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Determination of the Instantaneous Noise Level Using a Discrete Road Traffic Flow Method

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ABSTRACT
Noise pollution from the streets is a critical problem for those living or working near them. Although the traffic noise problem is not a new research topic, it is usually limited to providing average values. This paper aims to determine variations in the instantaneous noise level and its influencing factors using the experimental noise level and theoretical traffic flow using a discrete traffic flow model. The research results suggested that the noise level could be changed by properly managing traffic flow with existing traffic lights without changing the infrastructure. The results of this research may be useful for city transport traffic management institutions.

KEYWORDS
traffic flow; noise; discrete method; intersection; traffic light.

1. INTRODUCTION

The development of city streets is limited by the dense layout of buildings and structures near roads. Therefore, traffic flow control methods play an essential role in managing existing street networks. One of the most efficient ways to control the traffic flow is to use controlled traffic lights. Currently, deterministic traffic light management methods [1–3] use the average values of predefined vehicle density parameters at intersections. The traffic flow parameters (speed, density, flow and acceleration) vary stochastically not only at traffic lights (intersections) but also along the entire length of the street or section [4]. These traffic flow parameters can reach values that substantially increase the noise level [5]. Most modelling methods do not estimate such sudden changes in traffic flow parameters. The most important maximum noise level values can be experimentally measured or modelled to assess the urban living environment.

Sudden changes in traffic flow parameters cause sudden fluctuations in the noise level emitted by traffic flow, which are felt by people living, working or simply standing near these streets. The noise calculation methods allow the determination of average noise level values, but they do not allow the determination of the instantaneous noise level [6–8]. However, they do not provide necessary information about the reasons for the change in the noise level as the dynamic processes of the traffic flow change. Therefore, it is essential to determine the range within which the noise level changes and how quickly these changes occur. Therefore, there is a need to develop a methodology that would allow the modelling of the noise level at any point at any node in a modelled street. Such a model could help propose traffic flow management methods to reduce noise levels in a city.

The object of this research is to investigate interactions of road traffic flows in the streets, the surrounding environment, and the instantaneous noise level emitted by vehicles to ultimately apply a discrete approach to study road traffic flow. This involved analysing the aspects of the instantaneous noise level and the factors determining them and describing the basic principles of the discrete road traffic flow research method to perform an instantaneous noise level determination.

This article involved the systematisation and generalisation of scientific concepts, empirical research results and a discrete method of road traffic flows. Mathematical modelling and result processing software included Visual Studio – Fortran, Matlab, Brüel & Kjær – Measurement Partner Suite and Microsoft Office.

In this article, the parameters of the discrete traffic flow research method were obtained from experimental studies to obtain more accurate modelling results when the traffic flow starts to move since this limitation was observed in the related research. The main aim of the research is to create a methodology for determining the instantaneous noise level of traffic flow using experimental studies and a modified discrete traffic flow research method. Using this discrete road traffic flow research method and experimental noise level data made it possible to determine the instantaneous noise level at each junction of a modelled street to determine a revised average noise level, which will be the first step in advancing traffic noise models and noise mapping.

2. REVIEW OF RELATED RESEARCH

Numerous researchers have conducted assessments of population exposure to road traffic noise. The research [9] carried out in the article shows that noise in the traffic area is much bigger than in the industrial area. The difference can reach 30 dB. Additionally, [10] studied population exposure to road traffic noise through a social survey and the creation of a noise map. Research [11] evaluated noise pollution and its effects on exposed individuals through sample investigations and noise measurements. Research [12] used a noise prediction model to estimate population exposure to daytime and nighttime traffic noise. In contemporary research, the calculation of traffic noise has evolved into noise mapping [13], enabling the creation of large-scale urban traffic noise maps based on parameters such as traffic volume and vehicle speed within the road network [14]. Research [15] emphasises that the ease of acquiring traffic flow parameters enables the generation of dynamic traffic noise maps or facilitates swift updates to noise maps in response to changes in traffic flow within urban areas.

The aforementioned traffic noise models serve as tools for estimating the sound quality of the environment [16], assessing noise pollution experienced by residents [17], and understanding how sound pressure levels impact drivers, passengers and residents in urban areas near traffic-loaded roads [10, 18]. The precision of traffic noise calculation and the modelling of noise mapping predominantly hinges on the accurate measurement of noise in proximity to roads, representing a focal point for researchers. In a study by [19], an analysis of the distribution of differences between measured and calculated sound levels was conducted. The findings indicated that utilising measured noise data collected near roads, incorporating accuracy considerations, contributes to the development and enhancement of noise models and noise mapping with greater accuracy compared to relying solely on calculated sound levels.

Both traffic noise models and noise mapping serve as methodologies for calculating the sound pressure level of traffic noise, facilitating the prediction of its impact on residents in proximity to roads. The efficiency of both methods is contingent upon the availability of accurate initial data for modelling and calculation. The optimal approach for acquiring such data involves conducting noise measurements near roads, yielding results that capture the nuanced variations in noise levels based on the speed and type of vehicles traversing urban areas. The data obtained through these measurements will prove instrumental in future endeavours to enhance the vehicle noise emission model, incorporating considerations such as traffic volume and driving speed of the vehicles.

Traffic noise is a widely discussed topic because it has the greatest impact on the quality of life of residents living nearby. Thus, there is a need to assess the noise level and find ways to reduce it. Several noise modelling software packages are designed to predict the noise level, and each has its accuracy in different countries.

The federal highway administration traffic noise model (FHWA model) is a computer program used to analyse and model traffic noise [20, 21]. The environment and possible reduction methods depend on the speed of the vehicle, the volume of traffic flow, and the geometry of the roads. The FHWA model (*Equation 1*) was mathematically described by [22–25]:

$$LA_{eq(h),i} = LA_{0\,N,i} + 10lg\left(\frac{N_i \pi D_0}{v_i T}\right) + 10lg\left(\frac{D_0}{D}\right)^{1+\alpha} + 10lg\left(\frac{\psi_a(\varphi_1,\varphi_2)}{\pi}\right) + \Delta S, \quad (1)$$

where, $LA_{eq(h),i}$ is the hourly equivalent continuous sound pressure level for a given vehicle class, dB(A); $LA_{0\,N,i}$ is the average noise level at a known distance from the noise source, dB(A); N_i is the number of vehicles, the class of which corresponds to the relevant hour; v_i is the average vehicle speed of the specified class, m/h; T is the duration of the investigated period, hours; D is the perpendicular distance from the centerline of the traffic lane to the microphone, m; D_0 is the known distance from the noise source, m; $D_0 =$ 15 m; α is a parameter that depends on the properties of the road surface, where $0 < \alpha < 1$ indicates a surface that highly reflects noise, and $\alpha = 0.5$ indicates a surface that absorbs noise; ψ_a is the adjusted end-of-road function, rad; φ_1, φ_2 are the angles of the observer from the normal line from the observer to the source and the lines to the end of the boundary section, rad; ΔS is attenuation due to road structure or noise barriers, dB(A).

Another model is the calculation of road traffic noise model (CoRTN model), which defines the spectrum of vehicle type and driving speed. This model describes the noise source emission expression (*Equation 2*), which gives an hourly A-weighted sound pressure level for a 10% flow time at a distance of 13.5 m from the source [26]. The model divides vehicles into two categories: light and heavy vehicles [27]:

$$LA_{10(1\,h)} = 10log_{10}\left(v + 40 + \frac{500}{v}\right) + 10log_{10}\left(1 + \frac{500r_{HV}}{v}\right) - 26{,}6, \quad (2)$$

where q is the flow, veh/h; v is the average speed, km/h; $r_{HV} = 0$ for light and $r_{HV} = 1$ heavy-duty vehicles. The weighted equivalent continuous sound pressure level $LA_{10(1\,h)}$ is obtained from $LA_{(1\,h)}$minus 3 dB(A).

The Richtlinien für den Lärmschutz an Straßen (RLS 90 model) determines the noise level 25 m from the road and 4 m above the ground. LA_{me} is determined by traffic flow characteristics (*Equation 3*), such as vehicle speed, weight distribution, road surface with an appropriate slope, and the addition of noise energy due to the reflection of buildings near the road [28]:

$$LA_{me} = 37{,}5 + 10log_{10}\big(q(1 + 0{,}082P)\big) + C_s + C_{rs} + C_g + C_r, \quad (3)$$

where, q is flow, veh/h; P is the percentage of trucks over 2,800 kg of all vehicles in traffic; C_s, C_{rs}, C_g, C_r are correction factors for vehicle speed, road surface, slope and multiple reflections.

The Acoustical Society of Japan road traffic noise prediction model (ASJ RTN Model 2013) calculates the noise level as a function of vehicle speed (*Equation 4*) [29] and [30]:

$$LA_W = a + blg(v) + \Delta LA_{surf} + \Delta LA_{grad} + \Delta LA_{dir} + \Delta LA_{ect}, \quad (4)$$

where, v is the average speed, km/h; a and b are the regression coefficients; ΔLA_{surf}, ΔLA_{grad}, ΔLA_{dir}, and ΔLA_{ect} are correction factors for the road surface, road gradient, the direction of sound propagation and other factors.

The harmonize model divides vehicles into five categories: light vehicles (cars, vans and trucks), medium-duty vehicles, heavy vehicles, other heavy vehicles and two-wheelers. The model is based on statistics with a reference distance of 7.5 m [27], [31–32]. The noise level is divided into the following expressions (*Equations 5* and *6*):

$$LA_{WR}(f) = a_R(f) + b_R(f)log\left(\frac{v}{v_{ref}}\right), \quad (5)$$

$$LA_{PR}(f) = a_P(f) + b_P(f)log\left(\frac{v}{v_{ref}}\right), \quad (6)$$

where the coefficients a_R, b_R, a_P and b_P are given in the 1/3 octave frequency range from 25 Hz to 10 kHz; v_{ref} is a reference speed, 70 km/h.

The sonROAD model takes into account two types of vehicles (*Equations 7* and *8*): light and heavy vehicles. The noise level description is based on the A-weighted maximum noise level per vehicle, 7.5 m from the source and 1.2 m above the ground [33].

$$LA_{W,car} = 28{,}5 + 10log\left(10^{0{,}1(7{,}3+35log(v))} + 10^{0{,}1\left(60{,}5+10log\left(1+\left(\frac{v}{44}\right)^{3{,}5}+\Delta_s\right)\right)} + \Delta_{GB}\right), \tag{7}$$

$$LA_{W,truck} = 28{,}5 + 10log\left(10^{0{,}1(16{,}3+35log(v))} + 10^{0{,}1\left(74{,}7+10log\left(1+\left(\frac{v}{56}\right)^{3{,}5}+\Delta_s\right)\right)} + \Delta_{GB}\right), \tag{8}$$

where v is the vehicle speed, km/h; Δ_{GB} is the road surface correction; Δ_s is the uphill correction, %. $\Delta_s =$ 0.8 g.

The Nordic environmental noise prediction method (Nord 2000 model) is used to calculate the sound pressure level at a monitored street node (9) from the sound power level corrected for the geometric difference of source LA_W, ground effect $K(Z)$, scattering effect $Ae(r)$ and atmospheric absorption A_A [34]:

$$LA(r) = LA_w - 10log(4\pi r^2) + K(Z) + Ae(r) + A_A, \tag{9}$$

where LA_w is the noise level in the analysed frequency band.

The French road traffic noise forecasting method (NMPB-Routes-2008 model) describes the attenuation of noise levels due to environmental conditions (*Equation 10*) [35] and [36]:

$$LA_{A,C} = LA_w - \left(A_{div} + A_{atm} + A_{bnd,C}\right), \tag{10}$$

where LA_w is the source of the noise level; A_{div} is the geometric spread; A_{atm} is atmospheric absorption; $A_{bnd,C}$ is attenuation related to the speed profile and limit characteristic of sound; A_{atm} is calculated according to ISO 9613-1 [37] standard, at 15°C and 70% relative humidity.

In the publication [38], a recurrent neural network was applied to traffic noise prediction with multivariate traffic features as predictors. The trained model could predict traffic noise according to the traffic scenario instead of setting audio devices for traffic noise recording. With the proposed model, real-time traffic noise predictions can be potentially feasible using only traffic data collected by different sensors in the city.

All of the aforementioned methodologies and research endeavours encompass a broad spectrum of measurements pertaining to vehicle traffic noise in urban environments. Investigations into traffic noise models and noise mapping necessitate frequent updates in the realm of traffic noise spectrum measurements due to the continuous variability in the noise spectrum of urban traffic. However, extant studies on traffic noise measurements have yet to yield universally applicable data for the development of traffic noise models and predictive mapping models. This deficiency arises from the predominant reliance on qualitative analyses or the utilisation of recorded data from a limited number of vehicles, rendering these studies lacking in universality. Consequently, these approaches are unable to accurately model the traffic noise spectrum based on variables such as traffic volume and vehicle driving speed without access to contemporary and generalised datasets obtained through systematic measurements.

In static noise models, roads are divided into sections where traffic flow is considered smooth and homogeneous [39]. These noise models usually include a propagation correction term for noise levels near an intersection, the value of which depends on the distance to the intersection. Analytic noise models attempt to capture the impact of interrupted traffic on the average vehicle speed profile. They split each road section into subsections where vehicles are assumed to have a constant average speed and homogeneous traffic flow conditions. In such conditions, to determine the noise level, it is enough to have parameters that can be determined using fundamental diagrams of the traffic flow. How to determine the noise level based on these data is presented in the publication [40].

Dynamic noise models or micro-simulation noise models are based on a dynamic traffic model, and as such can capture the specific traffic flow conditions in the vicinity of intersections or other chosen nodes. Such as green/red traffic lights at intersections that change speed with acceleration/deceleration [41] and durations of green and red cycles [42]. Microscopic models of traffic flows are most appropriate for noise research models, as they clearly describe the communication interactions between vehicles [41]. However, macroscopic traffic flow models are commonly used to model larger street networks. As a result, there is a need for a noise research model that can produce results close to dynamic noise models but use the original results from static models.

In summary, the noise level depends on many factors [43], all of which should be taken into account when assessing the noise level. Widely used methods to research vehicle noise allow only the average vehicle noise to be determined over a selected period, usually the hourly average noise level.

3. RESEARCH METHODOLOGY

When determining the instantaneous noise level emitted by traffic flow, it is necessary to know the parameters that affect it over time. To calculate the instantaneous noise emitted by a vehicle, we have developed a traffic flow emitted instantaneous noise level research methodology that estimates the speed, acceleration and density of vehicles at a respective street node. These parameters are derived from the theoretical modelling performed using the modified discrete road traffic flow research method.

The discrete road traffic flow research method [44–45] uses a system of equations to calculate the traffic flow density and speed for each street node. This approach takes into account the density and speed data from the previous and next street node (*Figure 1*). This method divides the modelled street into elements of a certain length, marked with the symbol *L*. The length of these elements is selected according to the desired model accuracy, where a shorter element *L* provides more accurate results. Node *i* connects adjacent street elements. The coordinate of the nodes is described by adding or subtracting the *n-th* node.

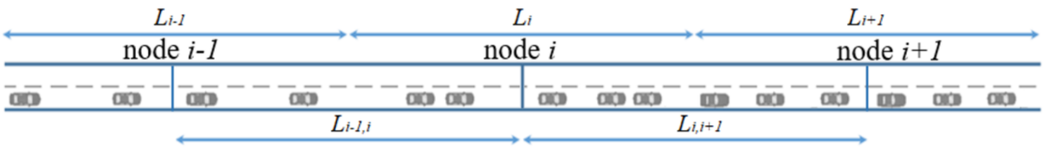


Figure 1 – Schematic representation of traffic flow values at each street node

Equations (11, 12) are given for each street node. *Equation 11* describes changes in traffic speed, and *Equation 12* describes changes in traffic density at each street node *i*:

$$\dot{v}_i = \sum_{j=1}^{N_{in}} p_{in,i,j}(t) r_{v_i,in,i,j} \Phi_{v,in,i,j}\left(k_j(t-\tau_{i,j}), v_j(t-\tau_{i,j}), k_i(t), v_i(t)\right) v_i(t) - \sum_{j=1}^{N_{out}} p_{out,i,j}(t) r_{v_i,out,i,j} \Phi_{v,out,i,j}\left(k_i(t), v_i(t), k_j(t), v_j(t)\right) v_i(t), \tag{11}$$

$$\dot{k}_i = \sum_{j=1}^{N_{in}} p_{in,i,j}(t) r_{k_i,in,i,j} \Phi_{k,in,i,j}\left(k_j(t-\tau_{i,j}), v_j(t-\tau_{i,j}), k_i(t), v_i(t)\right) k_i(t) - \sum_{j=1}^{N_{out}} p_{out,i,j}(t) r_{k_i,out,i,j} \Phi_{k,out,i,j}\left(k_i(t), v_i(t), k_j(t), v_j(t)\right) v_i(t), \tag{12}$$

where $k_i(t)$ is the vehicle density at the *i*-th street node; $v_i(t)$ is the vehicle speed at the *i*-th street node; $p_{in,i,j}$, $p_{out,i,j}$ is the coefficient of probability of traffic flow splitting or joining at a street node *i,j*; $r_{k_i,in,i,j}$, $r_{k_i,out,i,j}$, $r_{v_i,in,i,j}$, and $r_{v_i,out,i,j}$ are the discrete road traffic flow research method coefficients; $\Phi_{k,in,i,j}\left(k_j(t-\tau_{i,j}), v_j(t-\tau_{i,j}), k_i(t), v_i(t)\right)$; $\Phi_{k,out,i,j}\left(k_i(t), v_i(t), k_j(t), v_j(t)\right)$; $\Phi_{v,in,i,j}\left(k_j(t-\tau_{i,j}), v_j(t-\tau_{i,j}), k_i(t), v_i(t)\right)$; $\Phi_{v,out,i,j}\left(k_i(t), v_i(t), k_j(t), v_j(t)\right)$ are the discrete road traffic flow research method nonlinear functions; N_{in}, N_{out} are the number of lanes that enter and exit the *i*-th street node.

In the discrete road traffic flow research method, $r_{k_i,in,i,j}$, $r_{k_i,out,i,j}$, $r_{v_i,in,i,j}$, and $r_{v_i,out,i,j}$ coefficients are used in the equations of the modelled street node to describe changes in traffic flow density and speed. These are accepted as constant parameters in the method. However, when studying traffic flow using the discrete road traffic flow research method, when the traffic flow stopped in front of the traffic light, and then the green traffic light came on, the obtained values of traffic flow acceleration were too high. In addition, vehicles accumulated in the traffic lanes began to move with a delay compared with the first vehicle at the traffic light.

Experimental studies of traffic flow have shown that the most rational functions of these parameters are (*Equations 13* and *14*):

$$r_{k_i,in,i,j} = tanh\left(c_{k_{in}}\left(\frac{k_i(t)}{k_{i,max}}\right)^2\right), \tag{13}$$

$$r_{k_i,out,i,j} = tanh\left(c_{k_{out}}\left(\frac{k_i(t)}{k_{i,max}}\right)^2\right), \tag{14}$$

where $c_{k_{in}}$ and $c_{k_{out}}$ are coefficients, $c_{k_{in}} = 0{,}15$; $c_{k_{out}} = 0{,}15$; *tanh* is the hyperbolic tangent; $k_{i,max}$ is the maximum possible density, veh./m; $k_i(t)$ is the vehicle density at time *t*, aut./m.

These functions $r_{k_i,in,i,j}$, $r_{k_i,out,i,j}$ use a hyperbolic tangent to find the coefficients $c_{k_{in}}$, $c_{k_{out}}$, the function curve of which is determined experimentally. This most accurately replicates the trend of traffic flow rate change. Coefficients $c_{k_{in}}$ and $c_{k_{out}}$ are introduced to reduce the sensitivity of traffic flow acceleration. Their selection determines the correspondence of the traffic flow to the experimental results. Because the movement of traffic flow depends on the current density of vehicles $k_i(t)$ and the maximum possible density on the street $k_{i,max}$, the values of the coefficients $r_{k_i,in,i,j}$ and $r_{k_i,out,i,j}$ vary depending on current street conditions.

The sequence of the instantaneous noise level calculation of the traffic flow is given in *Figure 2*, which consists of both theoretical and experimental research data. Using the modified discrete road traffic flow research method, the results of theoretical studies of traffic flow dynamic processes were obtained. The instantaneous method requires knowing the traffic flow speed, acceleration and density to determine how the noise level changes from these dynamic traffic flow parameters. The experimental research results are designed to relate the parameters of traffic flow dynamic processes to the noise level emitted by vehicles. The following results from experimental studies of noise emitted by traffic flow were used to determine the instantaneous noise level: the dependence of noise level changes on the acceleration of vehicles and their speed.

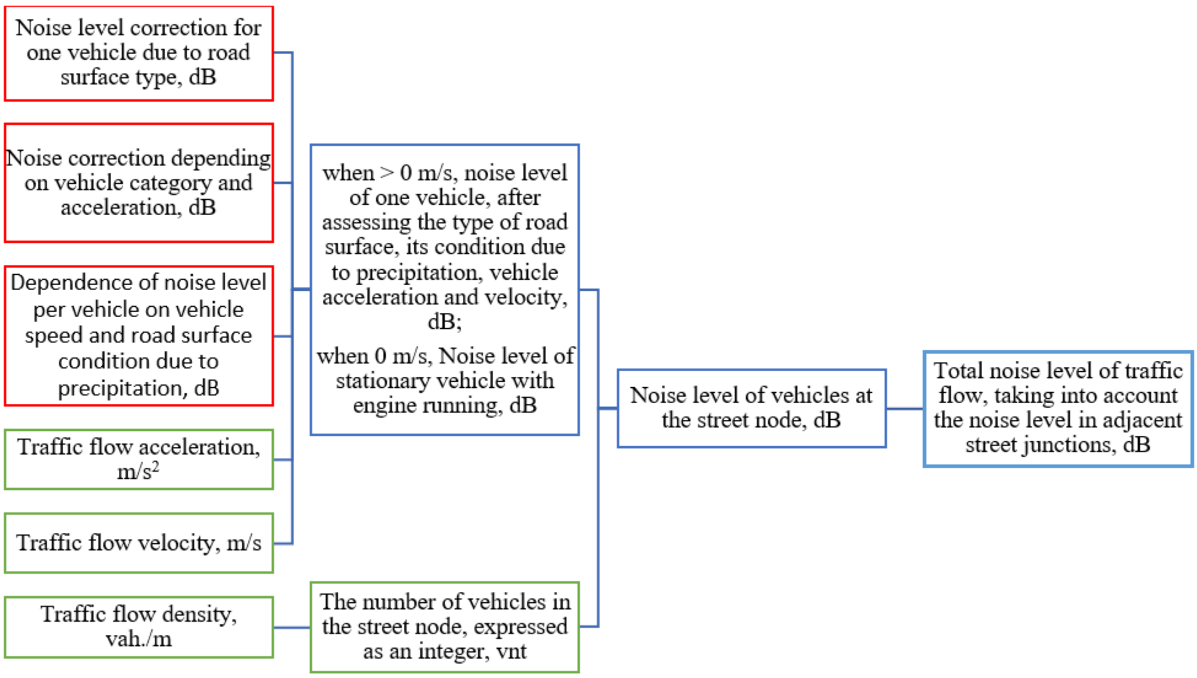


Figure 2 – Methodology sequence for calculating the instantaneous noise level emitted by traffic flow

The instantaneous noise level was calculated at each street node where the speed, acceleration and density of the traffic flow were known. To do this, we first created an instantaneous noise level calculation scheme (*Figure 3*) to indicate the location for the noise level determination. The distance between street nodes (L) is given in the scheme for calculating the instantaneous noise level emitted by the vehicles, where r_i is the distance from the vehicle to the reference point, at which the noise level is known from experimental measurements, and r_T is the distance from the vehicle to the reference point at which the noise level is unknown, m.

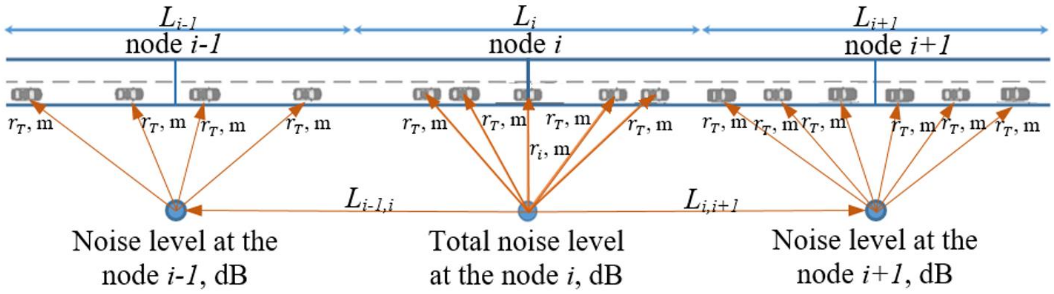


Figure 3 – Scheme for calculating the instantaneous noise level of vehicles on the street

From theoretical vehicle density research, there were 15 vehicles in the section of the street around the nodes i-1, i, i+1, where the noise level was calculated:

$$N_i(t) = k(t)L_{i,i+1}, \tag{15}$$

where $k(t)$ is the vehicle density, aut./m; $L_{i,i+1}$ is the length of the street element, m.

The resulting number of vehicles $N_i(t)$ was rounded to the nearest whole number. In this way, separate vehicles could be identified as the noise source.

Experimental studies were used to determine the dependence of the noise level of one vehicle on its speed. Based on the experimental data, regression equations were generated that related the instantaneous noise level to the theoretical traffic flow speed obtained from the modified discrete road traffic flow research method. These noise level values were further adjusted for one vehicle using correction factors that depended on a vehicle's acceleration.

The known value of a vehicle's density was assigned to the calculated node, which covered half of the street element around that node. Therefore, the calculated number of vehicles was evenly distributed around the street junction. Each vehicle was then at different distances from the reference point to calculate its noise level (*Figure 3*), for which the noise level was adjusted depending on each vehicle's distance to the reference point (*Equation 16*), dB [46]:

$$LA_{eq,T} = LA_{eq,i} - 20log\left(\frac{r_T}{r_i}\right), \tag{16}$$

where $LA_{eq,i}$ is the noise level at a distance r_i, dB; $LA_{eq,T}$ is the noise level at a distance r_T; r_i is the distance to the reference point at which the noise level is known, m; r_T is the distance to the reference point at which the noise level is unknown, m.

If the results of the theoretical calculations show that there is no vehicle in the node under study at that time, a background noise level shall be taken, which may be different due to other noise sources close to the street.

The direction of movement of vehicles does not affect the noise level at the nodes being calculated. However, more lanes can increase the number of vehicles. Vehicles in further lanes simply need to be included in the calculations when estimating the distance to the calculation reference point.

The propulsion noise depends on speed and cruising mode: accelerating, cruising or decelerating. The emission law is presented in the study published by [47], assuming no slope on the road. Changes in a vehicle's noise level due to its acceleration have been published by [48]. Using data from this report, a regression curve and its equations were obtained (*Figure 4*), which showed how much the noise level increased or decreased with certain acceleration and deceleration of the vehicle. These equations were used to estimate changes in the noise level with a vehicle's acceleration, the results of which were obtained using the modified discrete road traffic flow research method.

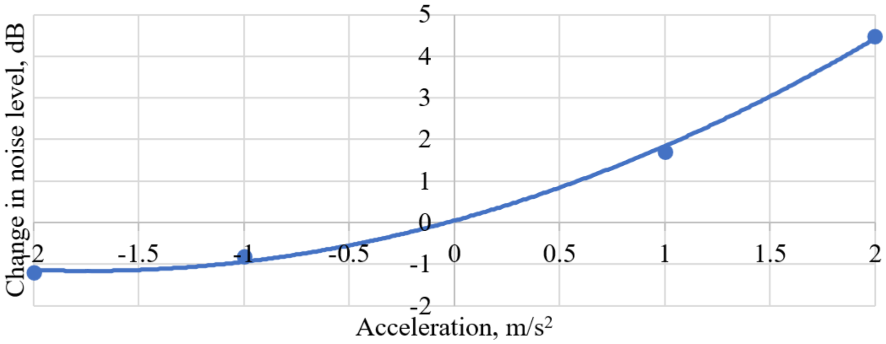


Figure 4 – Noise level dependence on passenger car acceleration regarding [48]

In general, vehicles need more power to accelerate uphill and less to decelerate downhill. Therefore, including terrain slope in the model would allow for a more accurate estimation of vehicle acceleration patterns, which in turn affects noise levels. This requires further experimental studies.

After evaluating the speed and acceleration of a vehicle, its instantaneous noise level was determined. If the vehicle speed was 0 m/s, the noise level of the vehicle with its engine stopped was taken. The traffic flow emitted instantaneous noise level research methodology does not evaluate vehicle features that allow an engine to shut down automatically using the "Start-stop" system when stopped.

The total instantaneous noise level of traffic flow was calculated by using *Equation 17* to estimate the instantaneous noise level emitted by each vehicle in the investigated street node at the reference point near the street where the noise level was known [46, 49].

$$LA_{eq,T,sum} = 10log\left(\sum_{i=1}^{n} 10^{\left(\frac{LA_{eq,T}}{10}\right)}\right), \tag{17}$$

where $LA_{eq,T}$ is the noise level emitted by one vehicle that reached near the street reference point, dB.

Finally, changes in the total instantaneous noise level over time were calculated by estimating the instantaneous noise level at adjacent streets and nodes at each street node (*Figure 2*). This required knowing the distances between nodes *i*-1 and *i*+1.

To improve the accuracy of the results, future improvements to the discrete road traffic flow research method should allow the inhomogeneity of the traffic flow to be assessed by evaluating the dynamic processes of the movement of the different vehicle categories in the traffic flow. By improving the traffic flow emitted instantaneous noise level research methodology it would be possible to assess the noise emitted by vehicle engines. Such studies are important for noise levels when vehicles travel at low speeds on city streets. It would also be relevant to assess the noise level of electric vehicles, which are becoming more popular.

4. EXPERIMENTAL SECTION

To obtain the speed dependence of the noise level emitted by a vehicle, experimental studies were performed according to the ISO 11819-1 [50] standard for the statistical method of measurement of noise (SPB – Statistical Pass-By) emitted by road vehicles. According to the instructions and to increase the reliability of the research results, the following rules were applied:

— The chosen research site had no loud ambient sounds;
— There were no sound-reflecting objects within a radius of 10 m around the microphone;
— The device with the microphone was mounted on a stand at a height of 1.2 m above the ground and 7.5 m from the centre of the lane under investigation.

A TC25 traffic counter classifier was built 2 m from the carriageway, at a height of 1 m, directed 45° to the road so that the recorded vehicles were all located in front of the noise analyser. Before recording the vehicles, the clock of the Brüel & Kjær 2250 noise analyser was synchronised with the clock of the TC25 traffic counter classifier. The time and speed of each vehicle were recorded in real-time.

The instruments used for the research included a Brüel & Kjær 2250 noise analyser and a TC25 traffic counter classifier. In accordance with the above-mentioned requirements, the measurements were carried out at Kairėnai street in Vilnius (Lithuania) (*Figure 5*). This road has asphalt concrete with up to 11 mm of crushed stone (AC 11), such road surface is common in the category of main roads on Lithuania roads [51].

Figure 5 – Noise measurement procedure upon applying SPB method

To relate these data to the speeds obtained using the modified discrete road traffic flow research method, the most appropriate regression curve and its equation were determined according to the maximum coefficient of determination. Then, after determining the most appropriate regression equations and applying *Equation 18* used by [52], the Pearson correlation coefficient was determined. Based on the volume of the correlation coefficient, conclusions about the strength of the correlation relationships were made;

$$r_{v_i,LA_{eq,i}} = \frac{m\sum_{i=1}^{m} v_i\, LA_{eq,i} - \sum_{i=1}^{m} v_i \sum_{i=1}^{m} LA_{eq,i}}{\sqrt{m\sum_{i=1}^{m} v_i^2 - \left(\sum_{i=1}^{m} v_i\right)^2} \cdot \sqrt{m\sum_{i=1}^{m} LA_{eq,i}^2 - \left(\sum_{i=1}^{m} LA_{eq,i}\right)^2}}, \quad (18)$$

where m is the number of registered vehicles; v_i is the speed of the i-th vehicle, km/h; $LA_{eq,i}$ is the noise level emitted by the i-th vehicle, dB.

The correlation coefficient of the regression curve indicates the strength of the relationship, and the scale of values is given in *Table 1*.

Table 1 – The scale of correlation coefficient values [53]

Very strong	Strong	Medium	Weak	Very weak	No correlation
1	1…0.7	0.7…0.5	0.5…0.2	0.2…0	0

The correlation coefficient of the regression curve must not be less than the calculated minimum correlation coefficient (*Equation 19*) [52] because only in this case does the obtained regression curve correlate with the obtained experimental results;

$$r_{min} = \frac{t_{\alpha,n}}{\sqrt{m - 2 + t_{\alpha,n}^2}}, \quad (19)$$

where $t_{\alpha,n}$ is the Student's coefficient with $n = m{-}2$ degrees of freedom and α level of confidence.

The limits of the confidence interval at which the measurand is likely to be a parameter were calculated using *Equation 20* [54]:

$$CI_i = LA_{eq}(v_i) \pm t_{\alpha,n} SE \sqrt{\frac{1}{n} + \frac{(v_i - \bar{v})^2}{\sum_{i=1}^{m}((v_i - v_i - \bar{v})^2)}}, \quad (20)$$

where $LA_{eq}(v_i)$ is the noise level, dB at speed v_i, km/h; SE is the standard error; n is the degree of freedom; v is the speed, km/h; $\bar{v}$ is the average speed, km/h.

The minimum correlation coefficient and the limits of the confidence interval were calculated at a confidence level of 0.05, which was sufficient to determine the correlation of the data.

During the measurement, 419 cars running on dry asphalt were recorded. The values for the noise level of passenger cars ranged from 66 dB to 84 dB at speeds between 50 km/h and 119 km/h (*Figure 6*).

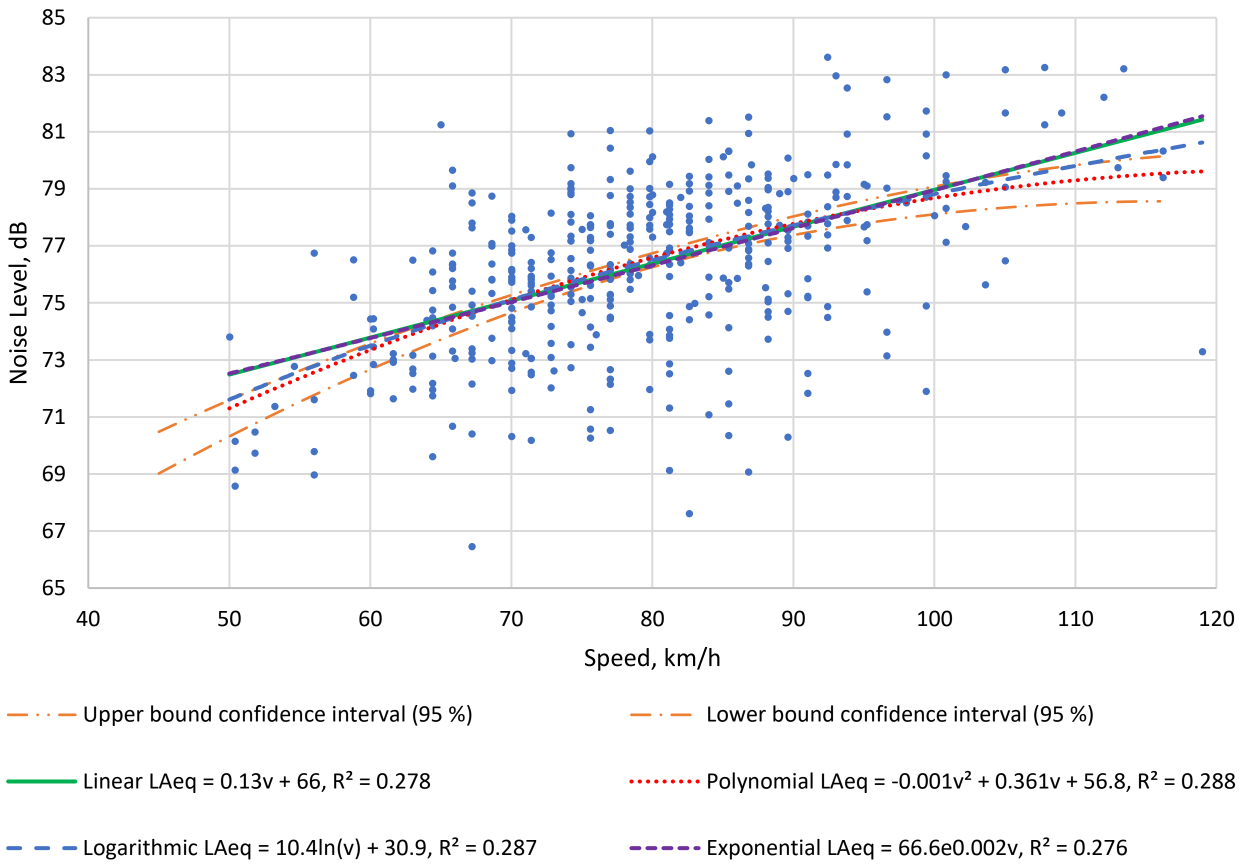


Figure 6 – Noise level dependence on the speed of passenger cars driving on dry asphalt

By analysing the speed dependence data of the noise level of passenger cars and drawing regression curves (their equations and coefficients of determination are presented in *Figure 6*), it was found that the polynomial curve corresponded the best to the measured values. The coefficient of determination of the polynomial curve was larger than the others ($R^2 = 0.288$). The correlation coefficient of this regression curve was $r = 0.527$ and showed an medium relationship with the recorded data. The lowest correlation coefficient for the number of vehicles was $r_{min} = 0.096$. This means that the regression curve correlated with the experimental results.

5. RESULTS AND DATA PROCESSING

The instantaneous noise levels of the modelled street were obtained using the traffic flow dynamic processes obtained by the modified discrete road traffic flow research method in the generated traffic flow emitted instantaneous noise level research methodology (*Figure 7*). Across the street, the instantaneous noise level varied from the model-specific background noise level (40 dB), with a value of 81.9 dB. To obtain results, a condition was introduced in which the traffic flow consisted of a homogeneous traffic flow, i.e. only the regression equation for cars running on dry asphalt (AC 11) was used.

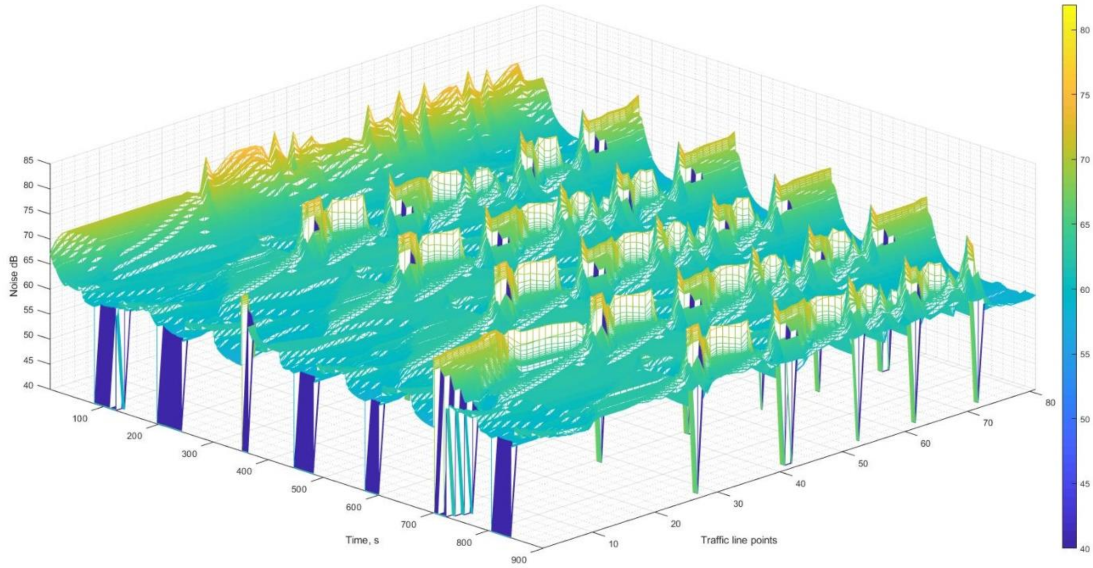
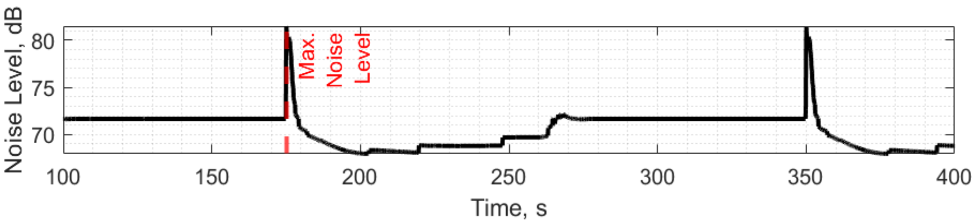
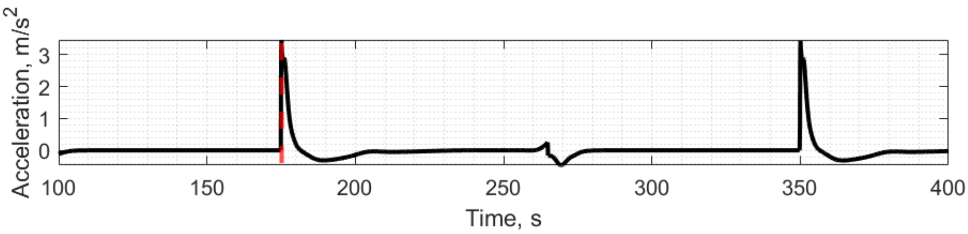


Figure 7 – Variation of instantaneous noise level emitted by traffic flow over time for all street nodes

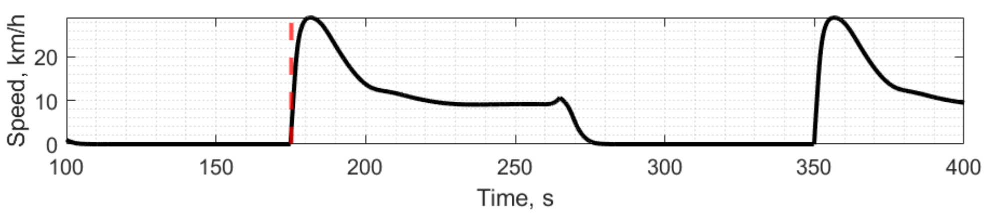
Changes in the instantaneous noise level over time are shown in *Figure 8a*, which depended on the traffic flow acceleration (*Figure 8b*), the traffic flow speed (*Figure 8c*) and the number of vehicles (*Figure 8d*) at the modelled street node. When the green traffic light came on (*Figure 8e*), the graph showed a signal value of 1. When the red signal was illuminated (a signal value of 0), the graph showed that traffic flow acceleration when the green traffic light came on increased the instantaneous noise level. It can also be seen that as the number of vehicles increased at a constant traffic flow rate, the instantaneous noise level gradually increased. There was also a slight change in the instantaneous noise level and a slight decrease or increase in the traffic flow speed.



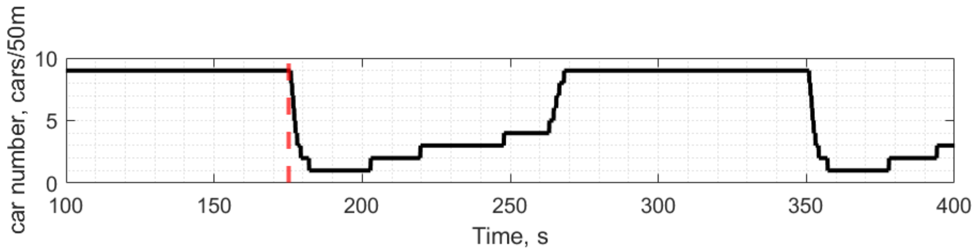
(a)



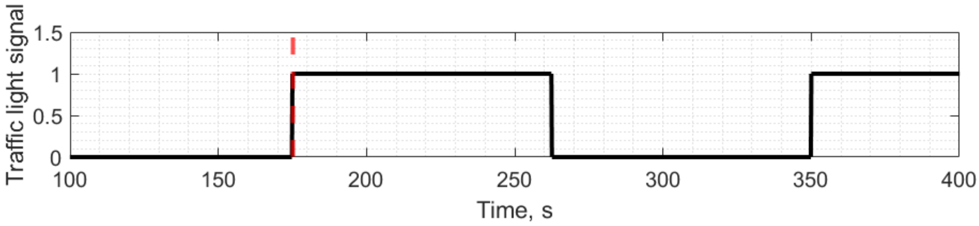
(b)



(c)



(d)



(e)

Figure 8 – Time dependence of the instantaneous noise level and traffic flow parameters at the 41st street node: a) – noise level; b) – acceleration; c) – speed; d) – number of vehicles; e) – traffic signal

The highest noise levels were found at the 41st node, which is one of the intersections regulated by traffic lights on one of the modelled streets. Here, the maximum instantaneous noise level was 81.9 dB when the traffic flow began to move when the green traffic light was activated because, at that time, the traffic flow acceleration (3.46 m/s^2) and the vehicle density (0.18 aut./m) were highest, and the traffic flow speed was 2.34 km/h.

These results indicate that traffic flow can be controlled to reduce the instantaneous noise level on the streets by controlling traffic light switching periods. Because acceleration was the parameter with the greatest influence, it would be appropriate to determine the switching of the traffic lights to obtain a green wave. In this way, traffic flow without braking could move at a constant speed over an entire stretch of a road. Regarding the final point – research indicates that the acceleration parameter plays a pivotal role in influencing noise levels. To achieve effective noise reduction, we propose the implementation of a traffic light control system designed to establish a “green wave” along the targeted road stretch. By adjusting traffic lights to match the acceleration patterns of vehicles, the goal is to ensure a smooth and uninterrupted traffic flow, reducing the necessity for frequent braking. This optimised flow will contribute to a more serene urban environment by minimising the abrupt acceleration and deceleration phases that typically generate higher noise levels.

Integrating the instantaneous noise level model into adaptive traffic control systems (ATCS) can enhance efficiency in mitigating the impact of traffic noise on the environment. As the model offers real-time monitoring of noise levels across various city areas, these data can be leveraged by ATCS to diminish noise levels in noise-sensitive zones. Furthermore, these data prove to be beneficial for adjusting traffic signal timings, considering not only traffic volume but also noise levels.

Accurate definition of noise levels allows targeted action to be taken in specific areas with higher noise levels due to motorised traffic. The results of this study are based on the results of traffic flow macro modelling. Therefore, the average traffic flow values obtained here were recalculated by separating them into individual vehicles. Microsimulation can be used to obtain even more accurate results Additionally, if necessary, this model does not account for the impact of vehicle accelerations on the emitted noise. This allows for the possibility of replacing all or some of the motorized vehicles in the model with electric vehicles, whose acceleration does not significantly affect the noise level.

Vehicle age, engine type and so on are areas of improvement for this model for further research.

In final, current research not only emphasises the positive correlation between traffic flow control and noise reduction but also outlines the essential components and measures required for the successful implementation of such a model. By incorporating advanced technology, infrastructure, public awareness and policy integration, cities can pave the way for quieter and more harmonious urban environments.

6. CONCLUSIONS

In the research, we developed an experimental method for determining the traffic noise level that considered the condition of the road surface, vehicle speed and vehicle type. This method allowed for the estimation of the instantaneous noise level at any node. The instantaneous maximum noise level was determined using the modified discrete road traffic flow research method and the developed traffic flow instantaneous noise level research methodology near intersections. The instantaneous maximum noise level varied by up to 81.9 dB on the simulated street when the vehicle density was 0.18 aut./m and the traffic flow speed was 2.34 km/h. The biggest influence on the noise level was when vehicles accelerated or decelerated. The second most significant parameter determining the noise level was the number of vehicles, while the vehicle speed had the least impact on noise.

Hence, the primary and fundamental objective of the present research endeavour was to establish an experimental methodology for quantifying traffic noise levels, accounting for variables such as road surface conditions, vehicle speed and vehicle types In future studies, it is essential to emphasize the importance of improving traffic noise models and noise mapping by conducting a thorough analysis that includes different types of vehicles, such as motorcycles, passenger cars, vans, buses, and both light and heavy trucks.

This analysis should extend to diverse environmental conditions in urban settings, incorporating distinct road pavements characterised by dry, wet, snowy and snow rut-affected surfaces.

DISCLOSURE STATEMENT

The authors have no conflicts of interest to declare that are relevant to the content of this article. The authors did not receive support from any organisation for the submitted work.

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Momentinio triukšmo lygio nustatymas taikant diskretinį kelių transporto priemonių srauto tyrimo metodą

Santrauka

Gatvių keliamas triukšmas yra didelė problema šalia gatvių gyvenantiems ar dirbantiems žmonėms. Nors eismo triukšmo problema nėra nauja tyrimo tema, dažniausiai apsiribojama vidutinių verčių pateikimu. Šiame straipsnyje siekiama nustatyti momentinio triukšmo lygio pokyčius ir jį įtakojančius veiksnius, naudojant eksperimentinį triukšmo lygį ir teorinį transporto priemonių srautą taikant diskretinį kelių transporto priemonių srauto tyrimo metodą. Tyrimų rezultatai parodė, kad triukšmo lygį galima pakeisti tinkamai valdant eismo srautus esamais šviesoforais, nekeičiant infrastruktūros. Šio tyrimo rezultatai gali būti naudingi miesto transporto priemonių eismo valdymo institucijoms.

Raktiniai žodžiai

Transporto priemonių srautas; triukšmas; diskretinis metodas; sankryža; šviesoforas.