Research Article

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Analysis of road traffic noise in an urban area in Croatia using different noise prediction models

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Abstract: Road traffic noise is the second largest environmental stressor in urban areas in Europe after air pollution. The harmful effects of noise arise mainly from the stress response it triggers in the human body, which can have significant consequences for physical and mental health. Therefore, the use of a reliable noise prediction model is an important prerequisite for the quality assessment of a number of residents exposed to excessive noise levels and for the selection of appropriate noise mitigation measures. In this study, the analysis of road traffic noise in an urban street in the narrower centre of the Croatian capital Zagreb was performed using four noise prediction models: "RLS-90", "RLS-19", "NMPB-Routes-96 (SET-RA-CERTU-LCPC-CSTB)", and "CNOSSOS-EU". LimA V2021 noise prediction software was used for the analysis, and the noise modelling results were validated with short-term noise measurements. The main objective of the research presented in the article was to test the "CNOSSOS-EU" method, recently introduced in Croatian noise control practice, and to gain initial insights into which of the aforementioned noise prediction models is the most reliable for the assessment of road traffic noise in urban environments in Croatia. A comparison of the noise modelling results with the results of short-term noise measurements has shown that the German national calculation methods "RLS-90" and "RLS-19" as well as the "CNOSSOS-EU" method provide significantly more accurate noise predictions than the "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)" method.

Keywords: road traffic noise, noise modelling, "RLS-90", "RLS-19", "NMPB-Routes-96 (SET-RA-CERTU-LCPC-CSTB)", "CNOSSOS-EU", comparative analysis

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1 Introduction

Road traffic noise is one of the biggest environmental problems of the last few decades in urban areas. The harmful effects of traffic noise arise primarily from the stress reactions it triggers in the human body, which can also manifest during sleep [1]. These can potentially lead to premature death, cardiovascular disease, cognitive impairment, sleep disturbance, hypertension, and, at the very least, annoyance [2–6]. Taken together, the societal costs of road traffic noise in terms of direct costs and externalities (medical treatment, reduced productivity at work, *etc.*) are estimated to be €40 billion per year in the European Union (EU) [7,8]. According to the 2020 report of the European Environment Agency (EEA) [9], the number of people exposed to road traffic noise far exceeds those exposed to rail, aircraft, and industrial noise. The reason for this is the extent of the road network, which is notably greater than that of other noise sources. Furthermore, it is estimated that about 82 million people within urban areas and about 31 million people outside urban areas are affected by road traffic noise at a level of at least 55 dB during the day–evening–night period. As for night time noise, the figures are 57 million and 21 million, respectively. This means that at least 20% of the EU population is exposed to high road traffic noise levels during the day–evening–night period and 15% during night time. In light of the above considerations, it can be concluded that road traffic noise is a serious environmental problem, especially in urban areas, which can have a significant impact on people's quality of life and health, and that a reliable estimate of the exposure of EU citizens to excessive noise levels is a prerequisite for supporting and evaluating a noise abatement policy at the European level.

In 2002, the EU issued the Environmental Noise Directive 2002/49/EC (END) [10] to reduce and manage environmental noise in EU Member States and to establish a common approach for the assessment of exposure to environmental noise in the EU. The END requires Member States to produce strategic noise maps, report the results of this assessment to the European Commission (EC), and prepare noise action plans to avoid, prevent, or reduce the harmful effects of environmental noise [11]. In order to produce strategic noise maps, EU Member States have initially used the so-called interim assessment methods or their own national noise calculation methods. In particular, the recommended interim assessment method for road traffic noise was the French national noise calculation method "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)" [12]. Since the end of 2018, EU Member States are obliged to use harmonized methods for assessing noise exposure in Europe "CNOSSOS-EU" [13].

Croatia is one of the EU countries that do not have national methods for noise calculation. Specifically, from the very beginning, Croatian engineers used the German standard DIN 18005 [14] and later the German national calculation method "RLS-90" [15], which is still widely used in Croatian noise control practice. After joining the EU, Croatia adopted the recommendations of END into its national legislation, and consequently, the interim assessment methods and "CNOSSOS-EU" were used for strategic noise mapping. It should be emphasized that the interim assessment method for road traffic noise "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)" [12] has been used mainly for strategic noise mapping and to a lesser extent for assessing the impact of a new road construction project on environmental noise, evaluating the effectiveness of various noise mitigation measures, estimating the number of residents exposed to excessive noise levels, *etc.* Specifically, previous studies conducted by the authors of this article [16–20] have shown that the noise prediction results obtained with this interim assessment method are not accurate enough and that the German national calculation method "RLS-90" provides more accurate results. On the other hand, the "CNOSSOS-EU" [13] is a noise calculation method that has only recently been introduced into Croatian noise control practice, and there are no scientific studies yet that have tested this method in the Croatian environment.

Accordingly, in this study, the analysis of road traffic noise in an urban street in the narrower centre of the Croatian capital Zagreb is carried out using different noise prediction models. These models are as follows: German national calculation method "RLS-90", new German national calculation method "RLS-19", interim assessment method "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)", and "CNOSSOS-EU". The new German national calculation method "RLS-19" [21] is included in the analysis because this method replaced the old German national calculation method "RLS-90", which has provided the most accurate noise predictions in noise control practice in Croatia so far. The analysis is performed using the noise prediction software LimA V2021, and the noise modelling results are validated with short-term noise measurements. As stated in the study of Murphy and King [22], the experience of EU Member States has shown that this is the best way to ensure that the applied noise model provides accurate results and reflects the real sound environment.

The main objective of the research presented in this article is to test the "CNOSSOS-EU" method and to gain initial insights into which of the above-mentioned noise prediction models is the most reliable for the assessment of road traffic noise in urban environments in Croatia. Section 2 provides the research background, i.e., the overview of EU and Croatian noise policies and related research. Section 3 describes the research methodology. This includes a brief description of (1) the urban street studied, (2) the field measurements of traffic volume and road traffic noise, and (3) the noise modelling procedure. Section 4 presents the research results and shows which of the noise prediction models used provided the most reliable results. Section 5 discusses the results and interprets them in light of previous studies and the working hypotheses. The limitations of the study and future research directions are also highlighted. Section 6 concludes the article.

2 Background

As mentioned earlier, one of the main objectives of the END [10] was to establish a common approach for the assessment of exposure to environmental noise in the EU using a set of harmonized noise indicators (L_{den} and L_{night}). EU Member States were required to produce strategic noise maps in accordance with Article 7 (1) from 30 June 2007, to enable authorities in EU Member States to set priorities for action planning and to assist the EC in identifying and informing the public about the number of people exposed to excessive noise [23]. Article 6.2 of the END authorized the EC to establish common assessment methods for determining the aforementioned noise indicators. Pending the adoption of such common assessment methods, the EU Member States could use either the interim assessment methods listed in paragraph 2.2 of Annex II of the END or their own national calculation methods.

Although it has been demonstrated that the national calculation methods of the EU Member States will provide similar or even the same results as those obtained by means of the interim methods, the EC found that in most cases these results differ significantly and that the figures on the number of people being exposed to harmful noise levels within and between the EU Member States are not consistent and comparable [24–26]. These problems arose mainly due to the differences between the assessment methods used by the EU Member States and the input data taken from national registers and databases; insufficient reporting of strategic noise mapping; different quality and format of data reported at the EU level; different strategies for selecting relevant roads, railways, airports, and urban agglomerations for noise analysis; unavailability of data needed for assessing the impact of noise on human health, *etc.* [16,27–34].

Consequently, in 2008, the EC initiated the development of harmonized methods for assessing noise pollution in Europe through the project entitled "Common Framework for Noise Assessment Methods (CNOSSOS-EU)" [13]. The main objective of the "CNOSSOS-EU" project was to develop a coherent methodological framework for the assessment of environmental noise and its effects on human health in order to enable consistent and accurate reporting of strategic noise maps by EU Member States [35]. This methodological framework was developed during the first phase of the "CNOSSOS-EU" process (2009–2012), based on the latest scientific, technical, and practical knowledge on the assessment of environmental noise in Europe and in conjunction with the experience gained from the first round of strategic noise mapping in 2007 [36]. In the second, so-called implementation phase of the "CNOSSOS-EU" process (2012–2015), a set of technical tools should have been developed to support the practical implementation of "CNOSSOS-EU" in the EU Member States. However, in 2015, an update of the END Annex II was published, requiring all EU Member States to use "CNOSSOS-EU" from 31 December 2018, and guidance on the practical implementation of "CNOSSOS-EU" is still lacking. As stated by Kumar *et al.* [29], a proof-of-concept version of the original ideas and features of these guidelines was created in the form of a website but has not been published, and no follow-up action has been taken to date.

The challenges of implementing this new harmonized calculation method for assessing noise pollution in Europe have been analysed in a number of studies in several EU countries. The results of these studies [37–45] have highlighted the critical issues on the "CNOSSOS-EU", mainly related to modified source/receiver heights in the formula for the lower bound of ground attenuation, problems that may occur when the source or receiver is located below the mean plane, insufficiently defined determination of the Rayleigh criterion, an error that can occur with more than one diffraction point under favourable conditions, the ground attenuation method that differs significantly from the one used in ISO 9613-2 [46], standardization of the noise simulation input and output data, *etc.* In 2018, an EU working group chaired by the Netherlands and mandated by the Noire Regulatory Committee was formed to identify and categorize all these issues and finally propose the best solutions for them [47].

Croatia applied for EU membership in 2003 and was in negotiations from 2005 to 2011 [48]. On 9 December 2011, EU and Croatian leaders signed the Accession Treaty, and on 1 July 2013, the country became the 28th member of the EU. Accordingly, Croatia incorporated the recommendations of the END into its first "Noise Protection Act" of 2003 [49], which required the preparation of noise maps, the designation of critical areas, and the adoption of action plans for noise abatement in places where permissible noise levels are exceeded. At that time, noise maps were prepared for several Croatian cities with less than 70,000 inhabitants (Bjelovar, Kutina, Pula, Sisak, Velika Gorica, and Varaždin) [50].

Since then, awareness of the problem of noise pollution has grown significantly in this country, and all further regulations in this area have been accompanied by amendments to the END and recommendations from EC and other relevant EU bodies [16–20,51–69]. As a result, strategic noise maps and action plans were prepared for the second and third reporting rounds in 2012 and 2017, in accordance with the provisions of the new "Noise Protection Act" of 2009 [70] and "Rulebook on the preparation and content of noise maps and action plans and on the method for calculating permissible noise indicators" of 2009 [71] using the interim assessment methods. These strategic noise maps and action plans were made for the following areas: (1) the four largest Croatian cities with more than 100,000 inhabitants (Zagreb, Split, Rijeka, and Osijek), (2) main railways and roads outside settlements (highways and other public roads), and (3) the airport in the city of Dubrovnik [50]. The results of the second reporting round of strategic noise mapping in Croatia were not submitted to EC timely and were therefore not presented in the 2014 EEA report [72]. However, in the third reporting round, Croatia submitted all required data to EC on time, and the results of the strategic noise mapping for 2017 were included in the 2020 EEA report [9]. The results of this reporting round showed that the noise situation in this country is notably better or at least comparable to the noise situation in other EU Member States and that the number of people exposed to excessive road traffic noise in Croatia is significantly higher than the number of people exposed to rail, aircraft, and industrial noise, especially in urban areas.

Strategic noise maps and action plans for the fourth reporting round in 2022 were prepared in accordance with the provisions of the new "Rulebook on amendments to the Rulebook on the preparation and content of noise maps and action plans and on the method for calculating permissible noise indicators" of 2018 [73] using the "CNOSSOS-EU" method. However, these documents have not yet been published and are not available to the public.

3 Methodology

This section contains a brief description of the following: the urban street studied, the field measurements of road traffic noise and traffic volume, and the noise modelling procedure.

According to the Croatian "Noise Protection Act" [70], noise analysis should be carried out in the following periods:
- "day" period from 7:00 a.m. to 7:00 p.m.,
- "evening" period from 7:00 p.m. to 11:00 p.m., and
- "night" period from 11:00 p.m. to 7:00 a.m.

The maximum permissible noise levels in these periods are specified in the "Rulebook on the preparation and content of noise maps and action plans and on the method for calculating permissible noise indicators" [71] and depend on the land use. Noise control in the city of Zagreb is also regulated by the "General Urban Plan (GUP) of the city of Zagreb" [74], a basic document that defines land use and prescribes all activities that must be carried out in the city. The time periods specified in "GUP of the city of Zagreb" during which noise analyses must be carried out correspond to the time periods specified in the "Noise Protection Act" [70], while the maximum permissible noise levels specified in this document are equal to or lower than the values specified in the "Rulebook" [71].

3.1 Location description

The analysis was conducted in Klaić St., which is located in the narrower centre of the city of Zagreb, the capital of Croatia. Klaić St. is an approximately 800 m long three-lane one-way street with high traffic intensity (Figure 1). This street extends from Savska St. to the Republic of Austria St. and is an integral part of the so-called "green wave", which is about 4 km long and connects the eastern and western parts of the city.

On the south side of Klaić St., there are parallel parking lots, and on the north side, there are angle parking lots with trees planted in between. On the sidewalks, which are about 2 m wide, there are bicycle lanes for one row of cyclists and pedestrian lanes for two rows of pedestrians. Klaić St. contains four three-legged intersections (Klaić St.–Medulić St., Klaić St.–Hochman St., Klaić St.–Primorska St., and Klaić St.–Krajiška St.) and one four-legged intersection (Klaić St.–Kačić St.). At the intersections Klaić St.–Medulić St. and Klaić St.–Kačić St., traffic is regulated by traffic lights. In the areas between the intersections, there are two crosswalks with traffic lights and one without traffic lights. The speed limit in Klaić St. and adjacent streets is set at 50 km/h. In Klaić St., most of the buildings are residential with four to five floors. Besides residential buildings, there are also educational institutions, hospitals, museums, a nursing home, a playground, and parks.

Figure 1: Location of Klaić St. in the city of Zagreb [75].

Table 1: Meteorological conditions during the noise measurements

Meteorological conditions	Time period			
	"Day"		"Evening"	"Night"
	8:00 a.m.–9:00 a.m.	4:00 p.m.–5:00 p.m.	9:00 p.m.–10:00 p.m.	11:00 p.m.–00:00 a.m.
Wind: direction speed (m/s)	SE 1.3	SW 2.0	W 3.0	SW 2.8
Air temperature (°C)	9.4	20.1	16.0	15.2
Relative humidity (%)	74	62	47	48
Atmospheric pressure (hPa)	1018.7	1014.0	1013.0	1013.0
Weather conditions	Clear	Partly cloudy	Clear	Clear

3.2 Field measurements

Field measurements included short-term noise measurements and traffic volume measurements. The short-term noise measurements were conducted to validate the noise prediction results once the noise modelling was completed. The traffic volume measurements were conducted simultaneously with the short-term noise measurements to provide the necessary input data on traffic volume for the definition of noise sources in the noise modelling process.

3.2.1 Noise measurements

Short-term noise measurements of 15 min duration were conducted under favourable meteorological conditions (Table 1) using two Brüel and Kjaer integrating sound level meters (Type 2260 and Type 2270) placed at a horizontal distance of 7.5 m from the edge of the roadway and at a height of 1.2 m above the ground. They were carried out at the four measurement points shown in Figure 2 (MP1, MP2, MP3, and MP4) at the following times: during the morning and afternoon rush hours from 8:00 a.m. to 9:00 a.m. and from 4:00 p.m. to 5:00 p.m. ("day" period), in the evening from 9:00 p.m. to 10:00 p.m. ("evening" period), and at night from 11:00 p.m. to 00:00 a.m. ("night" period). The daytime rush hours were selected for the analysis, as the hourly traffic volume was highest during this time (the worst noise scenarios), while the traffic volume was significantly lower in the evening and at night. In this way, the selected noise prediction models were validated under different traffic conditions.

The measurements were carried out in accordance with the HRN ISO 1996-1:2016 [76] and HRN ISO 1996-2:2017 [77] standards, and the selected measurement interval (longer than 10 min) covered all significant variations in noise emissions. The sound level meters (microphones) at all measurement points were located in incident sound fields (there were no reflective surfaces in the vicinity).

The uncertainty of the sound pressure levels was determined as described in the HRN ISO 1996-2:2017 standard [77], and the modelling approach consisting of identifying and qualifying all major sources of uncertainty (the so-called "uncertainty budget") was applied. The measurement uncertainty depended on the sound source and the measurement time interval, the meteorological conditions, the distance from the source, the measurement method, and the instrumentation.

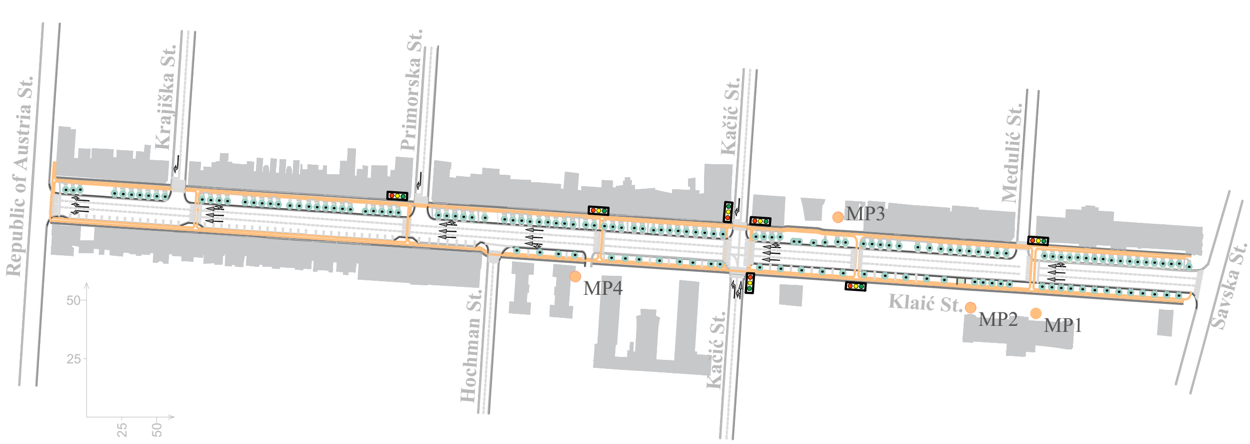


Figure 2: Positions of the measurement points MP1, MP2, MP3, and MP4 during the noise measurements.

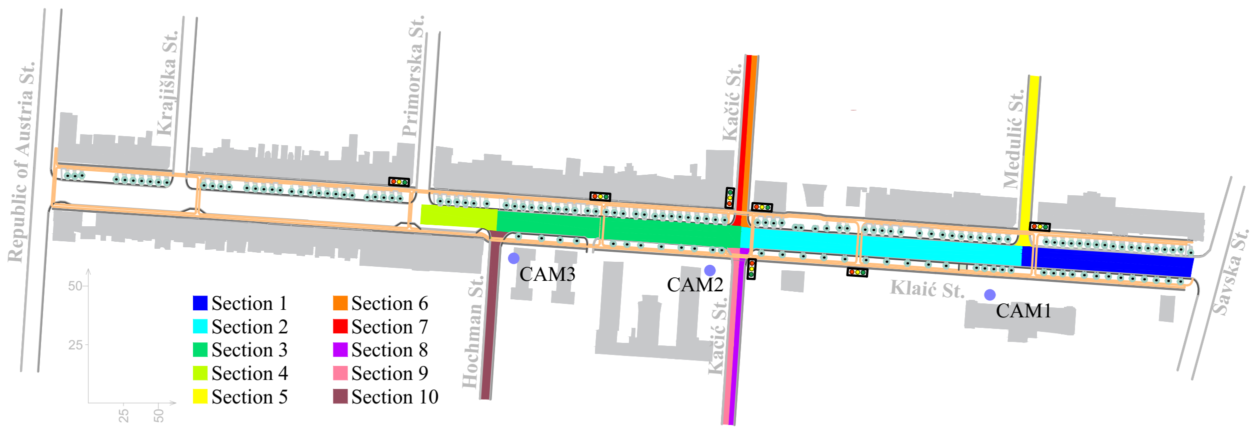


Figure 3: Positions of video cameras and ten characteristic sections with different traffic volumes.

3.2.2 Traffic volume measurements

Measurements of traffic volume of 60 min duration were performed with the three video cameras (CAM1, CAM2, and CAM3) placed near the following street intersections: Klaić St.–Medulić St., Klaić St.–Kačić St., and Klaić St.–Hochman St. (Figure 3). As mentioned earlier, these measurements were conducted on the same day and during the same time periods as the short-term noise measurements: during the morning and afternoon rush hours from 8:00 to 9:00 a.m. and from 4:00 to 5:00 p.m. ("day" period), in the evening from 9:00 p.m. to 10:00 p.m. ("evening" period), and at night from 11:00 p.m. to 00:00 a.m. ("night" period). In the traffic count based on video recordings, Klaić St. and the surrounding streets were divided into ten characteristic sections with different traffic volumes, shown in Figure 3, and the recorded vehicles were divided into two categories:

- Category 1 (C1): vehicles up to 3.5 t;
- Category 2 (C2): vehicles over 3.5 t.

As can be seen in Figures 2 and 3, the analysis of road traffic noise in Klaić St. was conducted on the section from Savska St. to Primorska St.

3.3 Noise modelling

Noise modelling was performed using LimA V2021 noise prediction software. Necessary input data for the calculation of noise levels with the noise prediction software is a digital terrain model (DTM) of the area for which the calculation is performed. In this study, the DTM was defined based on different types of obstacles (Figure 4). The areas within the corridors of Klaić St. and adjacent streets, as well as the surrounding terrain, were defined as flat areas using "contour lines" due to the low longitudinal slope of these streets and the general flatness of the terrain. The surrounding facilities were defined as "buildings with flat roofs" with a height of 3 m per floor.

Noise sources were defined with the different object types depending on the calculation method used:

- Road (RLS90) polyline "STL" for the German national calculation method "RLS-90",
- Street as a line according to the END "SLU" for the German national calculation method "RLS-19",
- Road (NMPB) polyline "RUE" for the interim method "NMPB-Routes-96",
- Road (CNOSSOS) polyline "CRO" for the "CNOSSOS-EU" method.

The defined attributes of these noise sources are shown in Table 2.

Noise calculations were conducted for the time periods "day", "evening", and "night" at four free-field receptors FF1, FF2, FF3, and FF4, which were located at the same place as the measurement points MP1, MP2, MP3, and MP4 during the short-term noise measurements (Figure 4). As can be seen from Figure 4, when using the "RLS-90" and "RLS-19" calculation methods, the source lines were placed in the centre of the outer lanes, and when using the interim "NMPB-Routes-96" and "CNOSSOS-EU" calculation methods, the source lines were placed in the centre of each lane of the road. As for the number of vehicles on the characteristic sections with different traffic volumes (Figure 3, Table 3), it was evenly distributed among all or only outer lanes of Kačić St. and the adjacent streets, depending on the noise calculation model used.

Figure 4: Positions of free-field receptors FF1, FF2, FF3, and FF4 and source lines during the noise modelling with (a) calculation methods “RLS-90” and “RLS-19” and (b) calculation methods interim “NMPB-Routes-96” and “CNOSSOS-EU”.

4 Results

4.1 Results of the measurements of the traffic volume

The results of the traffic volume measurements are shown in Table 3. As can be seen, traffic on Klaić St. was most intense during the afternoon rush hour from 4:00 p.m. to 5:00 p.m., and the share of heavy vehicles in the traffic flow was negligible.

4.2 Results of the noise measurements

The graphs of A-weighted 1 s equivalent continuous sound levels ($L_{\mathrm{Aeq,1s}}$) at measurement points MP1, MP2, MP3, and MP4 during the morning and afternoon rush hours from 8:00 to 9:00 a.m. and from 4:00 to 5:00 p.m. (“day” period), in the evening from 9:00 to 10:00 p.m. (“evening” period), and at night from 11:00 p.m. to 00:00 a.m. (“night” period) are shown in Figures 5–8.

The results of the short-term noise measurements, expressed as A-weighted equivalent continuous sound

Table 2: Attributes of the noise sources of the calculation methods used

Attributes of noise sources	Calculation method			
	"RLS-90"	**"RLS-19"**	**"NMPB-Routes-96"**	**"CNOSSOS-EU"**
Source type	Line source	Line source	Line source	Line source
Source height (m) (above the ground)	0.50	0.50	0.50	0.05
Road type	Community	Community	Urban	Urban
Road surface	Asphalt	Asphalt	Smooth asphalt	Dense asphalt
Correction for road surface	–[e]	Not applied	–[e]	–[e]
Road slope (%)	0	0	0	0
Traffic direction	–[e]	–[e]	Applied	Applied
Traffic flow state[a,b]	–[e]	–[e]	Applied	–[e]
Number of all vehicles (veh/h)[a]	Data from traffic volume measurements	Data from traffic volume measurements	–[e]	–[e]
Number of light vehicles (veh/h)[a,c]	–[e]	–[e]	Data from traffic volume measurements	Data from traffic volume measurements
Percentage of heavy vehicles (%)[a,d]	Data from traffic volume measurements	Data from traffic volume measurements	–[e]	–[e]
Number of heavy vehicles (veh/h)[a,d]	–[e]	–[e]	Data from traffic volume measurements	Data from traffic volume measurements
Speed limit for light vehicles (km/h)[a,c]	50	50	50	50
Speed limit for heavy vehicles (km/h)[a,d]	50	50	50	50
Correction for intersections	Applied	Applied	Applied	Applied

[a]In each period: "day"/"evening"/"night".
[b]Traffic flow states: steady/stop and go/accelerating/decelerating.
[c]Vehicles up to 3.5 t: for "RLS-90" Pkw/for "RLS-19" Pkw/for "NMPB-Routes-96" and "CNOSSOS-EU" C = 1,4.
[d]Vehicles over 3.5 t: for "RLS-90" Lkw/for "RLS-19" Lkw1 and Lkw2/for "NMPB-Routes-96" and "CNOSSOS-EU" C = 2,3.
[e]Attribute of the noise source is not available for the calculation method in question.

Table 3: Results of the traffic volume measurements

Section No.	Traffic volume (veh/h)							
	"Day"				"Evening"		"Night"	
	8:00 a.m.–9:00 a.m.		4:00 p.m.–5:00 p.m.		9:00 p.m.–10:00 p.m.		11:00 p.m.–00:00 a.m.	
	C1[a]	C2[b]	C1[a]	C2[b]	C1[a]	C2[b]	C1[a]	C2[b]
1	1,656	8	1,826	3	1,002	1	724	1
2	1,408	8	1,634	3	860	1	628	1
3	1,731	8	2,106	3	1,076	1	806	1
4	1,159	3	1,450	3	816	1	630	1
5	248	0	192	0	142	0	96	0
6	160	0	158	0	76	0	36	0
7	203	0	186	0	44	0	60	0
8	192	0	272	0	146	0	90	0
9	88	0	172	0	102	0	64	0
10	572	5	656	3	260	1	176	1

[a]Category 1: Vehicles up to 3.5 t.
[b]Category 2: Vehicles over 3.5 t.

levels (L_{Aeq}) over measurement periods of 15 min, are shown in Table 4. As can be seen, at most of the measurement points (MP1, MP2, and MP3), the highest noise levels were recorded during the afternoon rush hour.

4.3 Results of the noise modelling procedure

The results of noise calculations at the free-field receptors FF1, FF2, FF3, and FF4 using different noise prediction models (old German national calculation method "RLS-90", new German national calculation method "RLS-19", interim assessment method "NMPB-Routes-96 [SETRA-CERTU-LCPC-CSTB]" and "CNOSSOS-EU") are shown in Table 5.

4.4 Validation of the results obtained with the noise modelling procedure

To obtain comparable results, the logarithmic average of all L_{Aeq} noise level values obtained by noise measurements in the time periods "day" and "evening" at each measurement point was determined using equation (1) (Table 6)

$$\overline{L}_{\mathrm{Aeq}} = 10 \log \frac{1}{n}\left(\sum_{i=1}^{n} 10^{L_{\mathrm{Aeq}}/10}\right), \tag{1}$$

where $\overline{L}_{\mathrm{Aeq}}$ is the logarithmic average of A-weighted equivalent continuous sound levels in the time periods "day" and "evening" at a certain measurement point (dB(A)), n is the number of measurements in the time periods "day" and

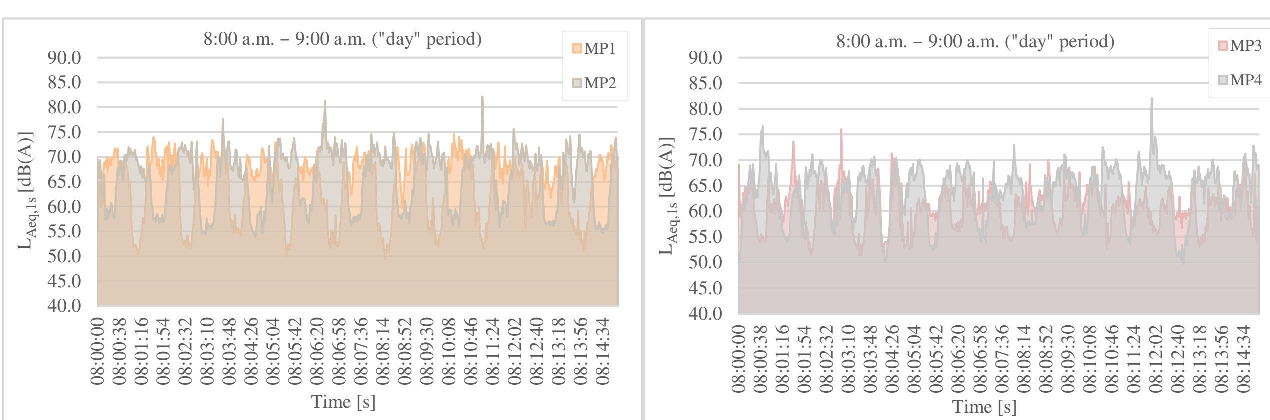


Figure 5: The graphs of A-weighted 1 s equivalent continuous sound levels ($L_{\mathrm{Aeq,1s}}$) at measurement points MP1, MP2, MP3, and MP4 during the morning rush hour from 8:00 to 9:00 a.m. ("day" period).

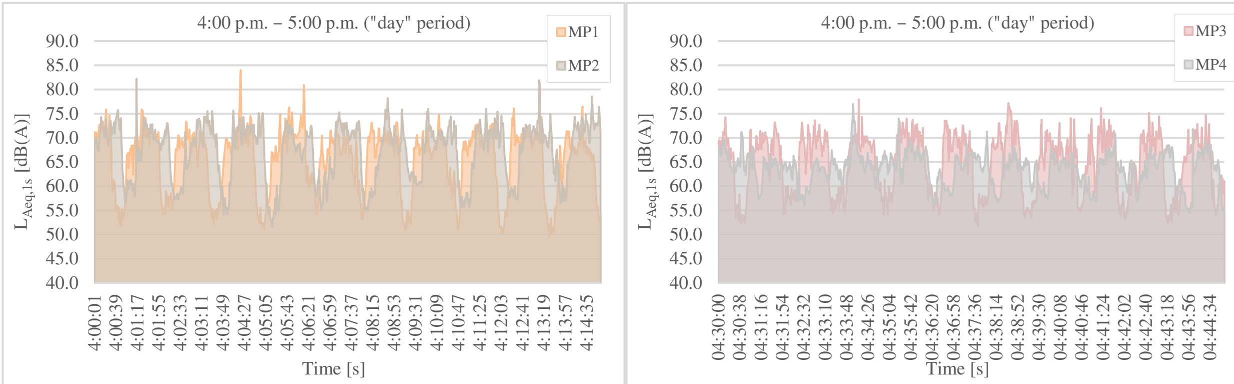


Figure 6: The graphs of A-weighted 1 s equivalent continuous sound levels ($L_{Aeq,1s}$) at measurement points MP1, MP2, MP3, and MP4 during the afternoon rush hour from 4:00 to 5:00 p.m. ("day" period).

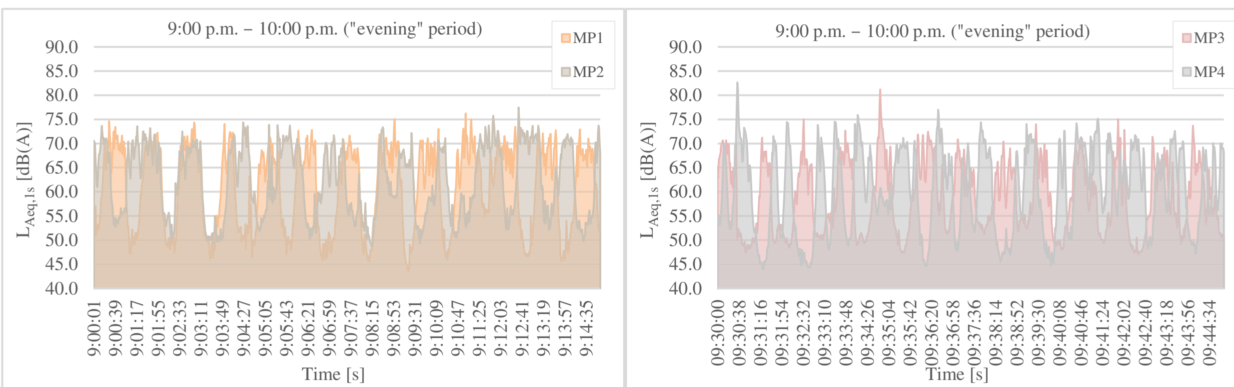


Figure 7: The graphs of A-weighted 1 s equivalent continuous sound levels ($L_{Aeq,1s}$) at measurement points MP1, MP2, MP3, and MP4 in the evening from 9:00 to 10:00 p.m. ("evening" period).

"evening" at a certain measurement point (–), and L_{Aeq} is the A-weighted equivalent continuous sound levels in the time periods "day" and "evening" at a certain measurement point (dB(A)).

A comparison of the noise modelling results obtained with the various noise prediction models (Table 5) with the results of the short-term noise measurements (Table 6) is shown in Figure 9. As can be seen, the interim "NMPB-

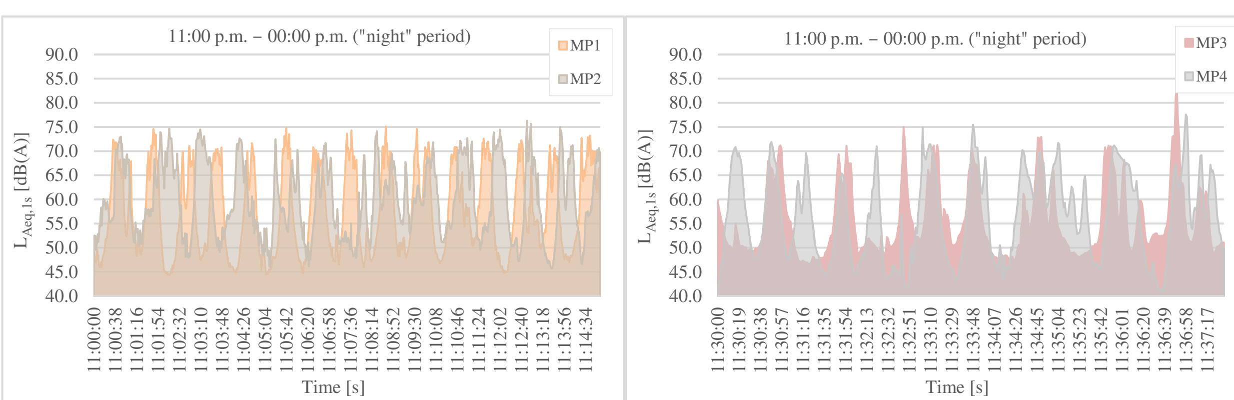


Figure 8: The graphs of A-weighted 1 s equivalent continuous sound levels ($L_{Aeq,1s}$) at measurement points MP1, MP2, MP3, and MP4 at night from 11:00 p.m. to 00:00 a.m. ("night" period).

Table 4: Results of the noise measurements at the measurement points MP1, MP2, MP3, and MP4

Measurement point	Noise levels L_{Aeq} (dB(A))			
	"Day"		"Evening"	"Night"
	8:00 a.m.–9:00 a.m.	4:00 p.m.–5:00 p.m.	9:00 p.m.–10:00 p.m.	11:00 p.m.–00:00 a.m.
MP1	67.1	68.5	66.3	64.8
MP2	68.6	70.1	66.9	65.6
MP3	62.5	67.8	64.5	63.3
MP4	66.4	64.9	66.5	63.6

Table 5: Results of noise calculations at the free-field receptors FF1, FF2, FF3, and FF4

Free-field receptor	Noise levels L_{Aeq} (dB(A))			
	"RLS-90"	"RLS-19"	"NMPB-Routes-96"	"CNOSSOS-EU"
"Day" period 7:00 a.m.–11:00 p.m.				
FF1	67.5	67.7	75.1	68.8
FF2	68.3	67.7	71.1	69.1
FF3	67.6	67.3	74.2	68.8
FF4	67.5	67.4	72.1	68.4
"Night" period 11:00 p.m.–07:00 a.m.				
FF1	63.6	63.8	70.4	65.0
FF2	64.4	63.9	66.8	65.3
FF3	63.7	63.5	70.3	65.0
FF4	63.8	63.7	68.4	64.7

Table 6: Summarized results of the noise measurements at the measurement points MP1, MP2, MP3, and MP4 for the period "day" and the period "night"

Measurement point	Noise levels L_{Aeq} (dB(A))	
	"Day"	"Night"
MP1	67.4	64.8
MP2	68.7	65.6
MP3	66.5	63.3
MP4	66.0	63.6

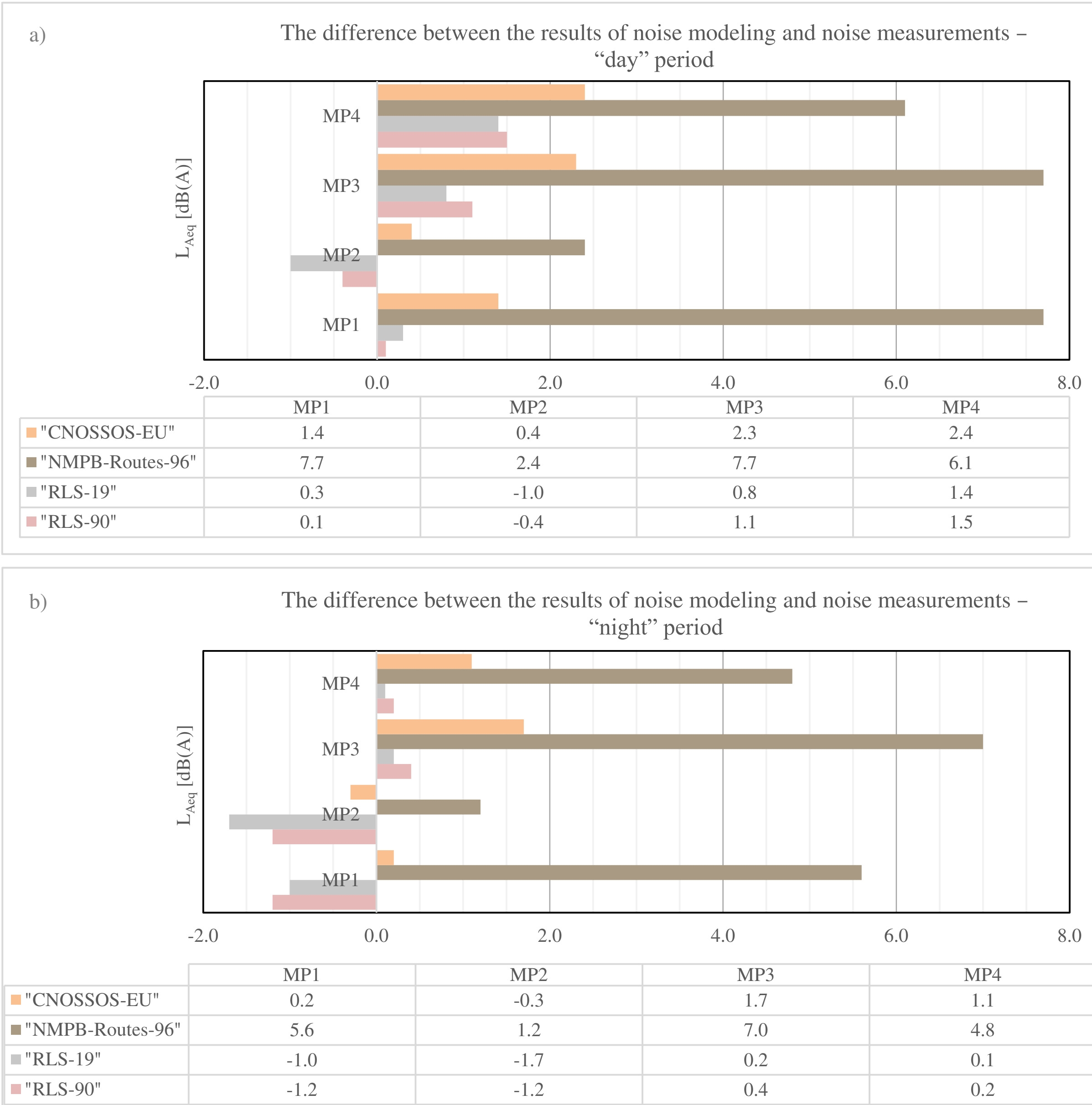
Routes-96 (SETRA-CERTU-LCPC-CSTB)" method deviated the most from the results of noise measurements at most measurement points in both time periods.

5 Discussion

A comparison of the noise modelling results with the results of short-term noise measurements has shown that the German national calculation methods "RLS-90" and "RLS-19" as well as the "CNOSSOS-EU" method provide significantly more accurate noise predictions compared to the interim assessment method "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)". In the "day" period, the difference between the results of noise modelling and noise measurements was from −0.4 to 1.5 dB(A) for the "RLS-90" method, from −1.0 to 1.4 dB(A) for the "RLS-19" method, from 0.4 to 2.4 dB(A) for the "CNOSSOS-EU" method, and from 2.4 to 7.7 dB(A) for the interim "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)" method. For the "night" period, these values ranged from −1.2 to 0.4 dB(A), from −1.7 to 0.1 dB(A), from −0.3 to 1.7 dB(A), and from 1.2 to 7.0 dB(A), respectively.

As can be seen from Figure 9, the noise predictions made using the interim "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)" method differed significantly from the results of the noise measurements at most of the measurement points (MP1, MP2, and MP3) and in both time periods. This difference was most evident in the "day" period, when traffic volumes were high and traffic flow was unstable (7.7 dB(A) at measurement points MP1 and MP3 and 6.1 dB(A) at measurement point MP4). These results are consistent with the results of previous studies conducted by the authors of this article [16-20], which showed that the interim "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)" method is not sufficiently reliable for the assessment of road traffic noise in urban environments in Croatia. On the other hand, the German national calculation method "RLS-90" provided quite reliable noise predictions at all measurement points in both time periods, which also corresponds to the results of previous investigations.

The new German national calculation method "RLS-19" provided very similar noise predictions as the old German national calculation method "RLS-90". Consequently, these two noise prediction models simultaneously resulted in either lower or higher noise level values compared to those determined by noise measurements at specific measurement points during both time periods. As can be seen from the diagrams in Figure 9, the lower noise values were recorded at measurement point MP2 in the "day"



a)

	MP1	MP2	MP3	MP4
"CNOSSOS-EU"	1.4	0.4	2.3	2.4
"NMPB-Routes-96"	7.7	2.4	7.7	6.1
"RLS-19"	0.3	-1.0	0.8	1.4
"RLS-90"	0.1	-0.4	1.1	1.5

b)

	MP1	MP2	MP3	MP4
"CNOSSOS-EU"	0.2	-0.3	1.7	1.1
"NMPB-Routes-96"	5.6	1.2	7.0	4.8
"RLS-19"	-1.0	-1.7	0.2	0.1
"RLS-90"	-1.2	-1.2	0.4	0.2

Figure 9: A comparison of the noise modelling results obtained with the various noise prediction models with the results of the short-term noise measurements for (a) “day” period and (b) “night” period.

period and at measurement points MP1 and MP2 in the “night” period, while the higher noise values were recorded at all other measurement points in the “day” and “night” periods.

The “CNOSSOS-EU” method also provided fairly reliable noise predictions at all measurement points and in both time periods. In general, the noise predictions of this method deviated somewhat more from the results of the noise measurements than the noise predictions of the German national calculation methods “RLS-90” and “RLS-19”. However, this method resulted in more accurate noise predictions at measurement points where the noise predictions of the German national calculation methods deviated the most from the results of the noise measurements (measurement point MP2 in the “day” period and measurement points MP1 and MP2 in the “night” period). In addition, the noise level values determined by the “CNOSSOS-EU” method were in most cases higher than the values determined by field measurements, which is favourable in terms of noise protection.

These discrepancies between the noise levels determined by the noise modelling procedure using the four calculation methods in question and the noise levels determined by field measurements were to a certain extent to be expected. As already mentioned in the introduction, German standard (DIN 18005) and guidelines ("RLS-90" and "RLS-19") for the calculation of road traffic noise have been used in Croatian noise protection practice from the very beginning, and the German noise prediction models proved to be the most accurate models for the assessment of road traffic noise in Croatia. Specifically, Croatian engineers have been using German standards and guidelines for years in many different areas of their design practice (road planning, pavement dimensioning, building construction, *etc.*), and consequently, the local conditions in these two countries are very similar. The interim "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)" method, which is originally a French method for calculating road traffic noise, often led to noise predictions that deviated significantly from the noise levels determined by field measurements in Croatia. The "CNOSSOS-EU" method, on the other hand, has only recently been introduced into Croatian noise control practice, and there is a lack of scientific studies that have tested this method in the Croatian environment.

Finally, the research results have shown that the German national calculation methods "RLS-90" and "RLS-19" as well as the "CNOSSOS-EU" method are adequate noise prediction models for the analysis of road traffic noise in urban environments in Croatia. However, it would be advisable to perform noise analyses in a larger number of urban streets in Croatia and test these methods under different traffic conditions. This is particularly important for two reasons. First, national noise calculation methods and all associated input data and other parameters are primarily adapted to local conditions in these countries [78–79]. Accordingly, numerous studies have been carried out worldwide in countries that do not have their own noise calculation methods to determine whether such methods can be used in different environments. For example, studies in Colombia [80] and India [81] have shown that the German national calculation methods "RLS-90" and "RLS-19" can also be used in these countries, often with certain modifications to the input parameters and other calculation parameters, and lead to sufficiently accurate calculation results. Second, many European countries faced the challenge of implementing the methods recommended by the END for strategic noise mapping and the assessment of noise pollution in Europe: the interim "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)" method and the new harmonized method "CNOSSOS-EU". As mentioned earlier, after the first round of strategic noise mapping, the EC assessed the degree of comparability of the results obtained with the different national noise calculation methods and found that in many cases the assessment methods used by the Member States differed significantly from the interim methods [23]. During the implementation process of the "CNOSSOS-EU" noise model, many questions were also raised, and some countries found this method accurate enough for strategic noise mapping, while others did not. The study from the Netherlands [41], for example, showed that the "CNOSSOS-EU" method leads to quite accurate calculation results, i.e. very similar to the results of the national "SRM2" calculation method for road and railway noise. The study from Finland [40], on the other hand, showed that the noise levels calculated using the "CNOSSOS-EU" method differ significantly from the noise levels determined using the "Nord2000" method and that the guidance given in the new Annex II of the END has a number of shortcomings and is not fully consistent.

6 Conclusion

Croatia is one of the EU countries that do not have national methods for noise calculation. Initially, Croatian engineers used the German standard DIN 18005 and later the German national calculation method "RLS-90" for the analysis of road traffic noise in this country. After joining the EU, Croatia adopted the recommendations of END into its national legislation, and consequently, the interim assessment methods and "CNOSSOS-EU" were used for strategic noise mapping. Previous studies conducted by the authors of this article have shown that noise predictions obtained with the interim assessment method for road traffic noise "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)" are not accurate enough and that the German national calculation method "RLS-90" provides more accurate results. On the other hand, the "CNOSSOS-EU" was introduced into the Croatian noise control practice only recently and there are no scientific studies that have tested this method in the Croatian environment to date.

In this study, the analysis of road traffic noise in an urban street in the narrower centre of the Croatian capital Zagreb was performed using four noise prediction models: "RLS-90", "RLS-19", "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)", and "CNOSSOS-EU". LimA V2021 noise prediction software was used for the analysis, and the noise modelling results were validated with short-term noise measurements. The main objective of the research presented in the article was to test the "CNOSSOS-EU" method, recently introduced in Croatian noise control practice, and to determine which of the above-mentioned noise prediction models is the most reliable for assessing road traffic noise in urban environments in Croatia. The new German national calculation method "RLS-19" was included in the analysis because this method replaced the old German national calculation method "RLS-90", which, as mentioned above, provided the most accurate results for the prediction of road traffic noise in Croatia.

A comparison of the noise modelling results with the results of short-term noise measurements has shown that the German national calculation methods "RLS-90" and "RLS-19" as well as the "CNOSSOS-EU" method provide significantly more accurate noise predictions compared to the interim assessment method "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)". In the "day" period, the difference between the results of noise modelling and noise measurements was from −0.4 to 1.5 dB(A) for the "RLS-90" method, from −1.0 to 1.4 dB (A) for the "RLS-19" method, from 0.4 to 2.4 dB(A) for the "CNOSSOS-EU" method, and from 2.4 to 7.7 dB(A) for the interim "NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)" method. For the "night" period, these values ranged from −1.2 to 0.4 dB (A), from −1.7 to 0.1 dB(A), from −0.3 to 1.7 dB(A), and from 1.2 to 7.0 dB(A), respectively.

Finally, the research results have shown that the German national calculation methods "RLS-90" and "RLS-19", as well as the "CNOSSOS-EU" method, which has been used for strategic noise mapping in Croatia since 2019, are suitable noise prediction models for the analysis of road traffic noise in urban areas in this country. However, further research should include noise analyses in a larger number of urban streets in Croatia to test these methods under different traffic conditions, i.e. the applied procedure should be extended to other pilot cases to expand the study to other scenarios, including variations in vehicle speed, road gradient, road surface type, traffic composition, weather conditions, *etc.* In addition, the time window of 15 min could be extended and continuous noise monitoring for days or weeks made in order to obtain even more conclusive results. Further research should also include relevant statistics and discussions on the number of highly annoyed individuals exposed to excessive noise levels in the urban areas analyzed. This would provide additional insight into the societal impact of road traffic noise when choosing an appropriate noise calculation method.

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