ARCHIVES OF ACOUSTICS
Vol. 44, No. 4, pp. 783–792 (2019)
DOI: 10.24425/aoa.2019.129733

Developing Assumptions for the Tram Noise Attenuation Passive System Using the Noise Maps Analysis Method

Tomasz NOWAKOWSKI*, Bartosz FIRLIK, Tomasz STAŚKIEWICZ

Poznan University of Technology
Piotrowo 3, 61-138 Poznan, Poland
e-mail: bartosz.firlik@put.poznan.pl, tomasz.p.staskiewicz@doctorate.put.poznan.pl
*Corresponding Author e-mail: tomasz.zb.nowakowski@doctorate.put.poznan.pl

(*received January 21, 2019; accepted September 11, 2019*)

The paper presents experimental research carried out to determine the possible actions to reduce the noise generated by trams in a highly urbanised area. A few design strategies affecting tram ride quality have been presented – especially in the aspect of the acoustic phenomena. Main sources of the noise in trams were characterised. The paper includes selected results of comprehensive studies of tram noise in the pass-by test based on the authors' research methodology. The tests were carried out on various types of trams to recognise the acoustic phenomena characteristic for the rolling stock in a selected tram system. The results of the measurements were analysed both in the field of amplitudes based on noise maps and in respect to frequencies based on noise spectra. The results indicated the rolling noise as important issue demanding taking some actions in order to reduce its level. In this area, elements for the application of individual attenuation solutions, i.e. at the source and during propagation, were presented. The results of the measurements were used as input data to the assumptions of the noise attenuation passive system, which was the final outcome of the study. Dedicated external dampers were used in the case of wheel and rail pairs, where the dominant power of the noise is emitted. The acoustic properties of the bogie area and the bogie side covers were redeveloped to hamper the noise propagation, which is a novel application. The presented results indicate measurable benefits from the applied solutions on the tram noise reduction.

Keywords: tramway; noise; rolling noise; bogie covers; noise maps.

1. Introduction

The main concept of the tram should refer to a reliable implementation of the transport process, also providing positive vibroacoustic features of the vehicle. The strategy should assume the emphasise on noise and vibration reduction – at the early stage of project evaluation (Niziński, Żółtowski, 2002). This particularly applies to specifying the product definition (Hubka, 1991), in particular with regard to legal characteristics, i.e. in compliance with the requirements of legal acts and standards. In Poland, the only condition related to acoustics currently permitting a tram to ride, is the equivalent sound level measured during pass-by test (Polish Minister of Infrastructure, 2011). However, the positive vibroacoustic features should be characterised not only by meeting the requirements of the regulation, but also by minimising the negative impact on the environment, regarding noise and vibration. Attention to these phenomena also results from the regulation of Polish environmental law and European Commission White Paper (European Commission, 2011). The discussed phenomenon – traffic noise, is classified as a kind of air pollution and is the main source of noise in the cities (Miedema, Van der Berg, 1988; Engel, 2001; Mandula *et al.*, 2002; Leśnikowska-Matusiak, 2014). This contamination has a number of negative effects, which may manifest themselves in the form of sleep disorders, anxiety disorders, general irritability, hearing impairments, and problems with the circulatory system caused by stress (Berglund *et al.*, 2000; European Parliament, 2002; Pawlas, 2015; Cik *et al.*, 2016). The noise of trams is widely considered in terms of annoyance, which is particularly important in urban areas (Kaczmarek *et al.*, 2006; Popescu, Moholea, 2010; Hume *et al.*,

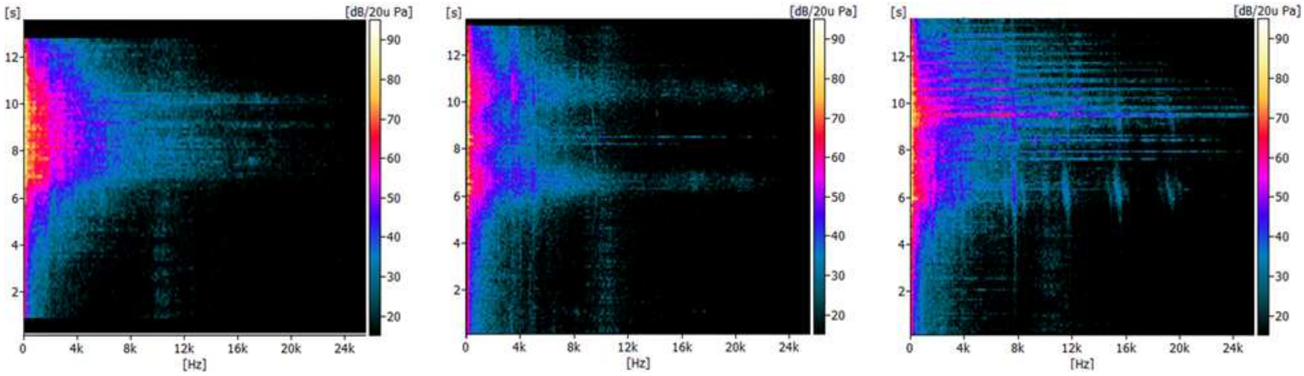

Fig. 1. Acoustic signatures up to frequency 25.6 kHz at constant speed 25 km/h; from the left: Düwag GT8, Solaris Tramino, Moderus Tatra.

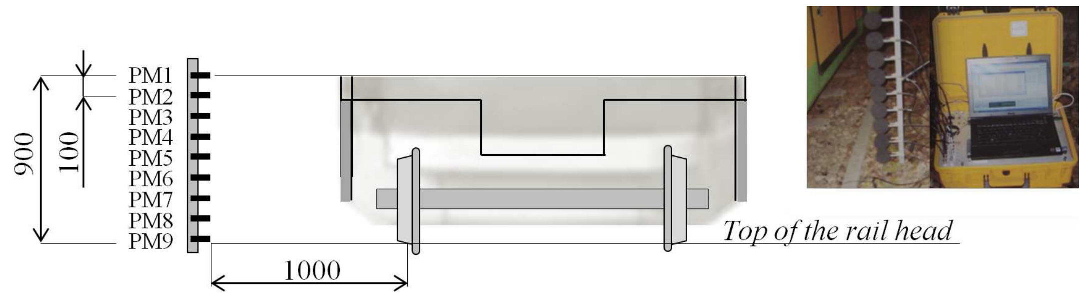

Fig. 2. View of the microphones array with the layout diagram on the measurement stand: PM1–9 – measurements points.

2012; Pawlas, 2015). The reduction of noise emission, which may contribute in total to lowering the daily equivalent sound level in the city (Fidell *et al.*, 1991; Berglund *et al.*, 2000), is an important issue for the quality of residents' life, definition in (Róg, 1992). The problem of the noise in the cities is so important that real time noise monitoring networks in cities are also being used (Sanchez-Sanchez *et al.*, 2018).

Regardless of the type of tram and its operational characteristics, the wheel and rail noise is the dominating sound source of the rolling stock (Madej, 2001; Hemsworth, 2008; Thompson, 2008; Lakušić *et al.*, 2011; Czechyra, 2012, 2013; Panulinova *et al.*, 2016). It depends inter alia on the design of the running gear, be it its motor or trailer bogie. An important issue is also the dynamic wheel loads resulting from the external excitations and vehicle design. Traction motors located close to wheels make another important source of the noise. Taking into account often contradictory technical requirements set for the drive system, in this area, in the first stage of product development, it is usually power demands that come as a priority. Also inverter assemblies used in modern trams constitute a group of electroacoustic sources. Differences in acoustic effects can be read directly from time-frequency spectrum constituting acoustic signatures of trams (Fig. 1) (Golay, 2008; Czechyra, Tomaszewski, 2009).

Electroacoustic sources are visible in the middle and right side drawing (Fig. 2) as the parallel components in the form of elongated artifacts, parallel to the time axis, which results from strong modulation of signals. These analyses are also presented in more detail in (Czechyra, Tomaszewski, 2009). In the analysis of vibroacoustic phenomena, special attention should be paid to boundary conditions depending, among other things, on the vibroactivity of track types (Targosz, Adamczyk, 2010; Nowakowski, Tomaszewski, 2017).

2. Research methodology

Due to the highlighted problem areas related to noise generation, research related to their minimisation at the stage of the tram design was undertaken. The areas of minimisation were focused on the issues of rolling noise, which in contrast to electromechanical sources is possible to model, interfering with the basic structure of the tram.

Results of the experimental tests carried out on representative types of trams were used as input data for changes in their structures. The tests included sound measuring arrays located in highest possible proximity to the wheel and rail contact (Fig. 2). Analysis of the obtained data was carried out in the time domain (noise maps), and in the frequency domain (noise spectra).

The first part of the research was the measurement of the sound levels on a selected tramway track in Poznań (Poland), which constitutes a straight, separated, ballasted track on concrete sleepers without additional noise-damping elements. The sound was recorded during the pass-by test of three different low floor trams – Siemens Combino, Solaris Tramino S105p, and Solaris Tramino S100 (the prototype version of the S105p model). Such a comparison was aimed at comparing the properties of typical low floor trams used by the local operator – "MPK Poznan". Each tram performed three passes for each constant speed: 20 km/h and 50 km/h. The results obtained were averaged for each speed. First microphone of the array was placed on the top of rail level. The spacing between the microphones was 100 mm each, so the last one was located 900 mm above the top of the rail. This allowed to cover the whole height of the bogie area, which is supposed to be one of the main sources of sound. Acquisition of signals was carried out through a PULSE® multichannel system from Brüel & Kjær.

The next part of the research was the development of a tram noise attenuation passive system based on the conclusions from track-side measurements and dedicated analysis of damping issues. In the last stage of the research, validation measurements were done to assess the effectiveness of the developed system.

3. Results and analysis

3.1. Analysis in the amplitude domain

Noise maps for the tested trams were obtained, which were imposed on the contours of vehicles for clear visualisation of the results. Signals were recorded and adjusted by the A frequency-weightings. The analyses were carried out for two speeds: 20 km/h and 50 km/h, which differ in terms of the main noise sources. For 20 km/h, the main sources relate to power supply equipment, and for 50 km/h to rolling noise (Hemsworth, 2008). Figure 3 shows that among low floor trams passing at a speed of 20 km/h, Solaris Tramino S100, (the prototype version of the S105p model) results in many areas in navy blue color that means lower sound levels, ca. 65 dB(A). Sounds of a slightly higher level were generated by the Siemens Combino tram, which is a design from 2003–2004. Solaris Tramino S105p, as a construction from 2011 in this combination looks the least favorable and generates the highest level of sound.

In the case of the Combino model, sound level of 85 dB(A) was already achieved in segments without bogies and behind the last bogie. Model S105p reached level 85 dB(A) on the entire length, and in addition it is interlaced with bands at the level of 90 dB(A). Bogies are the main sound generators, among the three vehicles, at the speed of 20 km/h, S100 model achieved the lowest sound level, i.e. 90–95 dB(A). S105p model achieved the highest sound level, up to 100 dB(A). In the case of Combino maximum sound level is 100 dB(A) in the last and middle bogie, and for the first bogie it is up to 95 dB(A). In the case of trams S100 and S105p, the areas of sound with a higher and constant level are clearly visible on the entire measuring height (in the form of stripes). In the case of Combino, they are more disrupted, especially in the first bogie. Moreover, only the S105p model clearly shows sound levels as high as 85–90 dB(A) outside the area of bogies. For Combino, the areas outside the bogie are at the level between 80–85 dB(A). The most homogeneous level below 75 dB(A) in this area was observed for the S100 tram.

Figure 4 shows noise maps for the ride speed of 50 km/h of the three trams. The sound level generated by the Combino tram at the speed of 50 km/h increased significantly. In the case of the wheel and

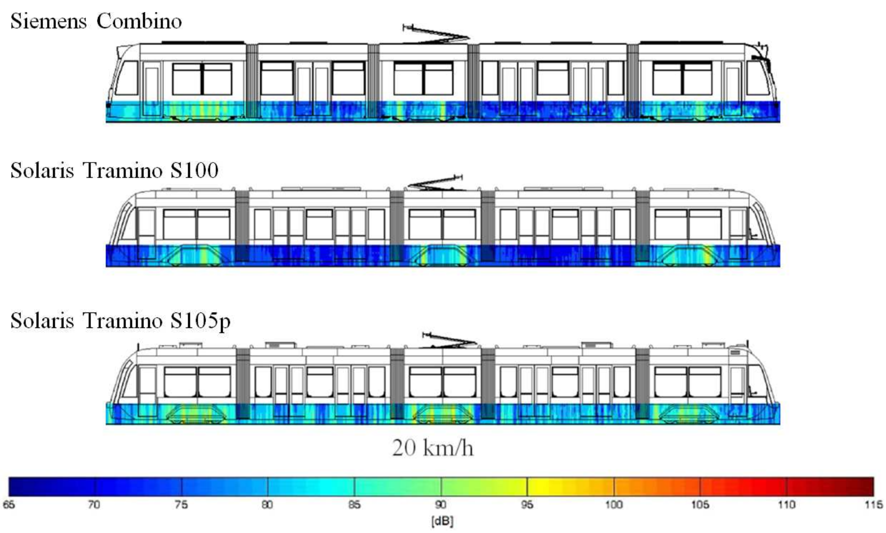

Fig. 3. Noise maps of Siemens Combino, Solaris Tramino S100 and Solaris Tramino S105p (speed 20 km/h).

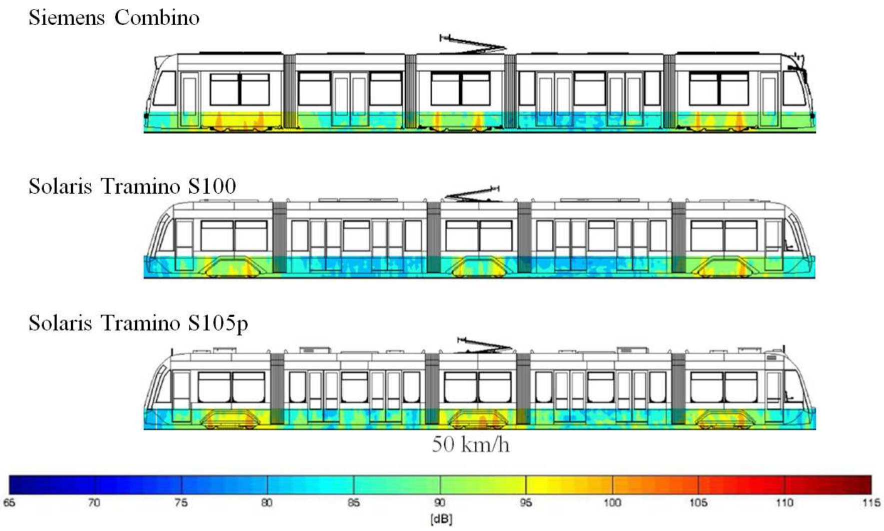

Fig. 4. Noise maps of Siemens Combino, Solaris Tramino S100 and Solaris Tramino S105p – speed 50 km/h.

rail contact, the sound level was around 100 dB(A), and at some points the tram reached even 110 dB(A). Beyond the bogies, the vehicle reaches the level of 85–95 dB(A). In addition, it has an elevated sound level over 95 dB(A) over the entire area of the last bogie. This bogie definitely stands out from the others. The S100 maintains good acoustic characteristics at the speed of 50 km/h. The maximum achieved sound level was equal to 103 dB(A), for the wheel and rail contact. However, still the major part of the bogie areas generate sounds lower than 95 dB(A). Areas between bogies reach the level of even 75 dB(A), which was not the case in other trams. A large part of the noise map for the S100 tram is around 80 dB(A) level, while in other vehicles these are small areas. In the S100 model, the sound level of 90 dB(A) was mainly observed for the bogies, while in the S105p and Combino models it is present in the entire vehicle.

In the case of the S105p model, it is easy to see the influence of speed on the change of sound levels which increased significantly at 50 km/h. For the S105p vehicle, the sound level was 85 dB(A) or more, although it reached lower values at several points. The bogies generated maximum sound level of 108 dB(A). The areas outside of bogies were characterised by noise at a similar level as in the Combino vehicle. On the rolling bogie of the S105p tram the sound level increased in the middle part, 92 dB(A).

3.2. Analysis in the frequency domain

The acoustic signals obtained from the tests were analysed in the frequency domain using the Fast Fourier Transform (FFT) algorithm and presented in the form of tertiary-time-spectrum maps. In this case, only the Solaris Tramino S105p trams, which is a serial construction and is important from the point of view of the implemented project (existing plans for further development of this platform by Solaris), were analysed. The following speed of 50 km/h was taken into consideration and two configurations were included: with and without bogie covers. The results obtained during the experimental research have a matrix form. The ordinate axis is made up of frequencies – from 20 Hz to 20 kHz. The abscissa is the time, measured every 125 ms. The sound levels are presented with colours. The data were processed using the previously described methods of visualising the sound. Due to the high number of data, only signals from the selected microphones (first: PM1 and last: PM9) were presented.

Figures 5, 6, and 7 present the results obtained at the speed of 50 km/h without and with bogie covers. In all cases, the characteristic areas where the sound level is the greatest (red colour), were areas corresponding to bogies. In addition, the darkest areas corresponding to the highest levels are more extensive for passages with bogie covers. In lower frequencies, the values are very similar. Visualisation of the signal for the speed 50 km/h for microphone 1 (Fig. 5) for both cases is mostly a homogeneous, darker area in the range of 200–8000 Hz. In particular, this applies to a vehicle without covers, where the sound level above 60 dB(A) has already been obtained at 50 Hz. At 160 Hz it has exceeded 70 dB(A), and from 1500 Hz it already extends over the entire length of the tram. For a vehicle with covers sound level above 70 dB(A) creates three intense areas recorded at 630 Hz. Particularly visible are the parts depicting the extreme bogies. In the areas behind the first and before the third bogie, approx. 60 dB(A) are achieved already at 125 Hz. In other areas, both left and right, the sound remains between 30 and 40 dB(A), only at the lowest frequencies the front of the vehicle gets quieter, up to 20 dB(A).

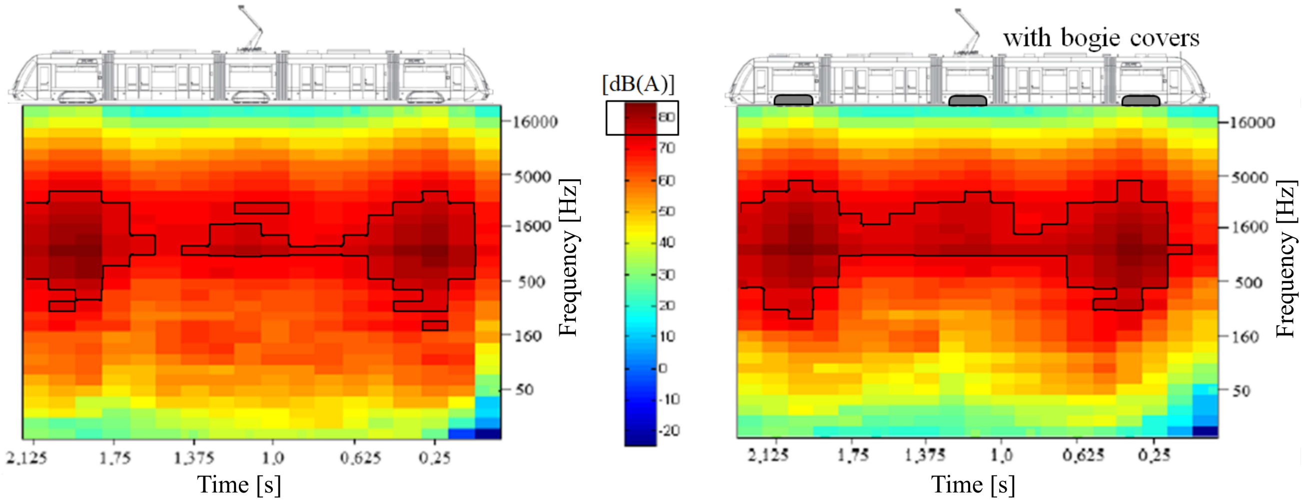

Fig. 5. Microphone No. 1, speed 50 km/h.

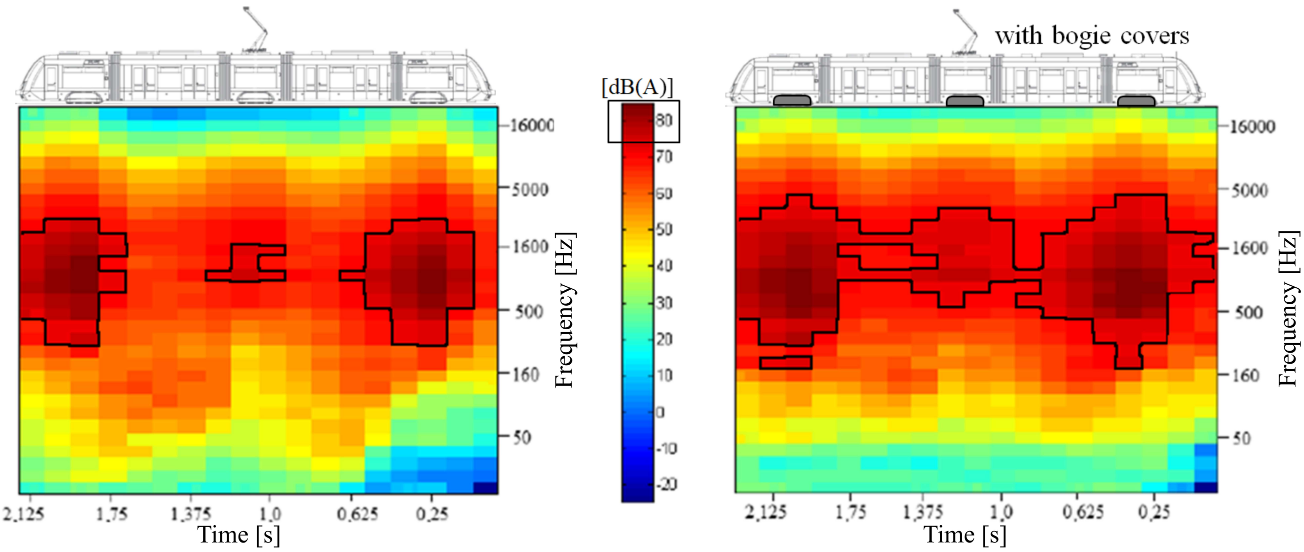

Fig. 6. Microphone No. 9, speed 50 km/h.

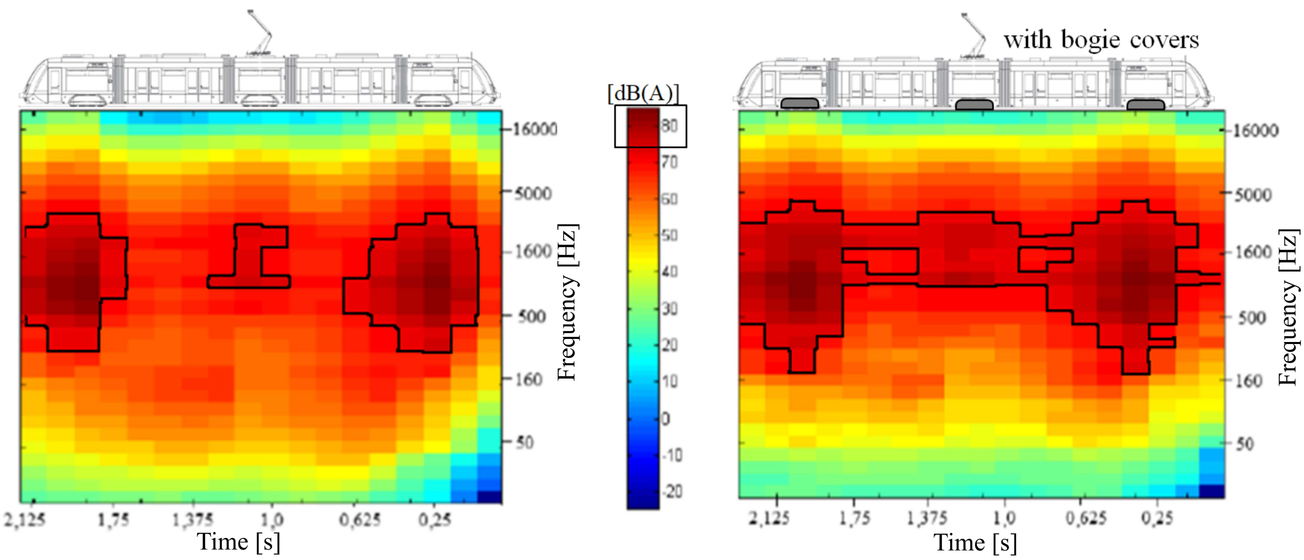

Fig. 7. Average results for all microphones, speed 50 km/h.

For the signal from the last microphone, the visualisation is very similar for both options (Fig. 6). The loudest points occupy a similar area, hence they form a similar shape. However, on the left, the phenomenon is a bit more extensive, mainly for lower frequencies. Differences in this area are the most visible. Only for the image on the left, the sound level reduction in the middle of the vehicle remains within a slightly wider time range.

In addition, sound levels between 50 and 60 dB(A) are achieved at slightly higher frequencies. For the image on the right, the level of 25 dB(A) occurs for ever higher frequency bands, reaching 40 Hz. The darker spot around the second bogie loses on clarity and depth. The middle bogie slightly stands out. On the left, the level of 20–30 dB(A) appears only in the front part of the vehicle, while on the right it extends over its entire length. The level of 0–10 dB(A) on the left was recorded in a greater number of points, at the lowest of frequencies. On the right there are several such readings located only in the first measurement element, even though for a wider frequency range. Invariably, for both runs, at 20 kHz, the sound remains at 25 dB(A). The average sound level from all microphones (Fig. 7) gives a fairly fuzzy colour area for the vehicle without covers, but with the selection of motor bogie. When the covers are mounted, a wide, dark strip located in the middle of the examined frequency band is a visualisation of the elevated sound level. In this case, it is also possible to indicate the elements of the running gear. In both options, similar values of the sound signal occur at 20 kHz. In the lowest band on the right, these are mostly readings with levels between 35 and 40 dB(A), while on the left this range is wider.

4. Developing the sound attenuation passive system for tram

The conducted research allows to develop a passive system based on the following assumptions:

1) adequate tuning of wheel vibration dampers used in the tram in close cooperation with the wheel supplier and development engineers of the running gear,
2) taking into account the need to meet the requirements of vehicle gauge, and to avoid direct, unwanted contact of absorbing/reflecting materials with the parts of the bogie,
3) utilisation of the tram structure to achieve good acoustic performance.

4.1. Damping in the wheels

Currently, resilient wheels are commonly used in tram engineering, which damp (to some extent) the vibrations due to a dedicated design. The vibrations are damped due to the embedding between the wheel disc and its rim with susceptible elements. Separation of the rim from the web with a rubber insert at a damping frequency below 1200 Hz reduces the rolling sound and minimises all the vibrations of the wheel web (Bouvet *et al.*, 2000). Increasing the frequency of damping will gradually increase the sound emitted by the rail, undermining the limitation of the sound emitted by the wheel (Suarez *et al.*, 2011). Similar conclusions also arise from other studies (Esteban *et al.*, 2006; Betgen *et al.*, 2012).

Depending on its design, the wheels may also be equipped with external damping, i.e. vibration damping systems arranged on the circumference of the wheel. Numerous studies on the impact of external damping indicate a clear reduction of sound emitted by the wheel, especially in the case of high frequency sounds when passing curves (Lopez *et al.*, 2000; Vinolas *et al.*, 2007).

The authors indicate that even though the reduction of the total sound power is not very large, when analysing the graphs for the emission of the wheel itself, it is easy to notice a significant reduction in the sound power of up to 15 dB(A) for the wheel with damping plates and 25 dB(A) for the wheel with layer silencers relative to the wheel without damping, especially when passing curves, as shown in (Merideno *et al.*, 2014). The wheels on the test tram were equipped with internal circumferential damping elements. In order to improve the sound minimising effect, external damping has been additionally applied in the form of specially developed, screw-in anti-resonance silencers. Guidelines for desirable characteristics of structural vibration dampers of the wheel web, taking into account damping in the range from 500 Hz to 5 kHz, have been met by the wheel supplier. An exemplary view of the wheel with the vibration damper installed is shown in Fig. 8.

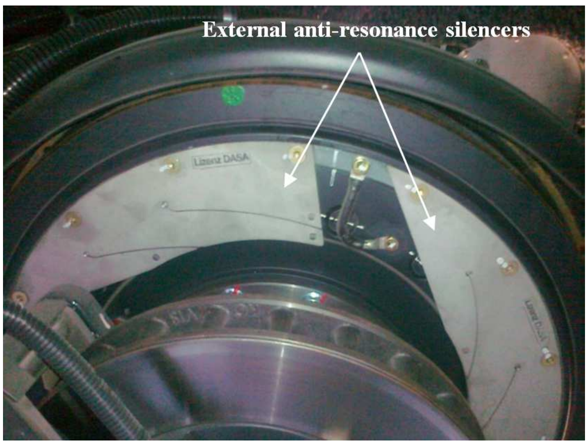

Fig. 8. Wheel dampers.

The effectiveness of the wheel dampers for the squeaking in the curve due to micro slip, was evaluated

Table 1. Efficiency of wheel vibration dampers.

	Motor bogie		Trailer bogie	
	Left wheel [dB]	Right wheel [dB]	Left wheel [dB]	Right wheel [dB]
Without dampers	92.6 ± 0.4	88.1 ± 0.4	76.3 ± 0.4	76.5 ± 0.4
With dampers	85.2 ± 0.4	84.5 ± 0.4	72.4 ± 0.4	72.8 ± 0.4
Results	−7.4 ± 0.4	−3.6 ± 0.4	−3.9 ± 0.4	−3.7 ± 0.4

during the tests in real conditions. Measurements of sound during driving were taken directly at the wheels. The tests were conducted on a representative track in the left curve under constant driving conditions. The measurements were taken from the first (motor) and second (trailer) bogie of new Solaris Tramino S111o tram, the results are presented in Table 1.

As it can be seen from Table 1, the sound reduction efficiency for the most adverse conditions (motor bogie, curve) is significant, and the reduction of the equivalent sound level was from 3.6 dB(A) to 7.4 dB(A).

4.2. Bogie covers

In the modern rail vehicles, in order to reduce the sound emission, running gears are protected by external bogie covers. Currently in Poland more than half of almost 4000 trams in total are operated without bogie covers – this mainly applies to old Konstal 105Na tram and its derivatives. About 26% of the bogie covers are mounted directly to the bogie, and about 19% of them make an integral part of the body. Bogie covers often do not have proper characteristics to attenuate the sound. The only function that is partially fulfilled by them is reflection of sound propagating into the environment back to the vehicle (Fig. 9). This functionality can be justifiably questioned in the case of using laminate covers. Due to their structure in the extreme case, they themselves can be a source of secondary acoustic signals, resulting from vibrations caused by passages on unevenness and vibrations of the bogie frame.

Fig. 9. Selected designs of bogie cover.

In the test tram, the structural and functional conditions made the covers attached to the bogie. Additionally, due to technological and economic reasons, the primary material of the cover was a composite made of a steel frame and a laminate.

The standard (laminate) cover has been enriched with acoustic functions through the application of a polymer damping material with mineral fillers (Fig. 10). Fixing with a flexible glue of previously prepared 10 mm thick acoustic panel to the inside of the cover was applied.

Fig. 10. Laminate bogie cover.

Tests on the new bogie cover were carried out in the same way as for the tests in Subsec. 3.2. Improved covers were mounted on the first motor bogie and compared with the next motor bogie (last one) equipped with standard covers. The results of the measurements are shown in Fig. 11.

The use of an improved bogie cover allowed significant sound attenuation at the level of 5–15 dB(A) depending on the frequency range (mainly in the range of 630–1600 Hz).

4.3. Bogie areas

As part of preventive activities aimed at minimising the penetration of sound into the vehicle interior it is a common practice to cover the floor from the underside with bitumen materials. The structure of this coating may have secondary functions of sound scattering through diffraction on its surface, but this phenomenon is considerably limited. In some modern

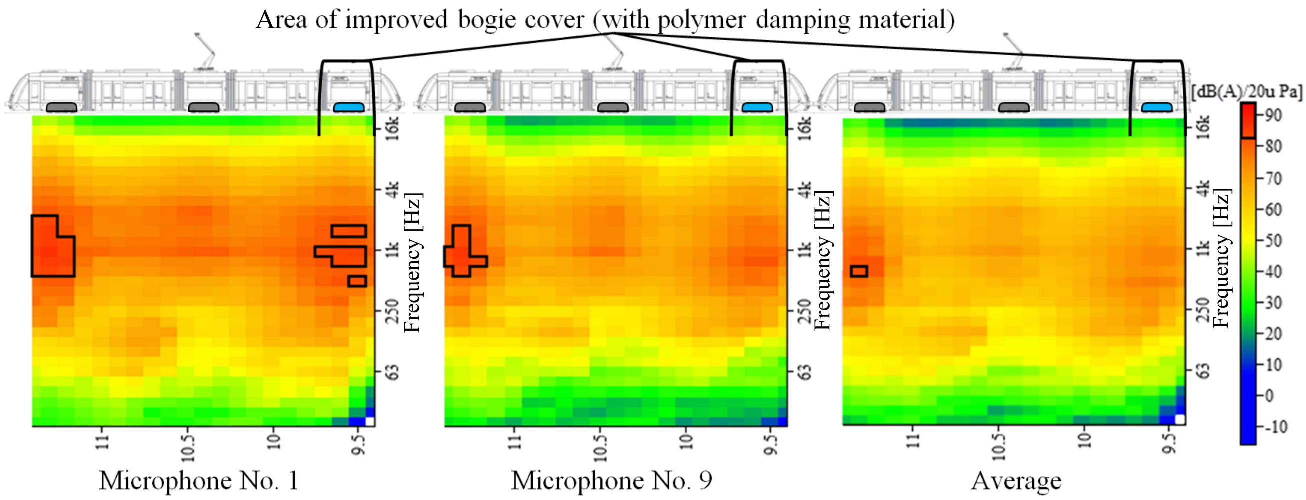

Fig. 11. Results for microphone No. 1 and No. 9 and average results of all microphones, speed 50 km/h.

constructions, there are other expositions of area above the body.

Laboratory tests of two materials were carried out, whose physico-chemical properties enabled their application on a rail vehicle. The tests were carried out using the author's own testing method in a divided acoustic tunnel. The tunnel was divided by a barrier in the form of tested damping material forming two parts of the tunnel. Signals were recorded in a part of the tunnel with the sound source (white noise, L_{Aeq} = 100 dB, t = 32 s) and in a part of the tunnel behind the barrier. The main purpose of the research was to assess sound attenuation using damping material. The analysis of sound attenuation of tested materials was based on difference in sound levels in individual CPB spectrum bands of acoustic signals recorded by microphones. The test results for material "M" (melamine foam) and material "P" (closed cell polyethylene foam) are presented in Fig. 12.

In the case of the material "M", the highest values of attenuations exceed the value of 11 dB(A) and occur in the 200 Hz and 20000 Hz bands. In addition, there is a sound attenuation of up to 5 dB(A) in the 31.5–125 Hz and 500 Hz bands. For the 3150–10 000 Hz frequency range, the attenuation level was up to 3 dB. The "P" material shows no attenuation in the 80–100 Hz and 500 Hz bands, giving the gain from 4.4 dB(A) to 8 dB(A).

In the low frequency bands 20–63 Hz and 160 Hz, the attenuation is relatively low up to 3 dB(A). Significant attenuation occurs in higher frequency bands above 5000 Hz and ranges from 15.2 dB(A)to 60.6 dB(A).

Taking into account the obtained results, material "P" with the structure of pressed plates is used. An example of such a solution is presented in Fig. 12.

The used material has ribs which have acoustic features other than the reflection of the sound wave. In the analysed area, closed cell polyethylene foam was used. As for the method of installing this material, it was decided to mechanically connect it with the load bearing elements of the body structure. This material is spot mounted, allowing the creation of local airbags between the front of the material and the walls of the vehicle. This action allowed to cause and use multiple reflections of the sound wave: falling on the front part of the bogie area, passing through it, reentering the free space (air cushion), and falling on the wall, the wave is reflected and directed in the opposite direction.

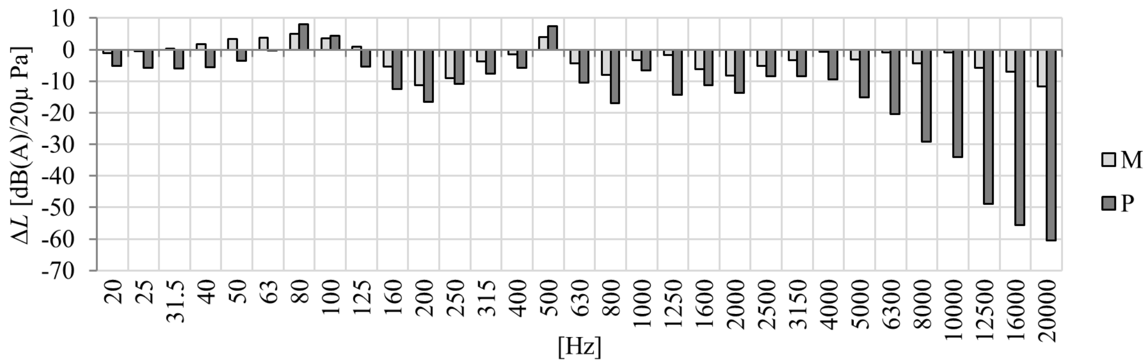

Fig. 12. Sound attenuation of materials in CPB spectra.

Fig. 13. View of area under bogie.

5. Conclusions

The results of the experimental research clearly show that from the acoustic point of view the most demanding area is that of the tram bogie, where the highest sound levels are generated. The research indicated that the S100 and S105p models differed significantly in terms of noise maps for all tested speeds despite their closely related design. For 20 km/h, the lowest levels of 90–95 dB(A) were observed for S100 and the highest one was for S105p – 100 dB(A). The S100 tram appeared to be less noisy, by around 5 dB(A) in the bogies sections and by around 10 dB(A) for the remaining areas of the vehicle. Frequency studies indicate that the critical frequency range regarding sound levels falls within the range of 500–5000 Hz. This is the frequency range that should be considered first to minimise the generated sound energy.

Due to technical limitations regarding sound absorbing systems design and a very complex spectrum of the generated sound, there is no possibility to apply active sound reduction appliances influencing sound propagation. For this reason, the authors focused on the passive noise attenuation solutions. Possible activities may focus on the design of bogie covers enhanced with acoustic attenuation properties, e.g. through application of damping materials. Actions should also be directed towards increasing the acoustic absorption of the car body surface facing the bogie by introducing sound absorbing covers with internal attenuation properties. The improved bogies covers, suggested in this paper, allowed for a significant noise reduction by 5–15 dB(A) in the band of 630–1600 Hz. Noise reduction at higher frequencies may be achieved by using sound attenuating material in the area of the bogie. The attenuating material used in this study resulted in noise reduction for frequencies above 5000 Hz by up to 61 dB(A).

The presented and applied technological solutions allowed to realise the double goal of the research project in the aspect of minimising the sound generated by the tram. The passive sound attenuation system for tram was developed as a standard procedure for managing the vibroacoustic activity of the tram and subsequently was implemented for production.

Acknowledgment

All work was realised as a part of the research project "Innovative package of subsystems improving the functional and operational properties of light rail vehicles" (POIG.01.04.00-30-336/13), financed from the European Regional Development Fund under the Innovative Economy Operational Program.

References

1. Berglund B., Lindvall T., Schwela D.H. (2000), *Guidelines for community noise*, World Health Organization, Geneva, https://apps.who.int/iris/handle/10665/66217.
2. Betgen B., Bouvet P., Thompson D., Demilly F., Gerlach T. (2012), *Assessment of the efficiency of railway wheel dampers using laboratory methods within the STARDAMP project*, Proceedings of the Acoustics 2012 Nantes Conference, Nantes, pp. 3733–3738.
3. Bouvet P., Vincent N., Coblentz A., Demilly F. (2000), *Optimization of resilient wheels for rolling noise control*, Journal of Sound and Vibration, **231**, 3, 765–777, doi: 10.1006/jsvi.1999.2561.
4. Cik M., Lienhart M., Lercher, P. (2016), *Analysis of psychoacoustic and vibration-related parameters to track the reasons for health complaints after the introduction of new Tramways*, Applied Sciences, **6**, 12, 1–17, doi: 10.3390/app6120398.
5. Czechyra B. (2012), *Noise and vibration activity of trams as a development of a tram acoustic signature*, Proceedings of 19th International Congress on Sound and Vibration. Vilnus: International Institute of Acoustics and Vibration, Vilnus.
6. Czechyra B. (2013), *Vibroacoustic properties and interactions of an urban tram*, [in:] *Vibrations in physical systems*, Cempel C. [Ed.], vol. 25, pp. 117–122, Poznan University of Technology, Poznan–Bedlewo.
7. Czechyra B., Tomaszewski F. (2009), *Acoustic signature of trams*, Proceedings of 16th International Congress on Sound and Vibration, pp. 1401–1407, Krakow.
8. Engel Z. (2001), *Environmental protection against vibrations and noise* [in Polish], PWN, Warsaw.
9. Esteban B., Serrano B., Rodríguez P., Blanquer F. (2006), *Comparison of vibration and rolling noise emission of resilient and solid monobloc railway wheels in underground lines*, Proceedings of the 7th World Congress on Railway Research, Montreal.
10. European Commision (2011), *White Paper – Roadmap to a single european transport area. Towards a competitive and resource efficient transport system*, Luxemburg.

11. European Parliment (2002), *The assessment and management of environmental noise – 2002/49/EC*, L189/12, Brussel.

12. Fidell S., Barber D.S., Schultz T.J. (1991), *Updating a dosage-effect relationship for the prevalence of annoyance due to general transportation noise*, The Journal of the Acoustical Society of America, **89**, 1, 221–233, doi: 10.1121/1.400504.

13. Fritschi L., Brown A., Kim R., Schwela D., Kephalopoulos S. (2011), *Burden of disease form enviromental noise – Quantification of healthy life years lost in Europe*, World Health Organization, Copenhagen, https://www.who.int/quantifying_ehimpacts/publications/e94888.pdf?ua=1.

14. Golay F. (2008), *Acoustic emission of trams. Modeling extended vehicles by point sound sources*, Ph.D. Thesis, University of Maine.

15. Hemsworth B. (2008), *Environmental noise directive development of action plans for railways*, UIC Noise Expert Network: International Union of Railways (UIC), https://uic.org/IMG/pdf/action_planning_paper_final-2.pdf

16. Hubka V. (1991), *Construct property-appropriate. Design for Propertie*, International Conference on Engineering Design, Zurich.

17. Hume K., Brink M., Basner M. (2012), *Effects of environmental noise on sleep*, Noise Health, **14**, 61, 297–302, doi: 10.4103/1463-1741.104897.

18. Kaczmarek T., Hafke H., Preis A., Sandrock S., Griefahn B., Gjestland T. (2006), *The tram bonus*, Archives of Acoustics, **31**, 4, 405–412.

19. Lakušić S., Dragcevic V., Ahac M., Ahac S. (2011), *Noise protection on railway stations* [in Croatian], [in:] *Designing of transport infrastructure* [in Croatian], Lakušić S. [Ed.], pp. 105–131, Faculty of Civil Engineering, University of Zagreb, Zagreb.

20. Leśnikowska-Matusiak I. (2014), *Impact of traffic noise on the state of human acoustic environment* [in Polish], Motor Transport, **3**, 37–62.

21. Lopez I., Vinolas J., Busturia J., Castanares A. (2000), *Railway wheel ring dampers*, Proceedings Inter-Noise 2000, Paris.

22. Madej H. (2001), *A gearbox housing modifications for minimizing noise radiation*, Scientific Journal of Silesian University of Technology – Series Transport, **43**, 131–136.

23. Mandula J., Salaiova B., Kovalakowva M. (2002), *Prediction of noise from trams*, Applied Acoustics, **63**, 4, 57–68, doi: 10.1016/S0003-682X(01)00047-0.

24. Merideno J., Nieto J., Gil-Negrete N., Landaberea A., Iartza J. (2014), *Constrained layer damper modelling and performance evaluation for eliminating squeal noise in trams*, Shock and Vibration, **3**, 1–11, doi: 10.1155/2014/473720.

25. Miedema H., Van der Berg R. (1988), *Community response to tramway nosie*, Journal of Sound and Vibration, **120**, 2, 341–346, doi: 10.1016/0022-460X(88)90444-0.

26. Niziński S., Żółtowski B. (2002), *Management of exploitation of technical facilities by means of cost accounting* [in Polish], Makat-B.Ż., Olsztyn-Bydgoszcz.

27. Nowakowski T., Tomaszewski F. (2017), *Analysis of dynamic tram-track interactions based on paraseismic vibration*, 24th International Congress on Sound and Vibration, pp. 3936–3944, London.

28. Panulinova E., Harabinová S., Argalášová L. (2016), *Tram squealing noise and its impact on human health*, Noise & Health – A Bimonthly Interdisciplinary Interantional Journal, **18**, 329–337.

29. Pawlas K. (2015), *Noise as environment al pollution – medical aspects* [in Polish], Environmental Medicine, **18**, 49–56.

30. Polish Minister of Infrastructure (2011), *The technical conditions of trams and trolleybuses and the scope of their necessary equipment,* Journal of Laws, No. 65, item 344.

31. Popescu D., Moholea I. (2010), *Monitoring the reaction and response of people to urban noise*, Archives of Acoustics, **35**, 2, 237–244.

32. Róg S. (1992), *Quality of life and living conditions* [in Polish], PWN, Warszawa.

33. Sanchez-Sanchez R., Fortes-Garrido J., Bolivar J. (2018), *Noise Monitoring Networks as Tools for Smart City Decision-Making*, Archives of Acoustics, **43**, 1, 103–112, doi: 10.24425/118085.

34. Suarez B., Chover J., Rodriguez P., Gonzalez F. (2011), *Effectiveness of resilient wheels in reducing noise and vibrations*, Proceedings of the Institution of Mechanical Engineers, **225**, 545–565.

35. Swedish Testing and Research Institute (1999), *Vibrations from railway traffic - Comparison of two methods of measurement and different guideline values – report 1991:44* [in Swedish], Boras [Göransson C.].

36. Targosz J., Adamczyk J. (2010), *Research and evalution vibroactiviti construction of tram tracks in Poland* [in Polish], Logistyka, **3**, 2267–2276.

37. Thompson D. (2008), *Railway noise and vibration: mechanism, modeling and means of control*, Elsevier, Oxford.

38. Vinolas J., Nieto F., Lopez Arteaga I., Egana J. (2007), *The effect of damping the wheels and varying wheel/rail friction coefficient on railway noise*, 19th International Congress on Acousitcs, pp. 1635–1641, Madrit.