Measurement and analysis of acoustic phenomena occurring in public transport buses based on surveys and field study

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Abstract. The article presents results and analysis of noise measurements in passenger compartments of public transport buses. Ten Solaris Urbino 12 m buses were selected for performing the measurements, including five buses with an automatic 4-speed transmission and five with a 6-speed transmission. The research related to the assessment of the acoustic climate in buses was conducted in two stages: in the first stage surveys were carried out, which were then followed by field study in the second stage. The aim of the performed research was to identify places inside the bus with potentially high sound levels and then a real assessment of the noise affecting passengers. The survey aimed at the assessment of vibroacoustic comfort in buses while driving. The questions answered by the respondents concerned places inside the vehicle and vehicle movement phases, during which noise and vibration are the strongest. Additionally, the respondents made a subjective assessment of noise and vibration inside the bus while driving. The filed study was conducted with 10 measuring microphones placed in the passenger compartment of the bus and consisted in simultaneous recording of sound levels and the speed at which the bus moved. The study was carried out at a standstill and while driving. The conducted measurements allowed the identification of the highest and lowest sound levels in the vehicle at a standstill and while driving.

1. Introduction
Transport noise is one of the most burdensome environmental problems perceived mainly by residents of large cities with significant, variable traffic flows of vehicles of various means of transport, as well as proximity of the residents’ living places to main transport corridors. The problem of noise and air pollution in large cities is the result of the increasing level of motorisation of the society and the lack of systemic solutions in the field of public transport. In Poland, in the year 2000 there were 250 passenger cars per 1000 inhabitants, and in 2017 – over 790 [1]. As a result of this situation, in many urban agglomerations, city authorities are trying to minimise the presence of passenger cars in city centres. Their actions are aimed at encouraging residents to use public transport. The most visible example of promoting public transport can be the replacement of existing bus or tram rolling stock with a newer and more modern one, which – in case of buses – draws the attention of carriers to so-called low-emission CNG, LPG, hybrid and electric vehicles. A great role is also attached to providing passengers with adequate ride comfort. The noise inside vehicles significantly affects the comfort of travelling with various means of urban and long-distance transport, as well as the comfort of the vehicle operator (driver). Currently, vehicles are built in a way that allows to meet increasingly stringent limits in terms of noise or exhaust pollution. The vehicle operator and the passenger have different expectations regarding comfort in the vehicle. It is important for the passenger that almost no
internal or external sounds disturb the journey. Subjective perception of sound phenomena is not an easy matter to assess, as it depends mainly on human psychophysical features. Harmfulness and subjective perception of noise depend on many factors, primarily on the intensity of the sounds that make it, their frequency, duration of impact, the nature of their changes over time or the duration of their changes over time, and even on the content of so-called inaudible components. Everyone has a different sensitivity to sounds, let alone to noise. For some people, even a small noise causes difficulty in concentration, nervousness and irritability, whereas for others it is almost imperceptible.

Therefore, the problem related to acoustic comfort inside a vehicle is so significant that it has been noticed and undertaken by many researchers. Papers [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16] present internal noise measurements, mainly in motor vehicles. The following was tested and analysed: the impact of different speed values, the effect of a drive with only high speed, the noise during acceleration; a subjective assessment of noise in vehicles was also made and indicators of acoustic comfort in the car were taken into account. The effect of vehicle suspension stiffness on interior noise was investigated as well [17]. The research involved sound volume testing and objective evaluation of car sound quality [18, 19, 20]. The research drew attention to low-frequency noise [21], impulse noise generated while driving [22] and structural and acoustic analysis of the car compartment [23], including the transformation of spatial noise in a car [24]. Comprehension of speech in the sound field inside the car [25] and the effect of side wind on aerodynamic noise inside the car [26] were also studied. In addition to noise measurements inside passenger cars, measurements were also performed in public transport vehicles. These studies mainly concerned the workplace of professional drivers and covered the noise affecting passengers only to a small extend [27, 28].

This paper presents the results of surveys and field measurements performed in public transport buses. The surveys were conducted on a group of 325 people who use bus transport on a daily basis. The measurements were performed in ten Solaris Urbino 12 m buses, including five buses with an automatic 4-speed transmission and five with a 6-speed transmission. The aim of the performed research was to identify places inside the bus with potentially high sound levels and then to carry out a real assessment of the noise affecting passengers.

2. Assessment of vibroacoustic phenomena by passengers of public transport – surveys
The survey was carried out in Poznań in 2013 among passengers (325 people) who use exclusively bus transport for travelling, every day or several times a week. The main objective of the survey was to allow passengers using public transport buses to indicate places in the vehicles (at a standstill and while driving) with high and low levels of sound and vibration. The age structure of people taking part in the survey was as follows: the largest group of people surveyed (41%) were people aged 18-30, 18% were people aged 31-40 and under 18, 15% were people older than 50. The smallest group of respondents, only 9%, were people aged 41-50. The average unit travel time of respondents by public transport buses ranged from 15 to 30 minutes. Figure 1 shows the distribution of answers to the question concerning the assessment of noise and vibration occurring in the bus while driving.
Figure 1. Distribution of answers to the question: How do you assess noise and vibration in the bus while driving.

The survey participants declared their answers in terms of both acoustic and vibration phenomena. In the case of assessing the impact of noise and vibration in a bus while driving, the ‘averagely annoying’ answer was chosen by 49% of respondents for noise and by 47% for vibration. The second most-popular answer was ‘not very annoying’, chosen by 22% of respondents. For 18-19% of respondents the noise and vibration were very annoying; only 6% of the respondents assess the phenomena as not annoying – and the same percentage as ‘extremely annoying’. The next question in the survey concerned the location where noise and vibration were the most annoying while the bus is driving. The summary of results for this question is presented in Figure 2.

Figure 2. Distribution of the answers to the question: At which location in the bus vibration and noise are the most annoying during the drive.
The survey participants stated that while the bus is driving, noise and vibration were the most annoying at the end of the vehicle, near the combustion engine. In the case of noise, 43% of respondents gave such an answer and in the case of vibration phenomena – 34%. The survey also showed that respondents had a problem with identifying characteristic places with high noise and vibration impact in the bus. This was indicated by the answers: ‘equal throughout the vehicle’ and ‘I have no opinion’. Respondents also stated that adverse vibroacoustic phenomena may occur in the middle of the vehicle, near the articulation. This mainly applies to buses with a length of 18 m. Other answers did not exceed 10%. One of the survey questions also concerned the passenger’s position (standing or sitting) in which the vibration is more noticeable. 35% of women indicated that this was more noticeable while standing and 18% while sitting. Men had a problem with indicating the answer: 28% of the surveyed men indicated a standing position and 29% a sitting position. 24% of respondents (women and men) also indicated that vibration was felt both in sitting and standing positions. About 23% of male and female respondents were not able to answer this question. Figure 3 summarises the answers to the question concerning the phase of bus drive when noise and generated vibration are the strongest.

Figure 3. Distribution of answers to the question: During which phase of bus drive are noise and vibration the strongest.

The distribution of answers to the question concerning the phase of bus drive when noise is the strongest is as follows. The highest number of respondents, 28%, pointed to the acceleration from a stop. Second most-popular answer chosen by 19% of responses was when the bus was driving on a damaged road surface. The driving phase with high noise is also: driving at high speed (11% of respondents), as well as when the bus is driving on paving stones (8% of respondents). 9% of the survey participants who indicated the answer ‘other’ (Fig. 3) claimed that the noise is the strongest during the following events: when the bus accelerates, when door are being opened/closed, and when stops are announced. According to the respondents, the strongest vibrations are generated when the bus is driving on damaged road surfaces – 26% of responses. Other answers related to vibrations with a large number of indications were: ‘standstill with the engine running’ – 16%, ‘accelerating from a stop’ – 15% and ‘when the bus is driving on paving stones’ – 12%.

Due to the fact that in Poznań several types of buses (with length of 8.6 m, 12 m and 18 m) from different manufacturers are in operation, two survey questions also concerned the assessment of noise and vibration in individual types of buses. However, when answering this question, respondents could not indicate in which buses (8.6 m, 12 m or 18 m) noise and vibrations are the highest. The most
frequently chosen answer was ‘I have no opinion’ (about 40% of responses) or an answer indicating that both phenomena are the same in all buses (about 20% of responses). The conclusions of the survey are such that the vibroacoustic phenomena that occur in Poznań buses are not a major problem for those using them. The respondents were unable to clearly indicate locations in the bus and the driving phases during which vibrations and noise are the most annoying. In addition, when asked for assessment of the comfort of travelling by public transport buses in Poznań, 40% of respondents rated it as average and 35% as good. Therefore, in order to objectively assess acoustic phenomena, an original method of measuring noise in buses was developed, consisting of placing ten measuring microphones inside the vehicle and recording the acoustic signal depending on the speed of the bus.

3. Assessment of noise in public transport buses

The objects used in the study were city buses operated by a municipal transport company. Solaris Urbino buses (length: 12 m) were selected for testing. Solaris Urbino buses are low-floor buses manufactured by the Polish company Solaris Bus & Coach S.A., located in Bolechowo near Poznań. The drive units in these vehicles are MAN and DAF engines cooperating with automatic 4 and 6 speed VOITH or ZF Ecolife transmissions. All vehicles are fully air-conditioned both in the passenger compartment and in the driver’s cabin. In addition, buses manufactured by Solaris Bus & Coach S.A. have a ‘kneeling’ function that reduces the height of the vehicle entrance by about 70 mm, as well as a ramp that opens manually or electrically, making it easier for people in wheelchairs to enter. Technical data of the tested buses are as follows: length 12,000 mm, width 2,550 mm, height 2,850 mm, weight 11,700 kg. The bus has a capacity of 100 passengers, 30 of them can travel on seats. For passenger exchange three doors in the 2-2-2 layout are used [29]. Ten buses were selected for the study, of which five were vehicles with a 4-speed automatic transmission and another five with a 6-speed automatic transmission. All buses used in the study were in a different technical condition. Most of the vehicles were delivered in the years 2010 and 2011. The testing route selected for the study was about 13 km long and about 20 minutes were needed to pass it. On the route, in addition to stops resulting from red traffic lights, two regular stops were also foreseen. Measurements were carried out without passengers, on city streets with normal traffic. The route on which the measurements were made consisted of asphalt streets in different, but generally good technical condition, with numerous cross-connections of the road surface, which caused a specific acoustic effect during driving.

To achieve the intended research goals (i.e. identification of places in the vehicle with high and low sound levels), ten measuring microphones were installed in the passenger space of the vehicle at the height of 1.6 m above floor level, which via the PULSE® measuring system from Brüel&Kjær enabled parallel recording of acoustic signals when driving and at a standstill of the public transport vehicles. Sound measurements were also supplemented by recording the current speed at which the vehicles were moving. During the study regarding the assessment of the acoustic climate in the interior of the bus, the following research tasks were adopted: analysis of the distribution of sound levels in the passenger space of the bus at a standstill (with internal combustion engine on idle) and while driving. In addition, before the actual measurements were taken in each of the tested vehicles, the acoustic background was measured. At a standstill, when all devices in the bus were turned off, the acoustic background was 40 dB. Figure 4 shows the arrangement of measuring microphones and sound pressure level distributions $L_{P(A)}$, registered in the passenger space of Solaris Urbino 12 m buses equipped with a 4-speed automatic gearbox.
Figure 4. Distribution of sound pressure levels $L_{P(A)}$ inside the 12 m Solaris Urbino bus equipped with a 4-speed automatic transmission.

On Solaris Urbino 12 m buses equipped with an automatic 4-speed transmission at a standstill when the engine was idling, the distribution of sound pressure levels $L_{P(A)}$ was from 60 to 72 dB. The lowest sound levels were recorded at the location of measuring microphone number 1, and the highest at the location of measuring microphone number 10. The difference between measuring microphones 1 and 10 at a standstill when the engine is idling was 12 dB. The interior of the vehicles selected for testing can be divided into two zones: the first sound impact zone includes the location of microphones from 1-7. In this zone, sound levels ranged from 60 to 68 dB. At the same time, at the location of microphone 1, the lowest sound level value in all tested buses (60 dB) was obtained. The second sound impact zone was the location of microphones 8, 9 and 10, in close proximity to the internal combustion engine. 70-72 dB was obtained at these locations. While driving, the sound levels in the tested buses achieved higher values: from 71 dB (location of measuring microphone number 1) to 76 dB (location of measuring microphone number 10). The entire passenger interior of the tested buses can also be divided into two sound impact zones. The distribution of these zones is similar to that at a standstill. The first sound impact zone was where the first six microphones were located. At measuring microphone locations 1, 2 and 3, the recorded levels were 71 dB, whereas in locations of microphones 4 to 6 the obtained result was 72 dB. Starting from the measurement microphone number 7 (73 dB), the recorded sound levels increased to 76 dB near the internal combustion engine (microphone number 10). The average difference in recorded values between the location of measuring microphone 1 and 10 while driving was 6 dB. The biggest difference of sound levels recorded at a standstill and while driving was at the location of microphone number 1 (near the driver’s cab) – 11 dB, and the smallest was near the combustion engine, with measuring microphone number 10 – 4 dB.

Figure 5 shows a diagram of the arrangement of measuring microphones in the passenger space and the distribution of sound levels $L_{P(A)}$ in the interior of a 12 m Solaris Urbino bus equipped with a 6-speed automatic transmission at a standstill and while driving.
In the 12 m Solaris Urbino buses equipped with an automatic 6-speed transmission, the range of recorded sound pressure levels \(L_{P(A)}\) was similar to that in buses equipped with a 4-speed transmission and was equal to 65-73 dB. The lowest measuring level of 65 dB was recorded by the first measuring microphone located next to the driver. In the next six locations, the range of measured values was between 66 dB and 68 dB. Starting from the location of the measuring microphone number 8, sound levels rose to 70 dB. At the location of the measurement microphone number 10, near the internal combustion engine – the highest value of 73 dB was recorded. The difference between the values recorded in buses equipped with an automatic 6-speed transmission by the measuring microphones in locations 1 and 10 equals to 8 dB. During the drive on the testing route, the range of recorded sound levels was 71-76 dB. At the locations of the first three measuring microphones, the recorded sound levels were the lowest in the entire bus and amounted to 71 dB. 72 dB was obtained by the microphones at locations 4 and 5, and 73 dB at locations 6 and 7. Starting from the 8th microphone, the recorded sound levels increased from 74 dB to 76 dB at the location of the microphone number 10. In connection with the above, the interiors of the tested vehicles were divided into two sound impact zones. The first zone included the location of microphones 1 to 7, and the second covered the locations of measuring microphones 8 to 10. The difference in sound levels recorded by the measuring microphone number 1 and 10 was 6 dB [30].

4. Conclusions
The conclusions of the survey and field measurements carried out are as follows. The surveys have shown that the ride comfort of Poznań public transport buses is average and good, while the noise and vibration generated while driving are moderately burdensome for respondents. The place where noise and vibration are the most annoying is near the location of the internal combustion engine (end of the vehicle). This is in line with the results of the performed measurements. At the end of the vehicle, near the internal combustion engine, the highest sound levels in the bus were recorded: 76 dB while driving and 73 dB at a standstill, when the engine was on idle. The respondents were not able to indicate the places in the bus where the vibroacoustic phenomena were the most burdensome. The driving phase.

Figure 5. Distribution of sound pressure levels \(L_{P(A)}\) inside the 12 m Solaris Urbino bus equipped with a 6-speed automatic transmission.
during which the respondents felt the most vibration and generated noise was acceleration from the bus stop and drive on damaged road surface. Based on the actual measurements carried out in Solaris Urbino 12 m buses equipped with a 4- and 6-speed automatic transmission, conclusions can be drawn. The range of recorded sound levels at a standstill when the combustion engine was idling was similar for both transmission types and ranged between 60 dB and 73 dB. The largest differences were observed at the location of the measuring microphone 1. Buses equipped with a 4-speed transmission were 5 dB quieter at this location compared to buses equipped with a 6-speed transmission. In other locations, the ranges of measured sound levels were at a similar level. On the testing route, the ranges of the measured sound levels were similar in buses with 4-speed and 6-speed transmission and ranged from 71 dB to 76 dB. Measurements and analyses allowed to divide the interior of buses selected for testing into two sound impact zones. Measuring microphones 1, 2, 3, 4, 5, 6 and 7 were located in the first zone. The second zone, where the highest values of sound levels were recorded, was the location of microphones 8, 9 and 10. The difference between the values of sound levels at a standstill recorded by measuring microphones number 1 and 10 in case of buses equipped with an automatic 4-speed transmission equals to 12 dB, whereas in case of buses equipped with an automatic 6-speed transmission it equals to 8 dB. When driving, there is a 6-dB difference between those places in all buses covered by the research.

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