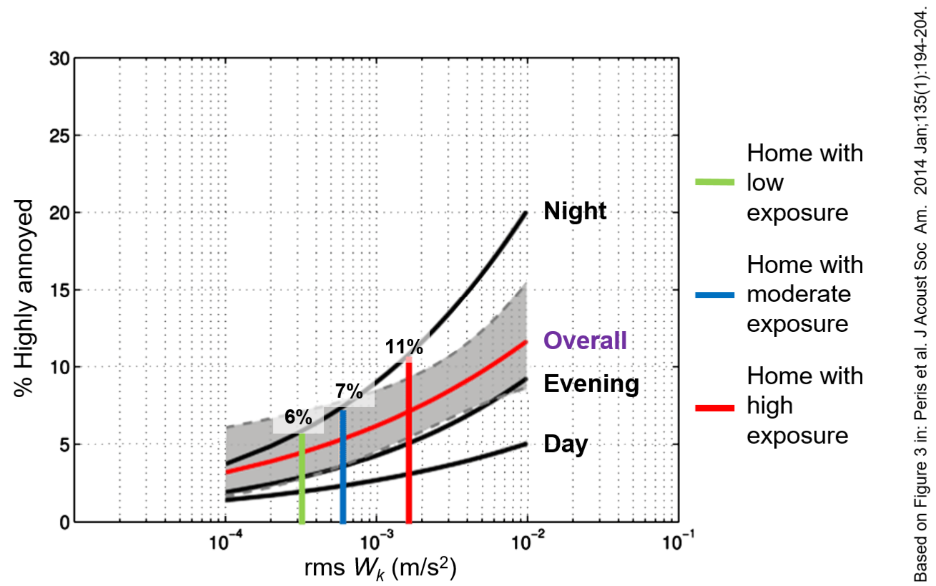

Figure A1. Comparison of the proportion of people reporting high annoyance (%HA) during the day, evening and night due to railway vibration (vertical vibration). Using the converted exposure data from the Graz immission survey (slow weighting).

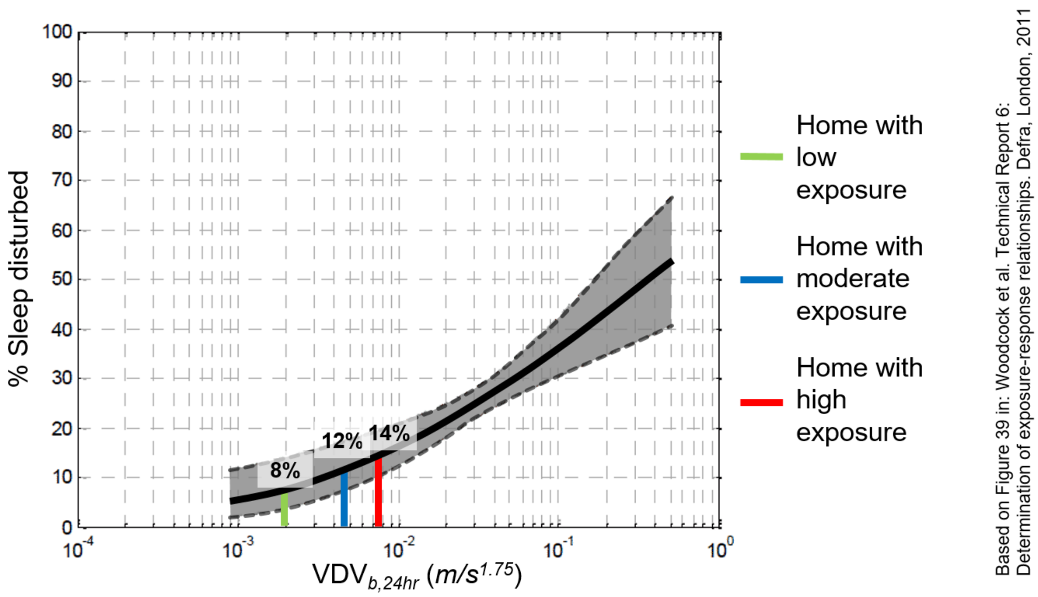

Figure A2. Exposure-response relationship showing the percentage of people reporting sleep disturbance for a given vibration exposure. Using the converted exposure data from the Graz immission survey (slow weighting).

Table A1. Vibration exposure of analyzed tramways by tram type and time weighting.

Measuring Points	Type of Tramway	Measured Tramways	Wm Weighted Peak Acceleration (SLOW) (m/s^2) Mean	Wm Weighted Peak Acceleration (SLOW) (m/s^2) SD	Wm Weighted Peak Acceleration (FAST) (m/s^2) Mean	Wm Weighted Peak Acceleration (FAST) (m/s^2) 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
Measuring point 6	New Tram	51	0.0050	0.0008	0.0076	0.0011
	Old Tram	26	0.0047	0.0007	0.0073	0.0009

Table A2. Maximum Sound Levels indoors during passing by tram type.

Type of tram	% above Threshold *	Lower 95% CI	Upper 95% CI
Variobahn ("new")	47%	41%	52%
CityRunner ("old")	20%	12%	29%
Series 500-600 ("very old")	32%	19%	49%

* Threshold $\geq$ 42 dBA, max indoors.

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