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Research Paper

An IT System for Assessing Noise Level Distribution in Historical Urban Centers

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This article explores the challenge of identifying noise-generating factors in traffic flows (TFs) within the constrained spaces and imperfect transport networks of historical cities, using Lviv as a case study. Experimental studies were conducted to measure the equivalent noise levels at different times of the day on selected streets in Lviv. These streets are characterized by dense development, paved surfaces, and a high volume of vehicular and rail traffic. The study identified correlations between noise levels, traffic volumes, and vehicle speeds during daytime and nighttime periods. Notably, vehicle speed was found to have a more significant impact on noise levels than the number of vehicles.

Through the analysis of these findings, empirical mathematical models were developed and validated using the Lagrange interpolation polynomial to predict noise pollution levels on selected streets at specific times. The developed computer system enables quick forecasting of noise levels for a given street while simultaneously provides data to manage TF as a factor affecting noise generation. Crucially, this tool can also assist in calculating the required specifications for acoustic insulation on building façades adjacent to these TFs.

Keywords: IT system; noise measurement; road noise; MATLAB; equivalent noise level.

1. Introduction

The continued growth in vehicle numbers and the intensification of traffic flows (TFs) within the constrained urban spaces and flawed transport networks contribute to escalating noise pollution issues in most large cities. Addressing these challenges proves particularly difficult in the city of Lviv, especially in its central, historical district, which is dense with intersections and narrow streets. Elevated noise levels pose a significant public threat that directly impacts the health of urban residents. Consequently, designing an efficient passenger transport system in such settings necessitates the development and implementation of sophisticated software models that account not only for TFs but also for all contributing factors.

In an effort to assess and evaluate the environmental impact of transport, experimental studies were proposed and conducted to measure equivalent noise levels at various times of the day, focusing on selected streets in Lviv as representative examples of old historic cities. The chosen research locations are characterized by dense urban development along roads with heavy traffic on deteriorating cobblestone surfaces and tram routes, revealing the compounded challenges of managing urban noise in such environments.

2. Analysis of the latest research and publications

The impact of road noise on urban areas has been the subject of in-depth global research due to its significant effects on public health and quality of life. Across Europe, substantial studies have examined the contributing factors of noise pollution and proposed potential mitigation strategies (Brown, 2015; Ow, Ghosh, 2017; Titu *et al.*, 2022).

Research by Ozer *et al.* (2008) and Zambon *et al.* (2018) identify urbanization, population growth, and the associated surge in vehicular traffic as primary contributors to rising noise levels, particularly in urban settings. Such noise adversely affects human health, leading to sleep disorders, cardiovascular diseases, and cognitive impairments (Basner *et al.*, 2014; Dzhambov, Lercher, 2019; Hegewald *et al.*, 2020).

Further studies, such as those by Petrescu *et al.* (2015), recognize road characteristics (notably road surface conditions), along with traffic intensity, speed, and vehicle type as major noise sources in urban environments. Several mitigation strategies, including the implementation of quieter road surfaces, have been explored.

In Ukraine, the study of urban noise pollution caused by vehicular traffic has gained significant importance. Recent research (Mironova *et al.*, 2021; Reshetchenko, 2018; Luchko, 2010; Adamenko *et al.*, 2017) has examined noise pollution levels on the streets of various Ukrainian cities, including Lviv. Notably, an analysis by Grynchyshyn *et al.* (2021) revealed significant noise pollution on the main streets in central Lviv, where levels frequently exceeded permissible standards, especially in areas with narrow streets and aged buildings.

Research by Kalyn and Sheleviy (2016) focused on the issue of noise pollution within the urban ecosystem of Lviv, identifying its sources and key characteristics, evaluating methods for its mitigation, and analyzing noise levels across different city road segments.

Studies by Kachmar (2013), Kachmar and Lanets (2020), Kachmar *et al.* (2018), and Zubyk and Khodan (2014) explored the impact of road surface conditions on noise levels in Lviv. These works highlighted that permissible noise standards are often exceeded in urban areas, particularly in central Lviv. The authors argue that while reducing traffic noise using traditional methods is challenging and financially demanding, controlling and decreasing noise at the source is more feasible. In this context, passenger cars, which constitute a major portion of TF, are significant noise contributors. The research conducted in Lviv presents valuable insights for developing information systems aimed at assessing noise levels in populated areas, especially in cities with prolonged road load times like Lviv. The analysis of recent advancements and research in this field underscores the significance of these experiments and highlights opportunities for further scientific inquiry.

Noise pollution studies are critically important in urban environments, where the population is continually exposed to various sources of noise. Traffic noise, a significant contributor, results from the operation of vehicle engines, wheels, brakes, and aerodynamics (Zubyk, Khodan, 2014). The primary metric for evaluating noise levels is the equivalent continuous sound level that transmits the same amount of energy over a specific period as fluctuating noise would during the same period. The equivalent continuous sound level is calculated using the following equation:

$$L_{\mathrm{eq}} = 10\log\left(\frac{1}{t_2 - t_1}\int\limits_{t_1}^{t_2} 10^{0,1L_{A(t)}}\,\mathrm{d}t\right), \qquad (1)$$

where $L_{A(t)}$ is the sound level value and t_1, t_2 are the time periods of measurement.

3. Conducting an experiment

To gain a comprehensive understanding of the fluctuations in noise levels throughout the day, experiments were conducted at various times. These results are intriguing, as they illustrate the onset of increasing noise pollution levels.

The collected data are invaluable for further analysis and practical application. While noise intensity is a significant factor, the distribution and perception of noise and factors influencing these two are equally crucial. Additional data gathered during the measurements, such as the day of the week, time of day, air temperature, pressure, humidity, and wind speed, are pivotal for in-depth analysis. For instance, air temperature and humidity influence the speed of sound, while wind direction can alter noise direction and intensity.

Video recordings enabled the classification vehicles by category, including trams, which aids in identifying noise sources and evaluating their impact on overall noise pollution levels.

This supplementary information can be employed to calibrate computer simulation systems for sound propagation or to test new methods of predicting road noise. Additionally, it enhances the accuracy and reliability of models used to analyze and forecast noise pollution in Lviv. Such a meticulous approach to data collection and analysis contributes to the development of more effective noise control strategies, ultimately improving the quality of life for local residents.

For better data usability, a detailed diagram was created to document the building, with all measurement points clearly marked (Fig. 1).

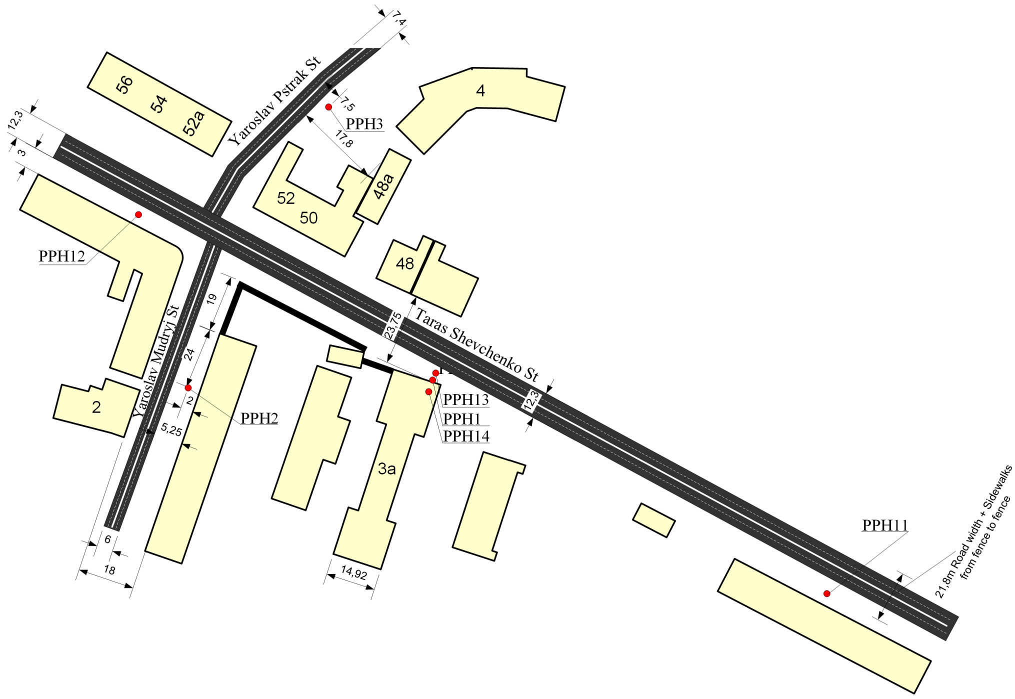

Fig. 1. Placement of measuring points on Shevchenko Street and adjacent streets.

4. Coordinates of measurement points

To facilitate further computational simulations, all points where noise levels were monitored were meticulously marked on the diagram, and their coordinates were accurately recorded using a GPS logger, as summarized in Table 1.

Additionally, extensive experiments were conducted on Taras Shevchenko Street (Fig. 2). The accumulated measurements adequately illustrate the diurnal trend of noise level fluctuations.

Fig. 2. Measurement of the equivalent noise level during the day on Taras Shevchenko Street.

The results are depicted in Fig. 3, where PPH1 represents the equivalent noise level [dB(A)] for Taras Shevchenko Street, PPH2 for Yarsolav Mudryj Street, and PPH3 for Yaroslav Pstrak Street. Notably, Taras Shevchenko Street exhibited the highest noise levels, which was anticipated due to the presence of trams. The analysis of Taras Shevchenko Street reveals a rapid increase in noise levels until 8:00, peaking at 10:00, followed by a gradual decline. However, this decline is minimal, only about 2.5 dB, during the rush hour from 17:30 to 19:00, after which noise levels rise again and only start to decrease after 21:30. The reduction in noise levels during the evening rush hour might initially appear counterintuitive due to the higher traffic volumes. However, it is the traffic congestion that significantly reduces vehicle speeds, which, particularly on cobblestone surfaces, results in lower noise levels.

An intriguing contrast is observed on Yaroslav Mudryj Street, where the conditions are reversed. Around 15:30, while noise levels are lower on Taras Shevchenko Street, they peak on Yaroslav Mudryj Street. This occurs because, with fewer cars on Taras Shevchenko Street, vehicles can move more swiftly along Yaroslav Mudryj street, generating more noise, and vice versa. When TFs onto Taras Shevchenko Street, Yaroslav Mudryj Street experiences congestion, causing vehicles near the measurement point to move at almost zero speed.

Table 1. Geographic coordinates of measurement points.

Measurement point number	GPS coordinates	Microphone height above road level [m]	Distance to the wall of the house [m]
PPH1	49.8440065, 24.0108481	1.5	2
PPH2	49.843972, 24.010861	1.5	2
PPH3	49.844806, 24.011583	1.5	7.5 (from the center of the road)

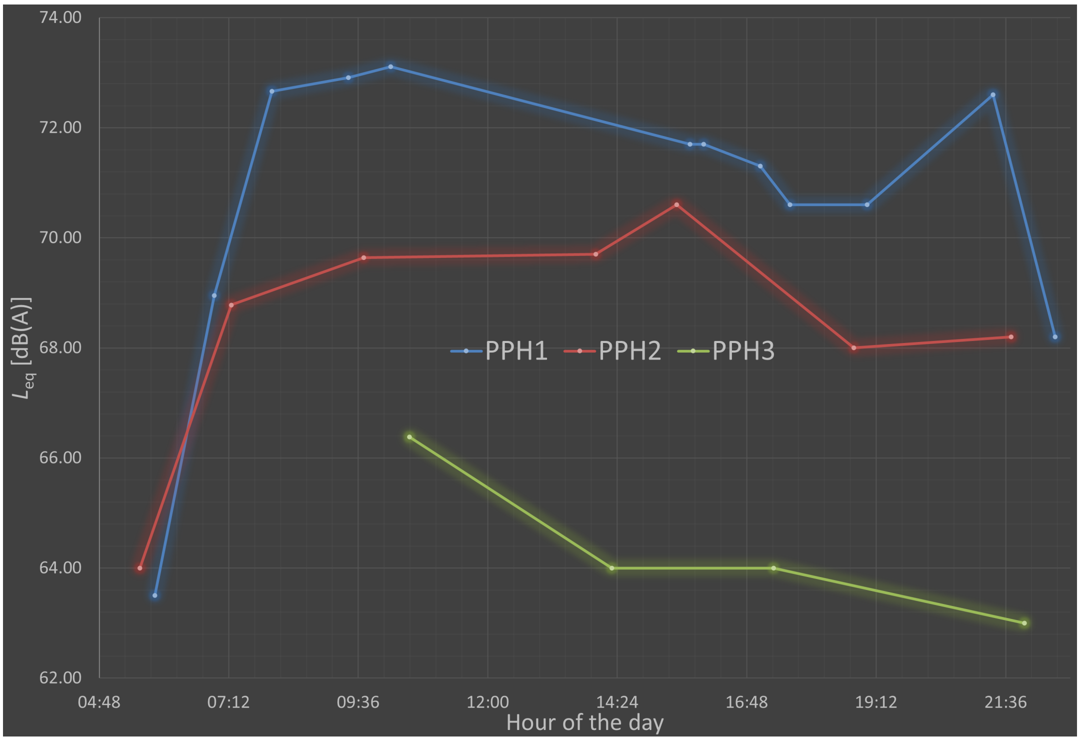

Fig. 3. Graph illustrating the dependence of noise level on the time of day.

Based on the experimental data, the hours with the most significant noise levels were identified: the most congested hour during the day is from 09:40 to 10:40 and at night from 22:00 to 23:00.

On Taras Shevchenko Street, vehicular traffic lacks smooth flow during the day, with vehicles frequently caught in traffic jams and moving at low speeds; conversely, at night, though fewer in number, vehicles tend to move at higher speeds.

5. Mathematical model

5.1. Mathematical model of the equivalent noise level for Taras Shevchenko Street

Using the Lagrange interpolation polynomial, a mathematical model was developed to determine the level of noise pollution on Taras Shevchenko Street in Lviv, as follows:

$$f(t) = \begin{cases} 67.482t + 48.395 & \text{for } 0.23 \le t \le 0.30, \\ 8.4245t + 66.235 & \text{for } 0.30 < t \le 0.40, \\ 0.3349t + 69.505 & \text{for } 0.40 < t \le 0.58, \\ 771.57t^3 - 1719.9t^2 + 1253.3t - 229.344 & \\ & \text{for } 0.58 < t \le 0.90, \end{cases} \tag{2}$$

where $f(t)$ represents the equivalent noise level [dB(A)] as a function of time, while t denotes the time of day, segmented into 24 hours. For instance, to calculate the noise level at 12:00, $t = \frac{12}{24} = 0.5$.

Observations from Fig. 3 indicate that noise levels vary significantly throughout the day. Consequently, to provide a more precise approximation of the experimental data, the time of day has been segmented into five distinct periods. A separate polynomial is calculated for each interval, specifically chosen to optimally reflect the temporal fluctuations in noise levels.

To evaluate the accuracy of the developed model (Eq. (2)), a graphical representation was constructed as depicted in Fig. 4. It clearly shows that the experimental data, indicated with red markers, align well

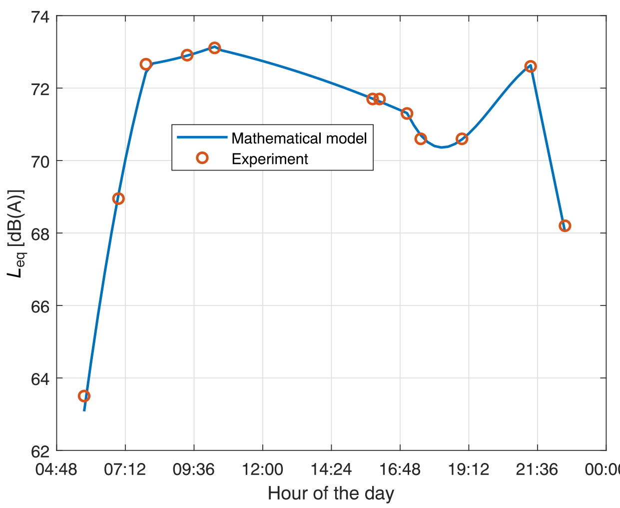

Fig. 4. Comparison of the mathematical model with experimental data of the equivalent noise level during the day for Shevchenko Street.

with the outcomes derived from the Taras Shevchenko Street model, represented by the blue line. This alignment validates the model's accuracy, confirming its suitability for estimating the equivalent noise levels from 5:00 to 23:00.

5.2. Mathematical model for determining the noise level on Yaroslav Mydryj Street

Similar to the previous model, the Lagrange interpolation polynomial was also employed to develop a mathematical model for determining the noise pollution levels on Yaroslav Mudryj Street in Lviv. This approach ensures consistency in modeling techniques across different urban settings, thereby facilitating comparative analyses and refined predictions:

$$f(t) = \begin{cases} -392.5t^2 + 327.7t + 7.0386 & \text{for } 0.24 \le t \le 0.33, \\ 20.644t^2 - 10.746t + 73.948 & \text{for } 0.33 < t \le 0.43, \\ -6.9624t^2 + 1.5893t + 73.692 & \text{for } 0.43 < t \le 0.71, \\ -1326.3t^3 + 3336.3t^2 - 2773.7t + 833.54 & \text{for } 0.71 < t \le 0.89, \\ -91.826t + 154.35 & \text{for } 0.89 < t \le 0.94. \end{cases} \tag{3}$$

The implementation of model (Eq. (3)) within the MATLAB system is illustrated in Fig. 5.

The program code, as depicted in Fig. 5, facilitated verification of the model's accuracy against experimental data. As the graph demonstrates, there is a congruence between the model and the experimental data, affirming the model's validity (Fig. 6).

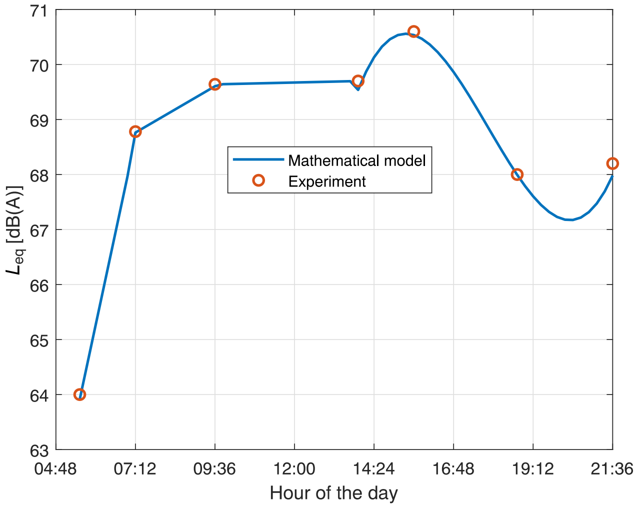

Fig. 6. Comparison of the mathematical model with experimental data of the equivalent noise level during the day for Yaroslav Mudryj Street.

Subsequent to model validation, a user interface was developed. Figure 7 displays this interface, which features a slider for rapidly adjusting the time of day, a drop-down list containing the names of streets for

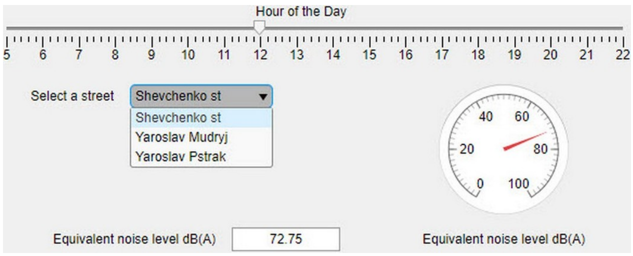

Fig. 7. User interface of the information system for determining the equivalent noise level for selected streets in Lviv.

```
twymSzew=[0.23 0.30 0.40 0.58 0.65 0.78 0.90];
ywymSzew=[64.00 68.78 69.64 69.70 70.60 68.00 68.20];

t=0.23:0.01:0.90;
[r c]=size(t);
for i=1:c
    if (t(i)>=0.23) & (t(i)<=0.30)
        y(i)=67.482.*t(i) + 48.395;
    elseif (t(i)>0.30) & (t(i)<=0.40)
        y(i)=8.4245.*t(i) + 66.235;
    elseif (t(i)>0.40) & (t(i)<=0.58)
        y(i)=0.3349.*t(i) + 69.505;
    elseif (t(i)>0.58) & (t(i)<=0.90)
        y(i)=771.57.*t(i).^3 - 1719.9.*t(i).^2 + 1253.3.*t(i) - 229.344;
    end
end

hp = plot(t,y,'LineWidth',1.5);
hold on
hpwym = plot(twymSzew,ywymSzew,'o','LineWidth',1.5);
ha = get(hp,'Parent');
Data = get(ha,'XTick');
timestr = datestr(Data,15);
set(ha,'XTickLabel',timestr);
```

Fig. 5. Segment of the program for determining the noise level on Yaroslav Mudryj Street during the day.

which the equivalent noise level will be calculated, and a display window that presents the results and a scale for expedient noise level assessment.

6. Conclusions

Experimental studies carried out on Taras Shevchenko Street and its vicinity revealed significant details regarding the acoustic environment. The findings indicate that vehicle speed has a more substantial effect on noise levels than traffic volume and correlates with the fluidity of TF. Furthermore, it was observed that the noise levels on these streets exceed the allowable daytime levels of 55 dB(A) (DBN V.1.1-31:2013, 2013). To mitigate noise pollution, measures such as reducing vehicle speeds or enhancing window insulation on building facades could be implemented to reduce the noise impact on residents.

The developed mathematical models for predicting equivalent noise levels based on the time of day have proven to be both effective and accurate in estimating noise levels on urban streets. The results validate the ability of our information system for the prompt and accurate assessment of noise levels on a designated street at a given time.

The findings and analyses from this research are essential for the further development of sound propagation modeling systems. They provide a foundation for calibrating and refining existing systems, as well as testing innovative methods and approaches within this field. This progress is expected to enhance the effectiveness and accuracy of noise prediction systems, ultimately contributing to reducing noise pollution and enhancing the quality of life for urban residents.

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