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PATTERNS OF CHANGES IN THE ACOUSTIC CHARACTERISTICS ON PUBLIC TRANSPORT LINEAR SEGMENTS

Summary. *The problem of noise pollution in cities becomes quite acute as soon as it comes to increasing the level of motorization. However, most researchers study the negative impact of traffic noise in general. In the era of sustainable mobility, there will be a trend to reduce the number of private vehicles on city streets. Still, the problem of acoustic load in residential areas will not be solved since public transport is a rather powerful source of traffic noise. The article solves the problem of determining the patterns of changes in the acoustic load from public transport vehicles at different speed modes and road surface.*

The article's objects of research are straight sections of public transport lines. The subject of the study is the patterns of changes in the noise level from public transport vehicles at different speeds, their position, and the type of surface.

The obtained results indicate that the main range of noise pollution from public transport on straight sections is 75–85 dBA, and this level can vary by 15–20 % depending on the type of line (trolley bus, bus, tram) and the type of road surface.

The regularities of changes in the level of noise pollution, which were revealed in work, indicate that for each type of surface and type of public transport line, there are such values of traffic speeds, when they are reached, there is an overtime acoustic load on residential areas at specific distances from them. The obtained results differ from the currently existing scientific studies in that they consider the acoustic characteristics of clear public transport lines and not the traffic flow as a whole. Therefore, it becomes possible to determine the maximum and not the equivalent level of noise from public transport.

The field of application of the results is transport planning of both new residential areas and areas of existing adjacent buildings. Thus, in the first case, recommendations were made regarding territorial gaps from the construction line to arterial streets with high volume of public transport, depending on its type and surface. On the other hand, recommendations have been established regarding the speed regime of public transport at different distances from existing buildings' lines.

Key words: *acoustic load, public transport lines, maximum noise level, tramway, public transport velocity.*

1. INTRODUCTION

The trend of sustainable development of cities began to develop in the 80s of the last century in certain European countries. This is when certain cities and agglomerations have realized that mass motorization, along with improving city dwellers' mobility, hurts the environment. This influence is growing at this time. Already today, most cities in Europe and Ukraine face constant environmental problems. Among them, the most significant increase in emissions of exhaust gases is considered, which has a positive trend not only due to the number of cars, but also environmentally harmful modes of operation of engines during significant downtime in queues and traffic jams. Respectively, strategies and plans are adopted which reduce car use and use of alternative types of movement in the city.

At this time, the problem of acoustic pollution in the urban environment is often overlooked, which, although smaller, has a significant impact on the quality and comfort of the life of city residents. In the transition from cars as the primary means of movement in the city to public transport, in the medium term, it will be necessary to solve the environmental problems created by vehicles intended for the mass transportation of passengers.

No matter how effective the measures to change the philosophy of urban mobility are, it is necessary to understand that ecological types of public transport do not exist. The problem of the negative impact of public transport on the environment is not apparent, but it will stand out more and more with the increase in the pace of its development in large cities. Even with the maximum rate of electrification of public transport, the problem of its harmful impact on the environment in acoustic pollution will remain at the same level.

Considering the prospects of urban development and the course towards sustainable mobility, the issue of studying the patterns of noise pollution generation by public transport must be raised now. This will increase the number of sustainable urban development goals that can be addressed shortly.

2. RESEARCH STATEMENT

Generally, the review of the problem and the results obtained so far can be divided into three parts. The first is the main regularities of changes in the urban environment noise level and the calculated indicators stipulated by the current regulatory documents. The second is generally acceptable levels of acoustic pollution in urbanized spaces and the limits of their deviation [1]. The third is currently appropriate methods of combating excessive acoustic load. A thorough review of these issues will provide a complete understanding of the problem being addressed in this article and a correct statement of the goal and objectives of the research.

In general, 60–80 % of the acoustic load in residential areas is generated by traffic flows and not by stationary sources of noise pollution [2]. Traffic noise is one of the most dangerous parametric pollutions of the environment. Its negative impact on residents' quality of life and their state of health is quite significant, which has been repeatedly proven by specialists in the field of medicine [3].

In paper [4], the authors single out means of road transport that significantly impact the acoustic pollution of city highways. Thus, it was established that passenger cars' noise intensity (in dBA) is 70–80; buses – 80–85; trucks – 80–90; motorcycles – 90–95. This study also states that the acoustic characteristics of trolleybus lines are similar to bus lines, and the tram can be considered the quietest vehicle. However, its acoustic characteristics differ significantly depending on the line type and location.

The results of research in the research [5] indicate that at traffic volumes on the city highway of 1600–1900 auto/hour, the equivalent noise level (LAeq) is 78 dBA, and the maximum (LAmax) is equal to 87 dBA. It is also worth noting that these results are obtained for a traffic flow where buses make up only 3.6 % of the total traffic volume.

Also, in the analyzed studies, some results indicated a significant influence of the road surface and the volume of the traffic flow on the noise level of sections of arterial streets [6]. The traffic flow moving on a cobblestone road surface was determined to generate a 20 dBA higher noise level than asphalt concrete (70 vs. 50 dBA). The issue of the available acoustic load using ground transport in cities was also considered in the paper [7]. It was determined that 70 % of all noise level measurements lie within 50–70 dBA.

Studies propose considering the problem of acoustic pollution due to tram lines [8]. This study established that tram cars generate on 10 dBA more noise than private cars and buses. At the same time, researchers in the article [9] determined the change in the level of acoustic pollution of tram lines depending on the speed of carriages (Fig. 1). The results indicate that at a rate of more than 40 km/h, a significant noise level of more than 80 dBA is reached.

A comparative assessment of the generated noise level for different types of tram tracks is also carried out in this research. For example, with a classic open (using sleepers) tram track, the generated noise is equal to 90–100 dBA; when using special plates – 80–85 dBA, and when laying a canvas on asphalt concrete – 75–80 dBA. Bus flow was also considered a separate source of acoustic pollution [10]. In this study, the maximum noise levels in the bus station area are determined, where 58 % of the total flow is made up of buses. In such places, the top noise level reaches 79 dBA.

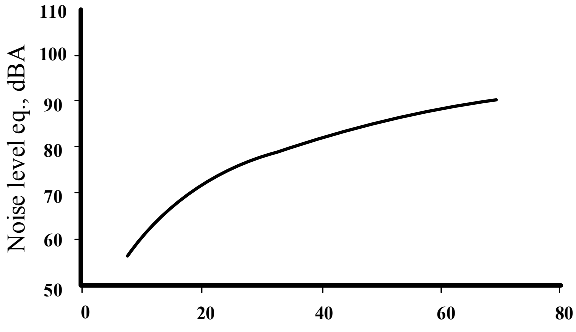

Fig. 1. Change in the noise level of tram cars, considering movement [9]

Considering the regulatory documentation, we can conclude that the noise level is calculated according to generally accepted methods, which differ little in one country or another [11–12]. In general, the noise characteristics of the sources, which are traffic flows (or individual vehicles), are calculated by the provisions of DSTU N.B.1.1-33:2013 [13]. This technique involves determining the acoustic characteristics of the traffic flow, taking into account its volume and speed, or determining the noise level from tram cars. Moreover, the speed of their movement is not taken into account. According to the calculated values, the maximum noise level of the flow of motor vehicles ranges from 88 to 92 dBA, and for tram cars – 82–92 dBA, depending on the type of road surface. It is worth noting that the acoustic characteristics of the noise source and its level at the calculation point are somewhat different concepts since the first is calculated strictly for a distance of 7.5 m from the track axis or traffic lane, and the second value depends on the distance to the calculation point, the noise-absorbing properties of the environment, and whether noise protection facilities are available.

Positions of DBN V.1.1-31:2013 [1] provide specific limit values of maximum and equivalent noise levels within residential areas (Table 1). It is worth noting that although this standard dates back to 2013, the limit values of the acoustic characteristics of the urban space were calculated back in the 50s of the last century and are related to the general recommendations of medical organizations. Thus, in Poland, the permissible noise level in residential areas near highways is 60 dBA at night and 68 dBA during the day [14], which practically does not differ from domestic standards.

Table 1

Maximum permissible equivalent and maximum sound levels

Surface type	Permissible sound levels (dBA)		Period
	LA eq.	LA max.	
Territories directly adjacent to the buildings of hospitals and sanatoriums	45	60	Day
	35	50	Night
Territories directly adjacent to the buildings of polyclinics, dispensaries, rest homes, boarding houses, boarding houses, children's preschools, schools and other institutions, libraries	55	70	Day
	30	45	Night
Territories adjacent to hotel buildings and dormitories	60	75	Day
	50	65	Night
Territories directly adjacent to residential buildings	55	70	Day
	45	60	Night
Recreation grounds on the territory of microdistricts, groups of residential buildings, rest houses, boarding houses, playgrounds of children's preschool institutions, schools and other educational institutions	45	60	Day

The regulations show that the permissible level of noise along the sections of the route (if we talk about public transport lines) is different, depending on the type of territories through which it runs. It is logical that for a particular line of public transport, the permissible noise level will be equal to the norm for the territory, the value of which is minimal.

It is clear that the level of acoustic load changes from the noise source to the calculation point; therefore, when conducting research and formulating practical recommendations, it is worth considering the noise reduction factors with distance. It is also essential to consider the characteristics of the urban environment [15]. Some studies prove the effectiveness of using green spaces to reduce the noise level on city streets [16]. The problem, in this case, is the questionable effectiveness of such a planning technique since it is necessary to use specific vegetation types. Still, they also effectively absorb mostly high-frequency noise at a time when acoustic pollution from traffic is of a low-frequency nature. Noise protection screens have the most excellent efficiency. As of today, there are a large number of industrial samples of various types and forms that can be used to protect against multiple sources of noise.

The variability of materials of noise shield manufacturing can change the effectiveness of their use by 5–10 % [17]. However, the distance and height of their installation are decisive characteristics that determine their effectiveness. Analyzing the regulatory documentation on the determination of noise levels and acoustic characteristics of the environment, we can conclude that the most effective natural method of reducing the noise level is to change the distance from the source to the calculation point (Fig. 2).

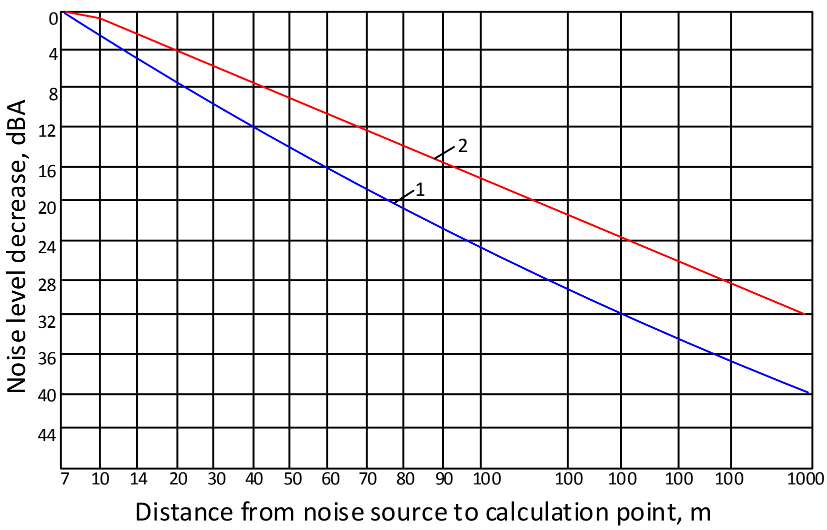

Fig. 2. Graph for determining the decrease in sound level depending on the distance between the noise sources and the calculation point: 1 – for stationary sources; 2 – for linear sources

Analyzing this graph, we can conclude that a significant decrease in acoustic load (16–20 dBA) is observed at a distance of 100 m or more. In urbanized spaces, such a gap distance is critical since the value of the built-up density is relatively high.

The studied sources provide understanding that the noise generation by public transport in cities is not entirely studied – mainly, the determination of the acoustic load is carried out for the entire traffic flow by a calculation method, which has several disadvantages. In these conditions, it is necessary to carry out field studies to identify regularities in the change in the noise level of public transport lines in certain urban planning conditions and at different speeds. It is also determined that currently available measures to reduce traffic noise cannot always be applied in densely built-up areas. Therefore, the study of the acoustic characteristics of direct sections of public transport lines is relevant in determining the changes in the noise level at different speeds of movement in other linear positions.

The purpose of the study is to identify dependencies in the change in the noise level of direct sections of public transport lines (bus, trolleybus, and tram) depending on the speed of movement and the position of the vehicles.

The tasks of research are:

– measure changes in the level of acoustic load on direct sections of public transport lines with different types of road surface;
– to establish the relationship between the noise level and the speed of movement of vehicles at different positions of straight sections;
– to provide practical recommendations on regulating the speed of public transport in areas where it generates excessive noise.

Solving these tasks will help supplement the issue of determining the acoustic characteristics of the urban environment and will provide an opportunity to obtain the limit values of traffic speeds on direct sections of public transport lines from the point of view of the acoustic load.

3. SURVEY OBJECTS AND PLANNING OF EXPERIMENT

The objects of research were chosen to cover all possible variations in the types of urban public transport and types of road surfaces. Therefore, to study the noise characteristics of tram lines, three straight sections with a length of 96–105 m were chosen, which had a road surface made of cobblestones on a monolithic concrete base (Fig. 3, *a*), PKP slabs (Fig. 3, *b*) and a separate canvas with sleepers and crushed stone base (Fig. 3, *c*).

a *b*

c

Fig. 3. Typical sections for tram lines noise detection:
a – section T1; b – section T2; c – section T3

The study of the noise characteristics of tram and bus lines was carried out on sections of streets 95–102 m long, with cobblestones (Fig. 4, *a*) and asphalt concrete (Fig. 4, *b*) serving as road surfaces. A characteristic feature of all sections is that vehicles started moving at the beginning and stopped at the end of the sections.

a *b*

Fig. 4. Typical sections for bus and trolleybus lines noise detection:
a – section AT1; b –section AT2

The first section is characterized by basalt paving, and the basis of the tramway is made of concrete slabs, passing through the city's historical center with existing buildings. The second plot is also located in the central part of the city, but the canvas is made of PKP plates. The last section – T3, is characterized by the tram cars moving along a separate track on a base of concrete blocks covered with paving slabs. Only Electron T5L64 (T3L44) and Tatra KT4 trams were chosen for research, the ergonomic characteristics of which are quite similar, which has been proven in work [18].

The section of AT1 is characterized by the presence of an asphalt concrete surface and mixed traffic of trolleybuses and buses located on the city's outskirts. The other team runs not far from the central core; the road surface is basalt cobblestone. This research stage included vehicle noise level measurements: Electron A18501, MAZ 203 (buses), and Electron T19, Bohdan T601.11 (trolleybuses).

Noise level measurements were carried out with the Flus ET-965 device at a distance of 3 m from the axis of the tram track or traffic lane every 20 m. At these same points, the speed of the vehicles was recorded with the Radio device. The research was conducted during the day (whether after or before peak periods) in June in sunny weather, air temperature +20–24 °C, relative humidity 64–78 %, and wind speed 1.5–2 m/s. It is also worth noting that the noise level measurement was carried out for single vehicles (with minimal influence of background acoustic load), and only its maximum value was considered.

The Statistica software environment was used to analyze the obtained results, in which correlation and regression analysis of dependencies was carried out. Their visualization is also provided.

4. MAIN PART

The first stage was the determination of the tram line's acoustic characteristics. Fig. 5 shows the dependence of the change in the noise level of tram cars on the movement speed on a straight section. To obtain representative data, 100 values of the maximum noise level were collected at each site. The analysis of changes in the acoustic characteristics of bus and trolleybus lines is shown in Fig. 6.

It is also worth noting that the dependencies are illustrated with the curves of the third-order polynomial regression equation, which will be used for all stages of the analysis and allow a correct comparison of the results.

It follows from the obtained dependence that the level of noise discomfort changes with the increase in the speed of tram cars movement. Most of the obtained values are from 75 to 85 dBA at speeds of 15–25 km/h. It is worth singling out section T1, where the level of acoustic load is less than 85 dBA at low rates. However, when speeds of 25–30 km/h are reached, this level exceeds 85 dBA.

Bus and trolleybus lines are characterized by higher maximum speeds (45–50 km/h) than tram lines (30–35 km/h). According to the received data, the main acoustic load is 75–85 dBA and is reached at speeds of 25–35 km/h. It is worth noting that this range is wider than tram lines. Table 2 shows the dependence equation of change in maximum noise level (y) from vehicle movement speed (x).

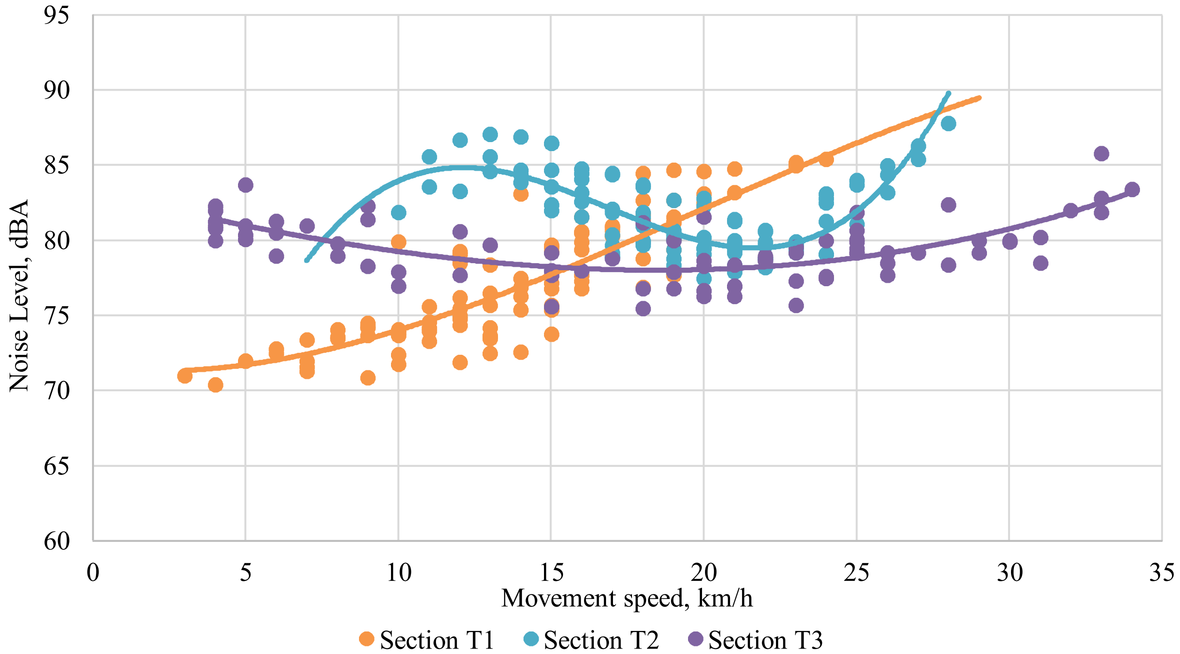

Fig. 5. Dependencies of the change in maximum noise level on the speed of tram line straight sections

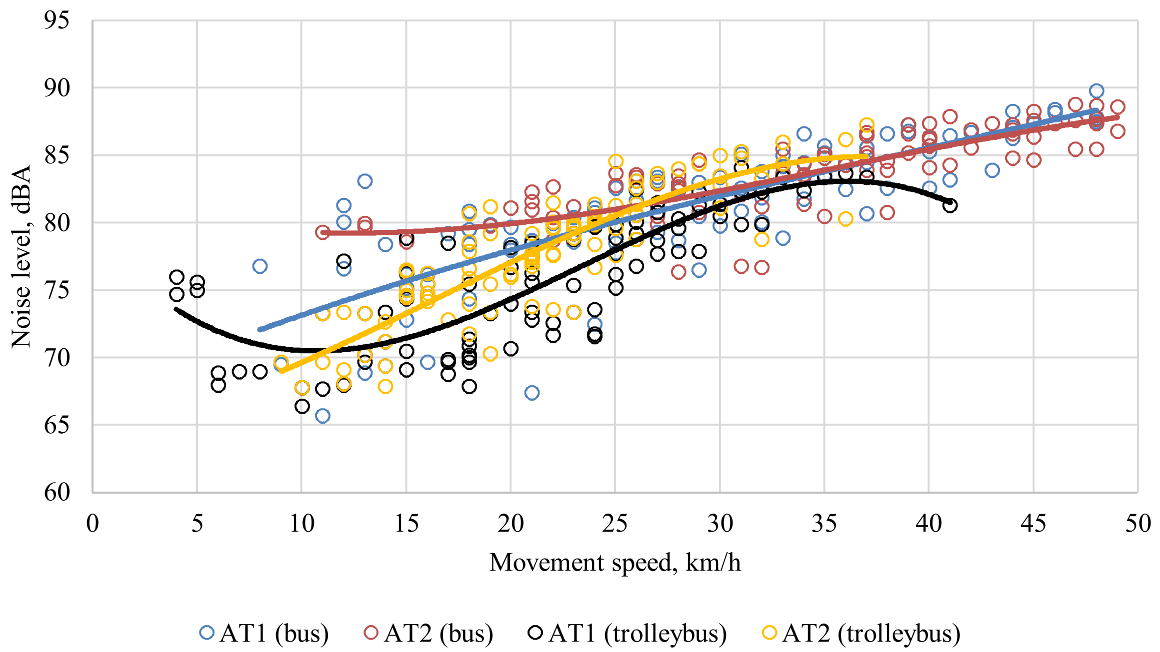

Fig. 6. Dependencies of the change in maximum noise level on the speed of bus and trolleybus line straight sections

As mentioned earlier, polynomials of the third degree were used to describe the regularities, and the coefficients of determination are in the range from 0.65 to 0.77, which confirms the adequacy of the obtained mathematical models.

Table 2

Parameters of change dependence in the maximum noise level on the route vehicle's movement speed

Section/line	Approximation equation	Coefficient of determination
T1/tram	$y = -0.0009x^3 + 0.0561x^2 – 0.2143x + 71.516$	0.7343
T2/ tram	$y = 0.0123x^3 – 0.6227x^2 + 9.6636x + 37.289$	0.6509
T3/ tram	$y = 0.0002x^3 + 0.0086x^2 – 0.506x + 83.284$	0.6824
AT1/bus	$y = 0.00005x^3 – 0.0077x^2 + 0.6696x + 67.172$	0.6591
AT2/ bus	$y = -0.0002x^3 + 0.0209x^2 – 0.4278x + 81.724$	0.6745
AT1/trolleybus	$y = -0.0015x^3 + 0.1078x^2 – 1.7788x + 79.081$	0.6726
AT2/trolleybus	$y = -0.0006x^3 + 0.0298x^2 + 0.2682x + 64.596$	0.7639

Based on the obtained regularities, it becomes possible to develop practical recommendations that are bilateral. From one point of view, it is possible to regulate the construction line of new residential complexes about the roadway or tramway. Having the calculated movement speed on straight sections of public transport lines, taking into account the dependence shown in Fig. 2, it is possible to determine the minimum permissible distance to the residential area, which will ensure the standard noise level. From another point of view, the results are interesting in that, in the presence of existing residential area, it is possible to determine the maximum permissible speed limit on public transport lines in straight sections, at which, at certain distances, the standard of the top allowable noise level will be observed. With this in mind, two tables are proposed that will indicate the restrictions on the distance to the residential area from the public transport lines (Table 3) and the speed limit of public transport depending on the distance to this area (Table 4).

Table 3

Limit distance to residential areas for different types of public transport lines

Section type	Minimal distance to residential areas, m	Maximum noise level, dBA	The difference in noise levels, dBA
T1	85	85	15
T2	110	90	20
T3	55	80	10
AT1	80	82	13
AT2	100	86	18

Table 4

Limiting of movement speed to ensure the permitted noise level

Line type	Speed limit at distance from buildings, km/h				
	20	40	60	80	100
T1	20	20	25	30	30
T2	15	15	25	25	30
T3	20	30	35	40	45
AT1 (bus)	25	30	40	45	50
AT1 (trolleybus)	25	35	50	50	50
AT2 (bus)	15	25	40	45	50
AT2 (trolleybus)	20	30	35	40	50

In these practical recommendations, it is worth noting that the estimated speed for tram lines is 35 km/h, and for bus and trolley lines – 45 km/h. The recommendations are helpful in developing development plans and detailed plans of the territory. The limit distances may change when there are certain obstacles between the calculation point and noise sources. The situation can also be affected by the presence of noise shields.

Due to the maximum permissible noise levels in residential areas, the speed limit for different types of linear sections is different. Thus, with tram tracks laid with PKP slabs and a distance to buildings of 20 m, the maximum permissible speed of carriages (from acoustic discomfort) should be no more than 10 km/h. At the same time, on a separate tramway, a speed of more than 35 km/h is permissible at distances from buildings of 60 m. If we talk about bus and trolleybus lines, their allowable rates can be 30–50 % higher than the same distance to facilities. It is also worth noting that the most profitable type of line in terms of speed characteristics is a trolleybus on an asphalt concrete surface. This type of connection at a speed of 50 km/h does not generate excessive acoustic load for building lines located at distances of 60 m or more.

5. CONCLUSIONS AND RESEARCH PERSPECTIVES

The article examines the main problems of acoustic pollution in urban spaces faced by scientists in modern research. It was found that the issue of excessive noise generation using public transport has not been thoroughly studied. This is observed in reviewing the scientific literature, which mainly investigates the problems of acoustic load generated by mixed traffic flows.

Conducted research on the level of noise pollution on straight sections of public transport lines. It has been established that tram cars produce from 75 to 90 dBA of noise pollution depending on the type of track laying. The level of noise pollution on bus and trolleybus lines is 10–15 % lower and strongly depends on the coverage.

Empirical dependences of changes in the noise level on straight sections of public transport lines on the instantaneous speed of movement of transport units have been established. If we talk about tram lines, we can confirm that when the speed of carriages increases from 15 to 30 km/h, the level of acoustic load at the measurement points increases from 75 to 90 dBA. The dynamics of this change depend on the type of tramway. Thus, when laying tram tracks on a separate way, the level of generated noise is 15 % lower than control values, mainly observed at low (up to 15 km/h) and high (more than 30 km/h) speeds. Along the straight sections of bus and trolleybus lines, a more consistent trend of noise level change with the movement speed is observed. However, it should be noted that noise levels greater than 80 dBA will be kept at speed larger than 35 km/h. Importantly, cobblestones generate 15–20 % more noise than asphalt, but this difference becomes smaller as speed increases.

Based on the obtained dependencies, recommendations have been developed regarding observing territorial gaps between residential area and public transport lines. Thus, for sections with bus and trolleybus traffic or tram lines, these gaps should be more than 100 m to ensure traffic at the calculated speeds. Recommendations have also been developed to limit speed modes of traffic on straight sections of public transport lines within already formed residential area. Based on them, if there is a building at a distance of 20–40 m, then the maximum speed of public transport should be limited to 15–30 km/h, depending on the type of line and surface. It is also worth noting that the speed limit of route vehicles will, in a certain way, affect their traffic schedules. Therefore, such measures should be developed comprehensively.

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ЗАКОНОМІРНОСТІ ЗМІНИ АКУСТИЧНИХ ХАРАКТЕРИСТИК НА ПРЯМИХ ВІДРІЗКАХ ЛІНІЙ ГРОМАДСЬКОГО ТРАНСПОРТУ

Анотація. *Проблема акустичного забруднення міст постає досить гостро, як тільки мова йде про підвищення рівня автомобілізації. Проте, більшість дослідників вивчають негативний вплив шуму від транспортного потоку в цілому. В епоху сталої мобільності спостерігатиметься тренд щодо зменшення кількості приватного транспорту на міських вулицях, але проблема акустичного навантаження на території житлової забудови таким чином не вирішиться, оскільки засоби громадського транспорту є досить потужним дже-релом транспортного шуму. В статті вирішується проблема визначення закономірностей* *зміни акустичного навантаження від засобів громадського транспорту за різних швидкісних режимів та типів покриття.*

В статті об'єктом дослідження є прямі ділянки ліній громадського транспорту. Предметом дослідження – закономірності зміни рівня шуму від засобів громадського транспорту за різних швидкостей руху, їх позиції в просторі та типу покриття.

Отримані результати вказують на те, що основний діапазон шумового забруднення від засобів громадського транспорту на прямих відрізках становить 75–85 дБА, при чому, цей рівень може відрізнятися на 15–20 % залежно від виду лінії (тролейбус, автобус, трамвай) та типу покриття.

Закономірності зміни рівня шумового забруднення, які були виявлені у роботі вказують на те, що для кожного типу покриття та виду лінії громадського транспорту існують такі значення швидкостей руху, при досягненні яких здійснюється понаднормове акустичне навантаження на райони житлової забудови за певних відстаней до них. Отримані результати є відмінними від існуючих в цей час наукових досліджень тим, що в них розглянуті акустичні характеристики конкретних ліній громадського транспорту, а не транспортного потоку в цілому. Відтак стає можливим визначити максимальний, а не еквівалентний рівень шуму від засобів громадського транспорту.

Сферою застосування результатів є транспортне планування як нових житлових районів, так і ділянок існуючої прилеглої забудови. Так, в першому випадку сформовані рекомендації щодо територіальних розривів від лінії забудови до магістральних вулиць з інтенсивним рухом громадського транспорту, залежно від його виду та типу покриття. З інакшого боку, встановлені рекомендації щодо швидкісного режиму засобів громадського транспорту на різних відстанях від лінії існуючої забудови.

Ключові слова: *акустичне навантаження, лінії громадського транспорту, максимальний рівень шуму, трамвайне полотно, швидкість руху засобів громадського транспорту.*