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THE EFFICIENCY OF TRAM ARTICULATIONS COMPARED TO VIBROACOUSTIC EMISSIONS

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Abstract: *Human quality of life is constantly increasing, and so does the comfort of travel by various means of public transport, especially rail transport. One of the more crucial criteria for assessment of travel comfort is vibroacoustic comfort. This aspect is also substantial among rail vehicle operators and manufacturers. Sound quality evaluation is related to psychoacoustic indicators, but reducing the levels of acoustic pressure does not always correlate to increased quality of the perceived sound and improvement of human sound perception. Moreover the cause of unpleasant noise has to be taken into consideration. In many examples it is induced by specific vibrations and/or friction forces through components.*
The following article presents experimental research carried out in the in-situ conditions, testing the quality of work carried out by tram articulations considering vibroacoustic emissions. Several measurements were taken of vibroacoustic signals in several urban rail vehicles of the same type. Two different trams were chosen for analysis and their vibroacoustic emission levels as well as sound quality parameters were compared. One of the more crucial aspects of the research was to determine the dependency between vibrations around the area of articulations and squealing noise. The results indicate a large correlation between signals and deterioration in the work quality of the articulation in the given tram. Moreover, the authors suggest expanding on currently carried out maintenance in order to minimise inconvenient vibroacoustic phenomena during use.

Key words: *tram articulations, sound quality, vibrations, squealing noise*.

1. Introduction

In a tram, there are many critical places which require a special attention during the building process to ensure that the components are appropriately durable, dynamically structured, and able to cooperate with other components. One of these places is at the articulation of the tram, whose job it is to link the tram segments, carry the traction forces, and provide access between tram segments for passengers. Due to the lack of continuity of the carbody in this area, it is necessary to close off the area around the tram articulation, using components that won't restrict the movement of individual tram segments. Hence, the construction of the articulation should consist of a transverse bridge to ensure open passage for passengers between the carriages, as well as a cover between the tram segments. The entire structure should be impermeable, fireproof, resistant to vandalism, easy to clean, acoustically insulated and, should ideally maintain a wide passage. Taking into account tram maintenance, it is essential that the covers between tram segments can be easily detached, and with them the electrical and hydraulic wiring. Considering safety precautions, it is also necessary to construct an articulation which prevents the unwanted, accidental disconnection of tram segments.

In addition to safety issues, acoustic insulation is of much importance, as it greatly influences the transfer of vibroacoustic phenomena into the passenger compartment, which – along with factors such as temperature, odour, or aesthetics – significantly influences driving comfort (Engel 2013). In the case of the articulations, the primary source of sound comes from mechanical sources such as vibrations and friction. The vibrations found in the analysed system are primarily a consequence of dynamic interactions in the vehicle-track system, but also a consequence of the movements of individual tram segments while driving through curves. The vibrations are also heavily influenced by the quality of the work of individual articulation elements, which are dependant, for example, on their wear or on setting a correct clearance between individual kinematic pairs. They are also dependant on the friction coefficient between adjacent surfaces.

The problem of vibroacoustic insulation is so complex, that it is not possible to use the same insulation used in the carbody construction, as it is necessary to maintain ease of motion. Currently, manufacturers offer a number of solutions for articulation covers, the most popular of which being a harmonica cover (Fig. 1. Examples of popular articulation covers in trams: Fig. 1a), but also a panel cover (Fig. 1b).

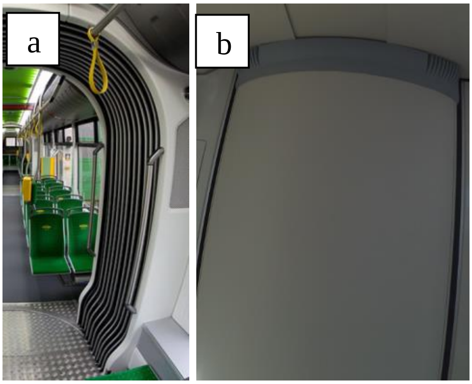


Fig. 1. Examples of popular articulation covers in trams: a – harmonica covers, b – panel covers

These solutions differ in the way they work, but also in the materials used. Manufacturers, however, highlight that panel covers are better quality products, which, besides greater resistance to damage, also provide better acoustic insulation. From the point of view of a public transport commuter, it is the aforementioned travel comfort (and not the type, appearance, technical operating time or technical condition of the vehicle) which matters most.

There are fewer examples of sound quality evaluation and vibroacoustic emissions in rail vehicles than in automotive and aviation industry. Listening tests and jury assessments are the most common approaches in this field. Also basic approaches based on simple vibroacoustic measurements and analyses are common. In (Letourneaux et al. 2000) the SNCF operator was trying to assess acoustic comfort in several TGV Duplex coaches. In (Parizet et al. 2002), an acoustic comfort model was estimated by loudness, A-weighted SPL, tonality and sharpness. In (Zhang et al. 2012) the aim of investigation was to compare the objective and subjective quality assessment in high-speed trains. Another investigation where passenger surveys were carried out is (Khan 2002). In this case the task was to point out the most annoying noise sources during train journeys. The results showed that cellular phones and crying children, as well as non-identified sources of noise such as rattling, squeaking and beating are the most annoying for passengers (Khan 2002). Short-term noise annoyance assessment in passenger compartments of high-speed trains was examined in (Park et al. 2015).The study included only the events of special noise during travel such as passing through a short tunnel, passing by another train in open space and inside a tunnel – all non-stationary sounds. The annoyance indicator was evaluated based on comparison of subjective assessments and psychoacoustic calculation of loudness, roughness and sharpness (Park et al. 2015). The next two examples of sound quality are very unique (Lei-ming et al. 2005; Hu et al. 2014). Besides the acoustic measurements in the Shanghai Metro, psychoacoustic calculation (such as A-weighted SPL, loudness, sharpness, roughness) and jury listening tests, a finite element model in Actran software was performed (Hu et al. 2014). Sound field simulation and optimization was carried out. The accuracy of the simulated results was verified with an experiment. The highest SPL positions in the sound field were confirmed by the SPL distributions. The optimization was investigated by the orthogonal experiment design which takes into account the SQ improvement in both the SPL and loudness (Hu et al. 2014). The results indicated that the proposed optimization scheme can be beneficial for vehicle acoustical design in engineering. In (Sandrock et al. 2008) the exterior noise emitted by trams and buses affecting the Poznan urban environment was investigated. One of conclusions was that psychoacoustic indicators and acoustic annoyance calculation of tram noise were more pleasant than bus noise (Sandrock et al. 2008). To sum up the examples of sound quality evaluation and sound perception investigation in the rail vehicles field, it is worth mentioning the (Orrenius & Carlsson 2014) report. It widely describes the main methods of psychoacoustic parameters estimation in rail vehicles, as well as the main sound and vibration sources in rail compartments.

These examples indicate a lack of implementation of the efficiency of tram articulations compared to vibroacoustic emissions inside urban rail vehicles. Also the decision to undertake this study was instigated by a recording published by a resident of Poznan on a community portal that links Poznan public transport users. The recording shows the tram articulation during use, with significant and disturbing sounds being emitted. The nature of these phenomena was presented by the residents who described the sounds as "squealing" and "creaking", and their annoyance was expressed by describing the sounds as an "ear massacre" which caused "their heads to burst" (Facebook Social Group “Spotted: MPK Poznan” 2017).

The aim of the following article is to highlight the need to keep tram articulations in a good working condition, taking into account vibroacoustic phenomena in the space around them. In addition to pointing out the problem of excessive noise and vibrations, the authors wanted to point out the significant degree of acoustic annoyance during the journey. In order to do so, analysis was carried out to compare the generation of vibroacoustic phenomena in two selected trams.

2. Research Methodology

2.1. Selecting test vehicles

The basic premise of the study was to perform a pre-selection of the tram type based on the occurrence of excessive vibroacoustic phenomena within the tram in the articulation. The trams were all selected based on their performance on a section of track which was identical for all tested trams. Finally, signals from 8 arbitrarily selected trams were recorded. From these results, vehicles were selected for further research based on the sound levels recorded during the tests. This way, the tram with significantly increased vibroacoustic signals was easily identified, and mirrored the complaints passengers had described previously. For comparative analysis, a tram with low vibroacoustic emissions was also selected.

2.2. Comparative studies - Research objects and location

In the end, two selected trams with multiple tram segments which had been indicated to emit acoustic signals around the articulations were put through tests on the Poznan tram infrastructure. Out of the two selected research objects, the tram previously agreed to be #1 replicated the described problem, whereas tram #2 didn’t demonstrate any meaningful, significant vibroacoustic phenomena.

For comparative studies, an identical track section was selected for the passage of both trams, which was characterized by a straight line in both the plan and profile views. The signals were analysed on the same sections of track, during which both trams were moving at a constant speed of about 50 km/h. The length of the analysed signals in both cases was about 13 seconds. The passage was completed in the evening, with minimal filling of passengers (last circuits).

2.3. Measurement points

Measurement points were located in the first articulation from the front of the vehicle between tram segments 1 and 2 (Fig. 2). In order to determine the quality and levels of sound, a microphone was placed on the central part of the articulation. Meanwhile, to determine the movements between carriages, vibration transducers were located at three measuring points: on the floor in the middle of the articulation, on the front wall of the second tram segment at half height and symmetrically on the wall of the first carriage. The locations of the measurement points are shown in Fig. 2.

The measuring devices were made by Danish company Brüel & Kjær and consisted of 3 vibration transducers and one condenser microphone. Signals were recorded and registered in the Brüel & Kjær 2050 module for acquisition and archiving. The synchronization and calibration of the system, together with the live monitoring during the run, was carried out in the NOTAR® software environment via a tablet.

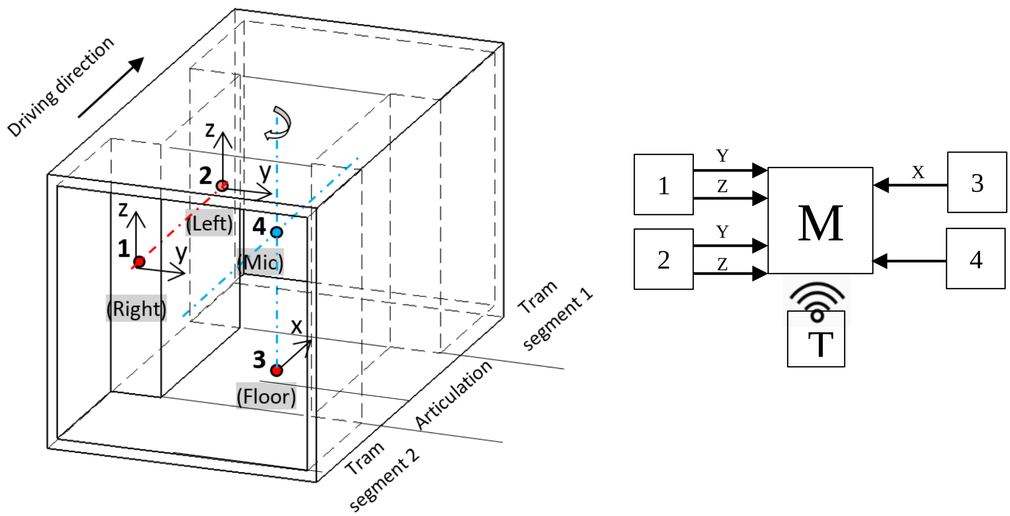
3. Analysis of research results

3.1. Acoustic signals

One example of an annoying sounds group in rail vehicles is squeal (squeak, squelch or moan) noise. It is caused by friction forces through two components in sliding contact (Orrenius & Carlsson 2013). Squealing noise is a tonal character sound, which is usually more unpleasant than sound consisting of lower, broadband frequencies. Two types of measured sound samples were selected for acoustic analysis, called:

a) the annoying sound sample – AS from the problematic tram #1,
b) the reference sound sample – RS from tram #2 without any problems.

Firstly, the CPB (Constant Percentage Bandwidth) analysis was performed, shown in Fig. 3. The annoying sound sample consists of much higher sound components in the medium and high frequency bands. The biggest differences in the SPL (Sound Pressure Level) are located in 1250 Hz and 2500 Hz frequency bands, equalling more than 15 dB(A) caused by high tonal character sounds. Also, the equivalent sound pressure level A $L_{eq(A)}$ was calculated, shown in Fig. 3, and is equal to nearly 85 dB(A) in the AS sample, nearly 10 dB(A) more than in the RS sample. This simple acoustics analysis has only shown the existing noise problem during the tram's passage. However, it does not show the psychoacoustic annoyance issue, which is very important for the passengers' ride comfort.



● - measuring point of vibration acceleration,
● - sound measuring point

Fig. 2. Diagram of distribution of measurement points together with their directionality in the tram space and diagram of measuring devices: 1, 2 – vibration transducer Brüel & Kjær 4524-A, 3 – vibration transducer Brüel & Kjær 4504-A, 4 –microphone Brüel & Kjær 4189, M – module for acquisition and archiving Brüel & Kjær 2050, T – tablet

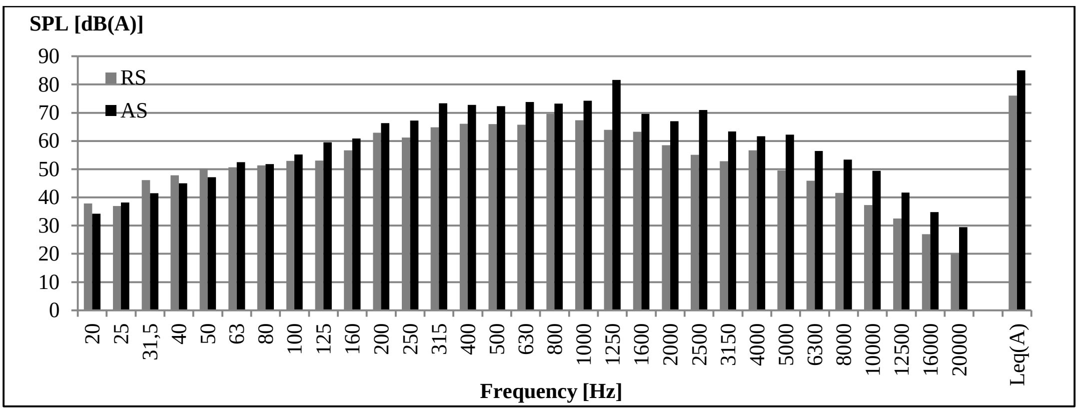


Fig. 3. Results of Constant Percentage Bandwidth (CPB) analysis for two selected samples

To show the high degree of acoustic annoyance during tram passage, the psychoacoustic objective metrics were calculated. The comparison of reference and annoying sound samples was carried out in terms of the acoustic comfort (annoyance) issue. The loudness N, sharpness S, roughness R, fluctuation strength F and tonality T parameters are shown in the Table 1. All parameters were calculated in accordance with the DIN 45631 standard (Standardization 2010) and the Zwicker assumptions (Fastl & Zwicker 2007). Indicators are estimated as the root mean values. The value N_5 is the loudness which is reached or exceeded in 5% of the measurement time, so this means that N_5 represents a loudness value close to the maxima of the loudness-time function of the noise emission (Fastl & Zwicker 2007). Furthermore, the psychoacoustic parameters were used for the psychoacoustic annoyance (PA) indicator evaluation (Fastl & Zwicker 2007), shown in the Table 1. The PA can quantitatively describe annoyance ratings obtained in psychoacoustic experiments and it is defined as equation (1):

$$PA = N_5 \cdot \left(1 + \sqrt{w_S^2 + w_{FR}^2}\right) \quad (1)$$

where:

- N_5 is percentile loudness [sone]
- $w_S = \left(\frac{S}{acum} - 1.75\right) \cdot 0.25 \lg\left(\frac{N_5}{sone} + 10\right)$
- $w_{FR} = \frac{2.18}{\left(\frac{N_5}{sone}\right)^{0.4}} \cdot \left(0.4 \cdot \frac{F}{vacil} + 0.6 \cdot \frac{R}{asper}\right)$

It can be concluded that w_S and w_{FR} describe the influence of sharpness, roughness and fluctuation strength on the PA value. However, the loudness indicator has the strongest impact on the final result of the PA. Thus, the two loudness curves (the AS and RS) in the time function are shown in the Fig. 4. Few temporary loudness values are higher than 70 sone, which can be compared to lawn mower noise measured in a near field.

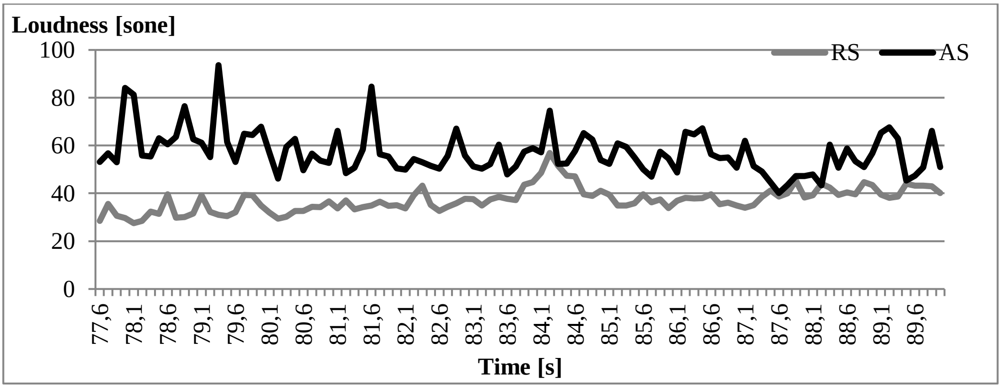


Fig. 4. Loudness curves for the AS and RS samples in the time function

Table 1. The psychoacoustic parameters for selected samples

	Loudness [sone]		Sharpness [acum]	Roughness [asper]	Fluctuation strength [vacil]	Tonality	Psychoacoustic Annoyance
	N_5	N	S	R	F	T	PA
The AS sample	77.58	67.10	1.40	1.52	2.43	0.11	135
The RS sample	46.87	40.70	1.22	1.56	1.21	0.06	80

There are significant differences in a few objective psychoacoustic metrics between the AS and RS samples, especially in the loudness, fluctuation strength and tonality parameters. It shows the high degree of tonal character sound components around the 1-2.5 kHz frequency bands, which can be an unpleasant sensation for passengers. The last evaluation of acoustic annoyance during the tram passage is the PA comparison. The PA of the AS sample is over 55 units higher than the PA of the RS sample. It confirms the significantly higher degree of uncomfortable ride conditions inside a few trams of this type.

3.2. Vibration signals - A general comparison of two journeys

To measure the overall dynamic interactions of both vehicles, root mean square values for vibration acceleration (a_{RMS}) was calculated in the band of 3.2 kHz which is the determined measuring range of transducers with linear averaging. The results for each measurement point of both vehicles are shown in Table 2.

Larger values at each measurement point were observed during vehicle #1's journey. The biggest difference (around 80%) between vehicles was observed at the left point in the horizontal (Y) direction, perpendicular to the tram's movement. For floor (X) and right (Y) points, this difference was also significant at around 75%. At the other points, the difference was about 40-55%. During passage, the highest vibration acceleration values for #1 were observed for the left (Y) point, while for the #2 it was the left (Z) and was 50% lower.

The above analysis indicates significant quantitative differences between selected journeys. The tram with degraded acoustic properties demonstrates increased dynamics especially in the transverse direction (Y).

Due to the aim of this study concerning the connection of adverse acoustic phenomena to the operating quality of articulation, we focused on the qualitative analysis of measurements made during #1's journey.

Firstly, a qualitative analysis of the audio signal from passage #1 was carried out in order to learn its structure. Frequency-based analysis was performed using the Fast Fourier Transform to measure the variability of the signal spectrum over time and the average spectrum. All analysis was carried out in a full, useful frequency band of the transmitter up to 3.2 kHz. The results are shown in Figure 5.

Table 2. Root mean square values for vibration acceleration

	a_{RMS} #1	Percentile [%]	a_{RMS} #2	Percentile [%]	$\Delta_{\#1,\#2}$ [%]
Left (Y)	0.83	100%	0.14	25%	83.1%
Left (Z)	0.66	50%	0.39	100%	40.9%
Floor (X)	0.47	0%	0.11	0%	76.6%
Right (Y)	0.69	75%	0.17	50%	75.5%
Right (Z)	0.57	25%	0.25	75%	56.1%

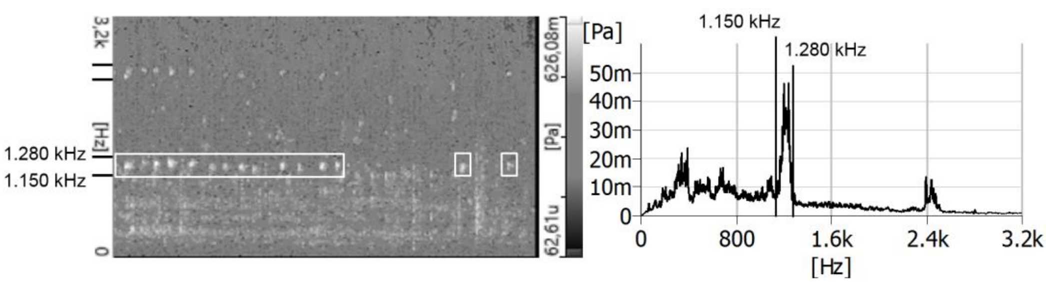


Fig. 5. The FFT spectrum with frequency correction A: the FFT in time (left), the FFT averaged (right) for microphone signal from passage #1

Listening to the signal, as well as its qualitative analysis indicates that the frequencies of the squeaks are in the band 1.150-1.280 kHz. In the 2.4 kHz band, higher amplitudes corresponding to the second harmonic were observed. A broadband frequency boost around the bands of 250-400 Hz and 450-800 Hz was observed in the spectrum of the microphone's signal. Ultimately, three frequency ranges with high acoustic pressure were obtained, as shown in Table 3 along with a description.

Table 3. Frequency bands for elevated amplitudes of acoustic pressure levels

Number of bandpass	Frequency
Bandpass 1 (B1)	250-400 Hz
Bandpass 2 (B2)	450-800 Hz
Bandpass 3 (B3) *Highest spectrum amplitude (squeal)*	1150-1280 Hz

The individual signals have been filtered according to the frequencies in Table 3. Then, for this data, a statistical analysis was performed starting with a normality test using K-S, Lilliefors and Shapiro-Wilk normality tests. These test statistics provide the basis for concluding that the data analysed does not have a normal distribution.

For filtered groups of signals from three frequency bands, a moving RMS value with a linear time window of 125 ms was calculated. Due to the nonparametric data, correlation coefficients for rank order variables were calculated to examine the relationship between the vibration signals and the acoustic signal. For this purpose, Spearman's rank correlation coefficients (r_s) were calculated according to the equation (2):

$$r_s = 1 - \frac{6 \cdot \sum d_i^2}{n\left(n^2 - 1\right)} \quad (2)$$

where:

$d_i^2 = (R_{i,x} - R_{i,y})^2$

$R_{i,x}$ – i-*th* rank of x variable

$R_{i,y}$ – i-*th* rank of y variable

The individual values of the coefficient r_s are shown in Table 4. The presented results show a significant relationship between the acceleration at the left point for both Y and Z directions and the floor point (X), with sound pressure levels at the Mic point.

Table 4. Spearman rank coefficients for filtered signal groups

	B1	B2	B3
	r_s	r_s	r_s
Left(Y) – Mic	0.57	0.41	0.76
Left(Z) – Mic	0.53	0.39	0.70
Right(Y) – Mic	0.41	0.34	0.48
Right(Z) – Mic	0.54	0.36	0.50
Floor(X) – Mic	0.40	0.54	0.72

In the other frequency bands B1 and B2, the relationship between the observed signal groups cannot be identified. The results indicate that the quality of work carried out by the #1 articulation during passage is related to the increased dynamics of the middle tram segment at all analysed measurement points.

4. Extending the tram maintenance system

In light of the obtained results, it therefore becomes essential that: the technical operating system of the trams (Ω_E) consists of a set of service systems (S) and a set of usage activities (U), as shown in the following formula:

$$S,U \in \Omega_E : S \notin U \quad (3)$$

A set of service system usually consists of a set of service operations (O) and a set of cleaning operations (C), which then divide into individual components (x_n). Examples of these operations are shown below:

$$O=\{x_M, x_E, x_{HP}\} \quad (4)$$

$$C=\{x_{CW}, x_{CZ}\} \quad (5)$$

where:

x_M – mechanical maintenance,

x_E – electrical maintenance,

x_{HP} – hydro-pneumatic maintenance,

x_{CW} – cleaning operations inside the vehicle,

x_{CZ} – cleaning operations on the outside of the vehicle.

Currently, servicing the tram does not include monitoring for emissions of vibroacoustic phenomena after restoration of operational properties of trams. Checking for these phenomena upon completion of servicing would allow for possible detection of irregularities which could increase the sound levels around the articulation. One example of these irregularities could be the incorrect setting of clearance in individual kinematic pairs, or an incorrectly diagnosed condition of the articulation bridge and cover. It is therefore necessary to include tests that verify the correct implementation of service procedures based on vibroacoustic phenomena (x_{WA}), thus extending the service system (S_E), as shown in the following expression:

$$S \rightarrow S_E \leftrightarrow \{x_{WA} \in O{:}O \in S \wedge C \in S\} \quad (6)$$

Verification in an extended system should include, for example, sound measurements or organoleptic sound assessments carried out by an experienced worker located on the articulation during a test drive within the premises of the depot. This would make it possible to determine the sound levels in the most demanding technical conditions, for example driving on bends with small radii, which causes significant movement between individual tram segments.

5. Conclusion

The studies show that the tram with degraded acoustic properties is characterized by a significantly higher sound quality index, which results in increased acoustic annoyance. This is closely related to the vibration phenomena caused by the working elements of the articulation and was found in carriages tested during the passage of the tram.

The everyday choice made by residents to use urban rail transport as a means of transportation helps to streamline the transport process in the city. This is related to better traffic flow through reducing traffic congestion, ecological benefits and increased mobility of the residents. To maintain this trend, it is important to plan user-friendly routes, and provide good ride comfort. Comfort can be expressed in aesthetic, thermal and vibroacoustic aspects. The latter can be influenced by the technical condition of the vehicle, and in this case, especially the quality of the articulation. Its deterioration can result in significantly increased acoustic annoyance, which in extreme cases may result in travellers choosing other means of transport.

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