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Research paper

Modeling the effect of electric vehicles on noise levels in the vicinity of rural road sections

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Abstract: Numerous European countries experience a steady increase in the share of electric (EV) and hybrid electric (HEV) vehicles in the traffic stream. These vehicles, often referred to as low- or zero-emission vehicles, significantly reduce air pollution in the road environment. They also have a positive effect on noise levels in city centers and in the surroundings of low-speed roads. Nevertheless, issues related to modeling noise from electric and hybrid vehicles in the outdoor environment are still not fully explored, especially in the rural road settings. The article attempts to assess the degree of noise reduction around these roads based on different percentages of EVs in the traffic stream. Input data for noise modeling was obtained from 133 sections of homogeneous rural roads in Poland. Based on their analysis, it was first determined on how many of these road sections electric-vehicle-induced noise reduction would be possible, taking into account the traffic speeds occurring on them. Next, a computational algorithm that can be used to calculate noise reduction in the CNOSSOS-EU model is presented, and noise modeling is performed based on it for different percentages of electric vehicles in the traffic stream.

Keywords: electric vehicles, noise, traffic noise modeling, environmental, acoustic calculation

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1. Introduction

The development of low- and zero-emission transportation is one of the top priorities of the European Union's environmental policy. This is expressed in published directives [1] and communications, [2] as well as highlighted in the European Commission White Paper [3]. The European Strategy for Low-Emission Mobility [4] was also published in 2016. In Poland, the key document defining the strategy for the development of electromobility is the Strategy for Responsible Development (Polish: Strategia na rzecz Odpowiedzialnego Rozwoju – SOR) [5], which was additionally included in the Electromobility Development Plan (Polish: Plan Rozwoju Elektromobilności – PRE) [6], developed in connection with the requirements of the European Union. It should be noted that in most of the justifications for the legislation, attention has been paid to the growing popularity of electric cars used in public transportation and by private owners. There is also a growing public awareness of using electromobility to improve the quality of the environment and thus people's health [7, 8]. This is directly related to the use of newer cars manufactured in recent years, generating less noise compared to older vehicles [9]. According to analyses conducted by PZPM (Polish Automotive Industry Association) and PSPA (Polish Alternative Fuels Association), there were just over 50,000 electric and hybrid vehicles registered in Poland at the end of July 2022, with 49% of them being fully electric [10].

Electric cars (EV – Electric Vehicle) and hybrid cars (HEV – Hybrid Electric Vehicle) have a positive effect, not only on reducing air pollution, but also on reducing acoustic impacts in the road environment. They result in a reduction of environmental noise, by completely (EV) or partially (HEV) reducing one of the main sources of automobile noise, which is the drivetrain noise that dominates at low traffic speeds (less than 40–50 km/h) [11–14]. Hybrid cars run in electric mode to a limited extent. The gasoline internal combustion engine in most models turns on when the battery is low (and starts charging it). These cars start emitting noise from the drivetrain in such a mode (the noise is generated by the internal combustion drive). Because of that, the reduction of this sound source is only partial, although vehicles of this type are still much quieter than internal-combustion-only vehicles [7, 15].

Increasing the share of electric cars in the traffic stream also has an effect on reducing the noise emitted into the road environment. Still, there are only a few publications in the literature on this subject. Mention should be made, e.g., of the results achieved in FOREVER [16, 17] and LEO projects [18–21]. The goals of these projects were related to reducing noise from electric cars, but did not directly address the topic of reducing acoustic impacts in the external environment.

The FOREVER (Future Operational Impacts of Electric Vehicles on National European Roads) [17] project commissioned by CEDR (Conference of European Directors of Roads) and article [16] determined the appropriate correction factors for the CNOSSOS-EU model [22, 23] lowering the acoustic power of the electric vehicles' drivetrain, while keeping the rolling noise acoustic power constant. These coefficients were determined only for light vehicles belonging to Category 1 (in the CNOSSOS-EU model). They are shown broken down into 1/1 octave frequencies at Table 1.

Table 1. Correction factors for the sound power level of the electric vehicle drivetrain in the CNOSSOS-EU model [16, 17]

1/1 octave band middle frequency [Hz]	63	125	250	500	1000	2000	4000
Correction factor [dB(A)]	–5.0	–1.7	–4.2	–15.0	–15.0	–15.0	–13.8

Different values of this coefficient have been adopted depending on the center frequencies of the 1/1 octave bands, with the arbitrary determination that these values must not be greater than – 15 dB(A) [16, 17].

Between 2013 and 2016, Gdańsk University of Technology (Poland) and SINTEF (Norway) performed research under the LEO (Low Emission Optimized tyres and road surfaces for electric and hybrid vehicles) project [18–21]. The main objective of this project was to study the latest, state-of-the-art car tyres and road surfaces that had the potential to reduce noise by electric and hybrid (when moving in electric mode) cars. The project included determining the impact of tyres used on electric cars in combination with various noise-reducing surfaces. An attempt was also made to predict noise reduction with the introduction of electric and hybrid vehicles into the traffic stream. The German TRANECAM model was used for this purpose. It was estimated that the reduction due to the introduction of 25% electric vehicles into the traffic stream (corresponding to Norwegian conditions) could result in a noise reduction of about 0.5 dB [19].

A Spanish study [24], which estimated what kind of noise reduction the introduction of passenger electric vehicles into urban traffic could bring is also noteworthy. In that paper, calculations were made for four scenarios: electric vehicles moving in smooth traffic, electric vehicles equipped with AVAS (Acoustic Vehicle Alerting System), electric vehicles moving in urban traffic, and electric vehicles moving in urban traffic and equipped with AVAS. Furthermore, the varying share of trucks in the traffic stream was taken into account. The calculations were made using the French NMPBRoutes-2008 method. The results of the study demonstrate that the introduction of electric vehicles into the traffic stream can improve the acoustic climate around urban roads and streets only at very low traffic speeds. It should be emphasized that simulations made in the publication [24] assume that 100% of internal combustion passenger vehicles will be replaced by electric vehicles, which seems impossible to achieve in the near future, having considered the forecasts (e.g. [8]). In addition, the contribution of other vehicles and the inclusion of AVAS significantly limit this reduction.

AVAS improves road safety conditions, yet at the same time increases the noise generated by electric and hybrid vehicles to the road environment. Directions to modify this system so that the sound emitted by AVAS is matched to the background sound level [25] (sound louder in urban areas and quieter in rural areas) seem to be a good solution. This will help maintain an adequate level of safety for road users while reducing vehicle noise, especially in quiet zones [7], in case of which it is often necessary to take appropriate measures to reduce environmental noise [26].

2. Calculation method

The research described in the article consisted of comparing the results of acoustic modeling performed with the CNOSSOS-EU model with and without the inclusion of electric vehicles in the traffic stream. Noise modeling without considering this parameter performed using input data in terms of traffic volume, with distinguishing detailed vehicle composition and the speed at which the vehicles traveled. In the second case, the share of electric vehicles in vehicle categories 1, 2 and 3 was included in the road noise modeling. Due to the lack of available data on the noisiness of electric motorcycles and their minimal contribution to the traffic stream, noise reductions for this category of vehicles (groups 4a and 4b) were not considered [7].

In order to determine the effect of introducing electric vehicles into the traffic stream, the study involved acoustic modeling using the following assumptions:

- an equal adjustment factor for the sound power level of the drivetrain noise was adopted for electric and hybrid vehicles,
- the correction factor for the sound power level of drivetrain noise was adopted only for those categories of vehicles for which the speed was equal to or less than 50 km/h (for higher speeds, rolling noise becomes dominant and the impact of the contribution of electric and hybrid vehicles is negligible),
- the calculations did not take into account the effect of AVAS (in case of all input data sets, speeds were greater than 30 km/h, at which the system is not activated),
- the percentage of electric vehicles in the traffic stream was assumed to be the same for all vehicle categories (from 0% to 100%, with a 10% step),
- the correction factors for the sound power level of the drivetrain noise for electric vehicles were adopted based on the results of the FOREVER project [16, 17], and were the same for vehicle categories 1, 2 and 3. For category 4a and 4b vehicles, no correction of calculation results was accepted due to the absence of available data.

The research and analysis used data from environmental studies performed in Poland between 2005 and 2019. A total of 58 studies covering 133 homogeneous road sections were used. Traffic volume forecasts were made for each road section, followed by "in situ" studies of actual traffic parameters (a total of 3,192 hours of measurements) – traffic volume, vehicle speed and the vehicle composition in the traffic stream. Thus, this research reflects the actual conditions that existed on the country's rural roads [7, 27].

The geometric model used for the acoustic calculations was developed in SoundPLAN (version 8.0) in such a way as to avoid the influence of other, unstudied factors and inputs. A straight road section of 1 km was assumed, located on flat terrain. A sound absorption coefficient of 1 was assumed for the terrain surrounding the road (sound-absorbing terrain: e.g., grass, meadow, etc.). This type of areas occur mostly adjacent to roads in rural areas. What is more, this type of terrain minimizes the impact of ground reflections, which can affect the calculation results. Acoustic calculations were made at a reference point (receptor) located 10.0 m from the edge of the outermost lane at a height of 4.0 m above ground level.

In order to determine the relationship describing the coefficient of sound power level reduction of a line source due to the participation of electric and/or hybrid vehicles in the traffic stream, two situations were compared with each other, in which different sets of input data were adopted for calculations. The first assumes that the traffic stream includes both internal combustion-powered vehicles, as well as EVs. Under this assumption, the sound power level of a line source was denoted as $L_{\mathrm{W,eq,line,ICE+EV}}$ (the subscripts next to the symbols follow the nomenclature used in the CNOSSOS-EU method). The second situation assumes that only internal combustion-powered vehicles are in the traffic stream. In this case, the sound power level of the line source is denoted $L_{\mathrm{W,eq,line,ICE}}$. Traffic volumes and speeds for the different vehicle categories are the same in both situations. Therefore, it can be assumed that the reduction in the sound power level of a line source based on the contribution of electric vehicles to the traffic stream is equal to the energy difference in sound power levels for situations one and two. It is expressed by the following relationship:

$$\Delta L_{\mathrm{W,eq,line,EV}} = L_{\mathrm{W,eq,line,ICE+EV}} \ominus L_{\mathrm{W,eq,line,ICE}} \quad [\mathrm{dB/m}] \tag{2.1}$$

where $\Delta L_{\mathrm{W,eq,line,EV}}$ is sound power level of a linear source for electric vehicles [dB/m], $\Delta L_{\mathrm{W,eq,line,ICE+EV}}$ is sound power level of a linear source for combustion and electric vehicles [dB/m] and $\Delta L_{\mathrm{W,eq,line,ICE}}$ is sound power level of a linear source for combustion vehicles [dB/m].

Assuming that in the traffic stream there are vehicles belonging to different categories m and that the share of electrically powered vehicles for each category is equal to $u_{\mathrm{EV,m}}$, one can assume that the sound power level of the sound source for each category m $L_{\mathrm{W,eq,line,m,ICE+EV}}$ [dB/m] is equal to the sum of the energy sound power of internal combustion powered vehicles $L_{\mathrm{W,eq,line,m,(1-u_{EV,m})ICE}}$ [dB/m] and electric vehicles $L_{\mathrm{W,eq,line,m,u_{EV,m}EV}}$ [dB/m] moving on the road, expressed by the relationship:

$$L_{\mathrm{W,eq,line,m,ICE+EV}} = L_{\mathrm{W,eq,line,m,(1-u_{EV,m})ICE}} \oplus L_{\mathrm{W,eq,line,m,u_{EV,m}EV}} \quad [\mathrm{dB/m}] \tag{2.2}$$

The relationship (2.1) thus takes the following form for each category of vehicles m:

$$\Delta_{L_{\mathrm{W,eq,line,m,EV}}} = L_{\mathrm{W,eq,line,m,(1-u_{EV,m})ICE}} \oplus L_{\mathrm{W,eq,line,m,u_{EV,m}EV}} \ominus L_{\mathrm{W,eq,line,m,ICE}} \quad [\mathrm{dB/m}] \tag{2.3}$$

When converted to logarithmic form, we obtain:

$$\Delta_{L_{\mathrm{W,eq,line,m,EV}}} = 10\log\left(\frac{10^{\frac{L_{\mathrm{W,eq,line,m,(1-u_{EV,m})ICE}}}{10}} + 10^{\frac{L_{\mathrm{W,eq,line,m,u_{EV,m}EV}}}{10}}}{10^{\frac{L_{\mathrm{W,eq,line,m,ICE}}}{10}}}\right) \quad [\mathrm{dB/m}] \tag{2.4}$$

By generalizing the relationship (2.4) for all categories of vehicles in the traffic stream, we obtain:

$$\Delta_{L_{\mathrm{W,eq,line,EV}}} = 10\log\left(\frac{\sum 10^{L_{\mathrm{W,eq,line,m,(1-u_{EV,m})ICE}}/10} + \sum 10^{L_{\mathrm{W,eq,line,m,u_{EV,m}EV}}/10}}{\sum 10^{L_{\mathrm{W,eq,line,m,ICE}}/10}}\right) \quad [\mathrm{dB/m}] \tag{2.5}$$

The algorithms adopted in the CNOSSOS-EU model are used in the following part. The directional sound power of a line source per meter in the frequency band i for a category of vehicles m $L_{\text{W,eq,line,i,m}}$ [dB/m] moving at an average speed v_{m} [km/h] and hourly intensity Q_{m} [V/h], and the sound power level of a single sound source $L_{\text{W,i,min}}$ [dB] this model is equal [22, 23]:

$$L_{\text{W}',\text{eq,line,i,m}} = L_{\text{W,i,m}} + 10\log\left(\frac{Q_{\text{m}}}{1000 \times v_{\text{m}}}\right) \quad [\text{dB/m}] \tag{2.6}$$

Similarly, the directional sound power of a line source for the category of electric vehicles m $L_{\text{W,eq,line,i,m,uEV,mEV}}$ [dB/m] with their percentage of the traffic stream equal to $u_{\text{EV,m}}$ and sound power level of a single sound source $L_{\text{W,i,m,EV}}$ [dB]:

$$L_{\text{W}',\text{eq,line,i,m,u}_{\text{EV,m}}\text{EV}} = L_{\text{W,i,m,EV}} + 10\log\left(\frac{u_{\text{EV,m}} \cdot Q_{\text{m}}}{1000 \cdot v_{\text{m}}}\right) \quad [\text{dB/m}] \tag{2.7}$$

While the directional sound power of a line source for the category of internal combustion engine vehicles m $L_{\text{W,eq,line,i,m},(1-\text{u}_{\text{EV,m}})\text{EV}}$ [dB/m] at their percentage of the traffic stream equal to $1 - u_{\text{EV,m}}$ and sound power level of a single sound source $L_{\text{W,i,m,ICE}}$ [dB]:

$$L_{\text{W}',\text{eq,line,i,m},(1-\text{u}_{\text{EV,m}})\text{ICE}} = L_{\text{W,i,m,ICE}} + 10\log\left(\frac{(1-u_{\text{EV,m}}) \cdot Q_{\text{m}}}{1000 \cdot v_{\text{m}}}\right) \quad [\text{dB/m}] \tag{2.8}$$

If we assume that there are only internal combustion engine vehicles in the traffic stream, the directional sound power of a line source for vehicle category m $L_{\text{W,eq,line,i,m,ICE}}$ [dB/m] and the sound power level of a single sound source $L_{\text{W,i,m,ICE}}$ [dB] is equal to:

$$L_{\text{W}',\text{eq,line,i,m,ICE}} = L_{\text{W,i,m,ICE}} + 10\log\left(\frac{Q_{\text{m}}}{1000 \times v_{\text{m}}}\right) \quad [\text{dB/m}] \tag{2.9}$$

The sound power level of a single sound source in the CNOSSOS-EU model corresponds to the sum of the acoustic energy of the rolling noise and the drivetrain (for categories 4a and 4b, the rolling noise energy is equal to 0). After denoting the sound power level of the rolling noise as $L_{\text{W,R,i,m}}(v_{\text{m}})$ [dB] and the sound power level of the drivetrain noise $L_{\text{W,P,i,m}}(v_{\text{m}})$ [dB], we obtain the following relationship [22, 23]:

$$L_{\text{W,i,m}}(v_{\text{m}}) = 10\log\left(10^{L_{\text{WR,i,m}}(v_{\text{m}})/10} + 10^{L_{\text{WP,i,m}}(v_{\text{m}})/10}\right) \quad [\text{dB}] \tag{2.10}$$

where $L_{\text{W,i,m}}(v_{\text{m}})$ is sound power level of single sound source [dB] at speed v_{m} [km/h].

The acoustic power of rolling noise in the frequency band i for vehicles of categories m = 1, 2 or 3 is the same as for internal combustion and electric vehicles, and equal to the acoustic power calculated directly from the CNOSSOS-EU model algorithms. However, the sound power of the drivetrain will differ in that case. After denoting the coefficients defined in the model algorithms as $\text{A}_{\text{P,i,m}}$ and $\text{B}_{\text{P,i,m}}$ for a reference speed v_{ref} of 70 km/h, and the sum of the correction coefficients (the effect of the pavement on the drivetrain in the form of absorption, the effect of the slope of the road gradeline and speed changes in the vicinity of intersections) as $\Delta_{\mathrm{LWP,i,m}}$ [dB], the general equation of the CNOSSOS-EU model for the sound power level of the drivetrain can be written as following [22, 23]:

$$L_{\mathrm{WP,i,m}} = \mathrm{A}_{\mathrm{P,i,m}} + \mathrm{B}_{\mathrm{P,i,m}} \cdot \frac{(v_{\mathrm{m}} - v_{\mathrm{ref}})}{v_{\mathrm{ref}}} + \Delta L_{\mathrm{WP,i,m}} \quad [\mathrm{dB}] \tag{2.11}$$

The sound power level of the noise of the drivetrain for internal combustion vehicles will be equal to the level defined directly in the CNOSSOS-EU algorithms in the relationship (2.11). For electrically powered vehicles, this relationship should be modified by adding an additional correction factor $\Delta L_{\mathrm{WP,i,m,EV}}$ [dB] to represent the reduction in sound power of the drivetrain due to the use of electric propulsion. In this case, the relationship (2.11) takes the following shape for electrically powered vehicles:

$$L_{\mathrm{WP,i,m,EV}} = \mathrm{A}_{\mathrm{P,i,m}} + \mathrm{B}_{\mathrm{P,i,m}} \cdot \frac{(v_{\mathrm{m}} - v_{\mathrm{ref}})}{v_{\mathrm{ref}}} + \Delta L_{\mathrm{WP,i,m}} + \Delta L_{\mathrm{WP,i,m,EV}} \quad [\mathrm{dB}] \tag{2.12}$$

When simplified, it can be written as:

$$L_{\mathrm{WP,i,m,EV}} = L_{\mathrm{WP,i,m}} + \Delta L_{\mathrm{WP,i,m,EV}} \quad [\mathrm{dB}] \tag{2.13}$$

Having considered the foregoing, the sound power level of a single sound source representing an internal combustion engine vehicle $L_{\mathrm{W,i,m,ICE}}(v_{\mathrm{m}})$ [dB] takes the following form:

$$L_{\mathrm{W,i,m,ICE}}(v_{\mathrm{m}}) = 10 \log\left(10^{L_{\mathrm{WR,i,m}}(v_{\mathrm{m}})/10} + 10^{L_{\mathrm{WP,i,m}}(v_{\mathrm{m}})/10}\right) \quad [\mathrm{dB}] \tag{2.14}$$

An analogy can be written for the sound power level of a single sound source representing an electric vehicle $L_{\mathrm{W,i,m,EV}}(v_{\mathrm{m}})$ [dB]:

$$L_{\mathrm{W,i,m,EV}}(v_{\mathrm{m}}) = 10 \log\left(10^{L_{\mathrm{WR,i,m}}(v_{\mathrm{m}})/10} + 10^{(L_{\mathrm{WP,i,m}}(v_{\mathrm{m}})+\Delta L_{\mathrm{WP,i,m,EV}})/10}\right) \quad [\mathrm{dB}] \tag{2.15}$$

By substituting the relationships (2.14) and (2.15) to (2.7), (2.8), (2.9), one obtains the relations (2.16), (2.17) and (2.18), respectively:

$$L_{\mathrm{W',eq,line,i,m,(1-u_{EV,m})ICE}} = 10 \log\left(10^{L_{\mathrm{WR,i,m}}(v_{\mathrm{m}})/10} + 10^{L_{\mathrm{WP,i,m}}(v_{\mathrm{m}})/10}\right) + 10 \log\left(\frac{(1 - u_{\mathrm{EV,m}}) \cdot Q_{\mathrm{m}}}{1000 \cdot v_{\mathrm{m}}}\right) \quad [\mathrm{dB/m}] \tag{2.16}$$

$$L_{\mathrm{W,eq,line,i,m,u_{EV,m}EV}} = 10 \log\left(10^{L_{\mathrm{WR,i,m}}(v_{\mathrm{m}})/10} + 10^{(L_{\mathrm{WP,i,m}}(v_{\mathrm{m}})+\Delta L_{\mathrm{WP,i,m,EV}})/10}\right) + 10 \log\left(\frac{u_{\mathrm{EV,m}} \cdot Q_{\mathrm{m}}}{1000 \cdot v_{\mathrm{m}}}\right) \quad [\mathrm{dB/m}] \tag{2.17}$$

$$L_{\mathrm{W',eq,line,i,m,ICE}} = 10 \log\left(10^{L_{\mathrm{WR,i,m}}(v_{\mathrm{m}})/10} + 10^{L_{\mathrm{WP,i,m}}(v_{\mathrm{m}})/10}\right) + 10 \log\left(\frac{Q_{\mathrm{m}}}{1000 \times v_{\mathrm{m}}}\right) \quad [\mathrm{dB/m}] \tag{2.18}$$

Next, by transforming the relationship (2.16), (2.17) and (2.18), one obtains (2.19), (2.20) and (2.21), respectively:

$$L_{W',\mathrm{eq,line,i,m},(1-u_{\mathrm{EV,m}})\mathrm{ICE}} = 10\log\left(\frac{\left(10^{L_{\mathrm{WR,i,m}}(v_m)/10}+10^{L_{\mathrm{WP,i,m}}(v_m)/10}\right)\cdot(1-u_{\mathrm{EV,m}})\cdot Q_m}{1000\cdot v_m}\right)\ [\mathrm{dB/m}] \tag{2.19}$$

$$L_{W',\mathrm{eq,line,i,m},u_{\mathrm{EV,m}}\mathrm{EV}} = 10\log\left(\frac{\left(10^{L_{\mathrm{WR,i,m}}(v_m)/10}+10^{(L_{\mathrm{WP,i,m}}(v_m)+\Delta L_{\mathrm{WP,i,m,EV}})/10}\right)\cdot u_{\mathrm{EV,m}}\cdot Q_m}{1000\cdot v_m}\right)\ [\mathrm{dB/m}] \tag{2.20}$$

$$L_{W',\mathrm{eq,line,i,m,ICE}} = 10\log\left(\frac{\left(10^{L_{\mathrm{WR,i,m}}(v_m)/10}+10^{L_{\mathrm{WP,i,m}}(v_m)/10}\right)\cdot Q_m}{1000\cdot v_m}\right)\ [\mathrm{dB/m}] \tag{2.21}$$

By substituting the relationships (2.19), (2.20), (2.21) to (2.5) and simplifying, the final relationship (2.22) was obtained, describing the reduction in the sound power level of a line source, meaning the road after the introduction of electric vehicles into the traffic stream, in a percentage for each category equal to $u_{\mathrm{EV,m}}$, and with the sound power level of the drivetrain reduced by $\Delta L_{\mathrm{WP,i,m,EV}}$. This relationship takes the following form:

$$\begin{aligned}\Delta L_{\mathrm{W,eq,line,EV}} &= 10\log\left(\sum\frac{\left(10^{L_{\mathrm{WR,i,m}}(v_m)/10}+10^{L_{\mathrm{WP,i,m}}(v_m)/10}\right)\cdot(1-u_{\mathrm{EV,m}})\cdot Q_m}{v_m}\right.\\ &\quad\left.+\sum\frac{\left(10^{L_{\mathrm{WR,i,m}}(v_m)/10}+10^{(L_{\mathrm{WP,i,m}}(v_m)+\Delta L_{\mathrm{WP,i,m,EV}})/10}\right)\cdot u_{\mathrm{EV,m}}\cdot Q_m}{v_m}\right)\\ &\quad-10\log\left(\sum\frac{\left(10^{\frac{L_{\mathrm{WR,i,m}}(v_m)}{10}}+10^{\frac{L_{\mathrm{WP,i,m}}(v_m)}{10}}\right)\cdot Q_m}{v_m}\right)\ [\mathrm{dB/m}]\end{aligned} \tag{2.22}$$

When deriving the relationship (2.22), a simplifying assumption was made about the equivalence of the sound power level of the drivetrain of both electric and hybrid vehicles. In reality, however, the levels are not equal. With a known percentage of the traffic stream of electric vehicles $u_{\mathrm{EV,m}}$ and hybrid vehicles $u_{\mathrm{HEV,m}}$, and a known correction factor for the sound power level of the drivetrain for electric vehicles $\Delta L_{\mathrm{WP,i,m,EV}}$ [dB] and hybrid vehicles $\Delta L_{\mathrm{WP,i,m,HEV}}$ [dB] by analogy, a relationship can be written for the reduction in the sound power level of the line source $\Delta L_{\mathrm{W,eq,line,EV,HEV}}$ [dB/m] with a distinction between the two vehicle types. The relationship then takes the following form:

$$\begin{aligned}(2.23)\quad & \Delta L_{\mathrm{W,eq,line,EV,HEV}} \\ &= 10\log\left(\sum \frac{\left(10^{L_{\mathrm{WR,i,m}}(v_\mathrm{m})/10} + 10^{L_{\mathrm{WP,i,m}}(v_\mathrm{m})/10}\right)\cdot\left(1 - u_{\mathrm{EV,m}} - u_{\mathrm{HEV,m}}\right)\cdot Q_\mathrm{m}}{v_\mathrm{m}}\right. \\ &\quad + \sum \frac{\left(10^{L_{\mathrm{WR,i,m}}(v_\mathrm{m})/10} + 10^{(L_{\mathrm{WP,i,m}}(v_\mathrm{m})+\Delta L_{\mathrm{WP,i,m,EV}})/10}\right)\cdot u_{\mathrm{EV,m}}\cdot Q_\mathrm{m}}{v_\mathrm{m}} \\ &\quad \left. + \sum \frac{\left(10^{L_{\mathrm{WR,i,m}}(v_\mathrm{m})/10} + 10^{(L_{\mathrm{WP,i,m}}(v_\mathrm{m})+\Delta L_{\mathrm{WP,i,m,HEV}})/10}\right)\cdot u_{\mathrm{HEV,m}}\cdot Q_\mathrm{m}}{v_\mathrm{m}}\right) \\ &\quad - 10\log\left(\sum \frac{\left(10^{L_{\mathrm{WR,i,m}}(v_\mathrm{m})/10} + 10^{L_{\mathrm{WP,i,m}}(v_\mathrm{m})/10}\right)\cdot Q_\mathrm{m}}{v_\mathrm{m}}\right) \quad [\mathrm{dB/m}]\end{aligned}$$

Relationships (2.22) and (2.23) can be used to model road noise using the CNOSSOS-EU method to determine noise reductions when electric and/or hybrid vehicles are introduced into the traffic stream.

3. Results

First, data obtained from actual environmental studies were analyzed in terms of vehicle speeds. For all the datasets studied, only a small proportion of the speeds for each group of vehicles was less than or equal to 50 km/h (Fig. 1 below). These results represent how vehicle speeds are distributed on Poland's rural roads. The following data is broken down by time of day (from 6:00 am to 10:00 pm) and time of night (from 10:00 pm to 6:00 am). This corresponds to the environmental noise limit values set in Poland for such intervals.

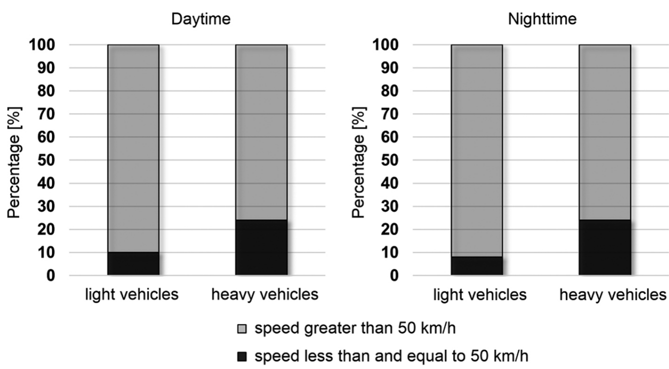

Fig. 1. Share of surveyed road sections on which vehicles traveled at speeds less than or equal to 50 km/h

Only about 10% of light vehicles and about 25% of heavy vehicles, traveled at speeds less than or equal to 50 km/h in the studied cases. These were mainly sections constituting village crossings, where the speed limit for built-up areas was in effect. In some of the cases studied, only one category of vehicles (generally heavy vehicles) was traveling at speeds less than or equal to 50 km/h. In such situations, the effect of road noise reduction due to the introduction of electric vehicles into the traffic stream was smaller (depending on the parameters and vehicles composition).

The results of noise modeling in the form of a correction (reducing) factor for the sound level due to the electric vehicle share in the traffic stream are shown below in Fig. 2 for the daytime and in Fig. 3 for the nighttime. These results represent only those road sections where speed for at least one group of vehicles was equal to or less than 50 km/h. The reduction in acoustic impact was zero in other cases.

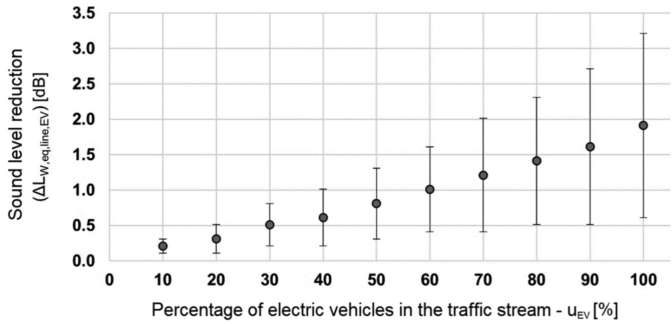

Fig. 2. Correction factors for road noise modeling results due to percentage of electric vehicles ($\Delta L_{\mathrm{W,eq,line,EV}}$) – daytime

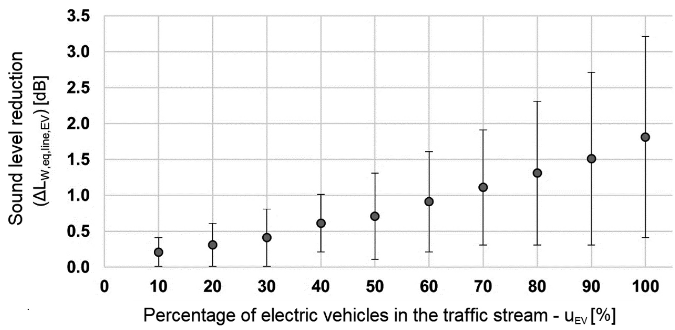

Fig. 3. Correction factors for road noise modeling results due to percentage of electric vehicles ($\Delta L_{\mathrm{W,eq,line,EV}}$) – nighttime

When analyzing the data presented in the charts above, it should be noted that the average values of noise reduction after the introduction of electric vehicles into the traffic stream, expressed by the coefficients $\Delta L_{\mathrm{W,eq,line,EV}}$, range from 0.2 dB to 1.9 dB for the daytime and from 0.2 dB to 1.8 dB for the nighttime. In some cases, the reductions were much larger. For example, for the percentage of EVs in the traffic stream at 50%, they were 1.7 dB for daytime and 2.7 dB for nighttime, and for the 70% share: 2.5 dB for daytime and

3.1 dB for nighttime, respectively. In practice, however, EV percentages at this level are very high and unrealistic to be met in most European countries in the near future. It should be noted that the results obtained are consistent with the conclusions formulated within the LEO project (which estimated a reduction of about 0.5 dB, assuming 25% electric vehicle share in the traffic stream [19]).

The speed at which all vehicle categories travel must be effectively reduced in order to achieve the greatest possible reduction in road noise achieved by electric vehicle contribution to the traffic stream. It should be no more than 50 km/h (with 30–40 km/h being desirable), especially in built-up areas.

It should also be clarified that in each case of traffic flow analyzed, different percentages of each vehicle category (light vehicles, medium heavy vehicles, heavy vehicles) could be observed. In some situations, vehicles of all categories moved at speeds of less than 50 km/h, while in others there were only heavy vehicles or medium and heavy ones. As mentioned before, noise reduction after the introduction of electric vehicles into the traffic flow occurs only when these vehicles move at speeds less than 50 km/h (in which case propulsion noise is dominant). In other cases, tyre-road noise is dominant and it does not matter if the vehicle is electric or not. Therefore, in Figures 2 and 3, you can see the variation in results indicated by the black lines. The maximum values of noise reduction occurred when vehicles of all categories moved at speeds less than 50 km/h. Minimum values of noise reduction could be observed when only heavy vehicles moved at speeds less than 50 km/h, and light and medium vehicles moved faster.

4. Conclusions

Modeling road noise while including the effect of electric and hybrid vehicles is still not a fully explored issue. Commonly used computational models do not have algorithms that could directly account for the effect of this vehicle type on reducing sound emissions in the road environment. Difficulties in modeling road noise with electric and hybrid cars are related to access to data on this vehicle type share in the traffic stream. General data is available on the number of registered electric and hybrid vehicles, but their share in the traffic stream on individual roads is unknown. It is also troublesome to obtain these data from “in situ” measurements due to the difficulty of identifying these vehicles in the traffic stream or situations where the type of propulsion (drivetrain in hybrid cars) is unknown at any given time.

Modeling road noise with electric and hybrid vehicle share in the traffic stream requires adopting a correction factor for the sound power level of the line source, which will take into account the reduction in drivetrain noise for this vehicle group. In the CNOSSOS-EU model, this type of noise is one of the two main sources of sound generated by passing cars. The second is rolling noise, which is does not change when compared to internal combustion engine vehicles.

The average noise reduction values after the introduction of electric vehicle traffic into the stream range from 0.2 dB to 1.9 dB for the daytime and from 0.2 dB to 1.8 dB for the nighttime. The reductions were much larger in some cases. Larger reduction values occur for certain electric vehicle shares in the traffic stream which are currently not present in most European countries, including Poland. Currently, there is virtually no improvement in the state of the acoustic climate surrounding the vast majority of road sections (given their very small share in the traffic stream and speeds higher than 50 km/h).

The analysis shows that acoustic modeling performed for extremely distant horizons of traffic parameter forecasts (20–30 years) should estimate the reduction in acoustic impact that may occur during this time due to electric vehicle share. The correction factors specified in the relationships (2.22) and (2.23) can be used for this purpose. When performing acoustic calculations for the current time horizon (or near-future forecasts), there is no need to take these coefficients into account.

Instead, as a direction for further research, there is a need to determine the acoustic power correction factors of the drivetrain for all electric vehicles categories (light, heavy, and motorcycles), which can be used in road noise modeling.

The rolling tyres are the main noise sources of electric and hybrid vehicles for all driving speeds, including low speeds when these cars are driven by electric motor. Thus nowadays the influence of acoustic quality of tyres becomes very important when modelling the noise emission to road surroundings. Simply: quieter tyres result in lower environmental noise emission. To determine the impact of using tyres with different external noise (based on the European Tyre Label noise values) an extensive measurement program has been launched in 2021 within the ELANORE project [28]. The results obtained in this project will hopefully allow to precisely forecast changes in environmental noise depending on the noise level of car tyres.

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Modelowanie wpływu pojazdów elektrycznych na poziom hałasu w otoczeniu odcinków dróg zamiejskich

Słowa kluczowe: pojazdy elektryczne, hałas, modelowanie hałasu drogowego, środowisko, obliczenia akustyczne

Streszczenie:

W wielu krajach europejskich obserwowany jest stały wzrost udziału pojazdów elektrycznych i hybrydowych w potoku ruchu. Pojazdy te, zwane często nisko lub zeroemisyjnymi, ograniczają w znacznym stopniu zanieczyszczenia powietrza w otoczeniu dróg. Mają także pozytywny wpływ na poziom hałasu w centrach miast oraz w otoczeniu dróg charakteryzujących się małymi prędkościami. Zagadnienia związane z modelowaniem hałasu pochodzącego od pojazdów elektrycznych i hybrydowych w środowisku zewnętrznym nie są jednak nadal w pełni zbadane, szczególnie w otoczeniu dróg zamiejskich. W artykule podjęto próbę oceny stopnia redukcji hałasu w otoczeniu tych dróg z uwagi na różny udział procentowy pojazdów elektrycznych w potoku ruchu. Dane wejściowe do modelowania hałasu uzyskano z 133 odcinków jednorodnych dróg zamiejskich w Polsce. Na podstawie ich analizy określono najpierw na ilu z tych odcinków dróg możliwa będzie redukcja hałasu powodowana przez pojazdy elektryczne, biorąc pod uwagę występujące na nich prędkości ruchu. Następnie przedstawiono algorytm obliczeniowy, który można wykorzystać do obliczeń redukcji hałasu w modelu CNOSSOS-EU i wykonano na jego podstawie modelowanie hałasu dla różnego udziału procentowego pojazdów elektrycznych w potoku ruchu.

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